

DECISION MAKING FRAMEWORK FOR THE
**ASSESSMENT OF CIRCULAR
PAVEMENT INNOVATIONS**

CASE STUDY OF AMSTERDAM FIELD LABS

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MASTER THESIS

DECISION MAKING FRAMEWORK FOR THE ASSESSMENT OF CIRCULAR PAVEMENT INNOVATIONS

CASE STUDY OF AMSTERDAM FIELD LABS

MASTERS THESIS

*In partial fulfilment of the requirements for the degree of Master of Science in Construction
Management and Engineering at Delft University of Technology*

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Preface

Two years ago, I made the steadfast decision to pursue my masters degree in Construction Management and Engineering at TU Delft, and on the first day of lectures, I knew I had made the best decision for myself. It was the first time I was confident in the future of my career, and I knew I belonged in the field of construction, working with people and leading teams with innovation, strategy and resilience. One year ago, I discovered circularity and urban redevelopment, and I haven't looked back since. I started this thesis with a vision to truly bring circularity to life through a practical and implementable project, but I was unsure how to realise this dream.

When reading about circularity and innovations, I was surprised by how challenging it was to bring innovation to the construction industry and how one of the main issues was collaboration between diverse stakeholders. It was then that I decided to make a decision making tool that would not only optimise the process of selecting circular products, services and innovations, but bring together numerous stakeholders in the process.

Through this thesis I have had the privilege of speaking to some of the most inspiring professionals from the field, and I was in awe to witness their passion for circularity despite the challenges they faced. I realized the importance of my contribution to the field, and brought this research study to completion.

I am truly grateful to my thesis committee from TU Delft, for their constant guidance and honesty. I thank my committee chair, Daan Schraven for his detailed reviews of my work and constantly steering me in the right direction. I thank my first supervisor, Ruben Vrijhoef, for his unique feedback that helped me consider aspects I hadn't thought of before, and improve my work from new points of view. I am extremely grateful to my second supervisor, Felix Froehling, for his immense knowledge in the subject, constant encouragement and being the rock throughout my project, without whom this would not have been possible. I am especially grateful to my company supervisor Tatiana Zwart, who first inspired me to explore the practical approach to circularity, and who supported me continuously throughout this process, who was there for me for the good times and the bad times, and believed in my work when I doubted everything. I would not be here today without you. I am also thankful to the team of experts at Brink, who were always available to help me with their knowledge no matter how busy they were, and inspired me to continue my career in circularity after my thesis.

I am extremely grateful to my family and peers, whose motivation kept me going, and provided me with a support system that I know I can rely on. My parents, who have seen me work through this thesis for three seasons and my sister, who is always there for me. I would like to extend a special thank you to my roommate Soumya, who cried with me, laughed with me, made sure I stayed healthy and kept me sane, who was always ready to help me, review my work, improve my data, and most of all, believed in the potential of my research. I would also like to thank my best friend Achintya, whose support during this process helped me shape my ideas and complete the project. I would not be here without all of you.

I hope you experience the inspiration and excitement I felt every time I uncovered a new piece of the puzzle, as I pursued my masters thesis research. It has been one of my most fulfilling achievements to complete my master thesis through this study.

Executive Summary

Introduction

Circularity is an integral part of the construction industry and numerous initiatives are undertaken by the municipalities and market players of the Netherlands to evaluate and maximize the potential for circularity in their projects. There still remains risks and uncertainties with the application of circular innovations in projects that causes contractors and others to hesitate when choosing circular innovations over conventional technologies. While circularity for buildings has been vastly explored, emerging research also focuses on public spaces. Road infrastructure is an excellent opportunity for the widespread application of circularity due to its standardization and scalability, and it can thus enable the implementation of circular innovations rapidly across diverse landscapes. An important tool to enable the circular transition is decision making frameworks, that can accelerate the process of choosing circular innovations and checking their performance against other materials, equipment and processes. This Master's thesis focuses on studying the process integration of various new road construction materials and technologies and a detailed comparison of alternatives to create a decision making framework based on the road renovation projects and field labs testing set up by the Municipality of Amsterdam. Through interviews with primary stakeholders from the projects and industry experts, diverse perspectives were captured to define indicators and trade-offs with a Multi Criteria Decision Making analysis, which can systematically combine indicators from diverse disciplines for a uniform scoring scale. In line with the research objectives, the main research question has been formulated as below:

“How can a decision making framework be developed based on the Amsterdam case study that balances trade-offs in circularity and is evaluated by stakeholder perspectives to rank circular innovations?”

Methodology

To best answer the research question, a Research through Design + Action Research approach was adopted, with the theories of MCDA (Multi-Criteria Decision Analysis), Value Focused Thinking, Behavioural Decision Theory and Systems Dynamics. The process was divided into Phase 1 (Theoretical Background- Coupling), Phase 2 (Iterative Design and Reflection using Empirical Data- Interweaving), Phase 3 (Final Results and Conclusion- Decoupling). The theoretical background from Phase 1 using a literature review was used to drive the research processes in Phase 2 and Phase 3. Interviewing stakeholders was the main research method for empirical data collection, and creating a quantitative model to apply the framework in Phase 2, where MCDA was selected to create an Excel tool. The framework and MCDA tool were then tested by the case study of the field labs of project Nieuwe Straat, in collaboration with the municipality of Amsterdam, the AMS Institute and TU Delft. The literature review and interviews were used to set up the structure, parameters and indicators of the MCDA model, while data about circular materials from the field labs was used to test the functionality of the model, and stakeholders were asked to provide feedback for it as well. Iterative cycles of plan-act-observe-reflect were used to create four prototypes of the DMF and tool.

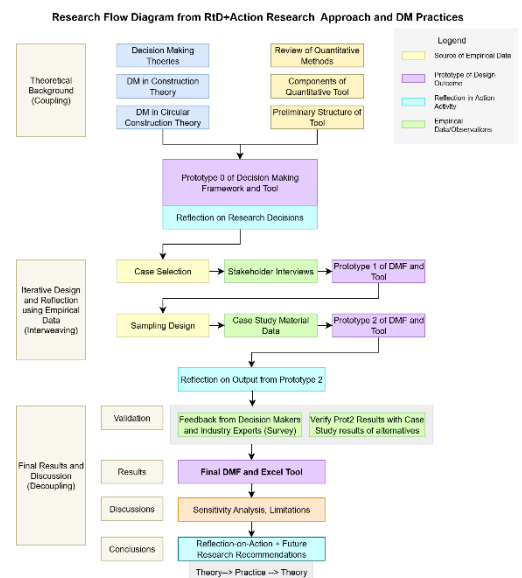


Figure 1- Research

Results

From the results, the MCDA method selection was the first step. This was done using an exploration of the MCDA methods used to create decision making frameworks for similar project cases, and using the MCDA-MSS tool created by Cinelli et al. (2022). The method selected was the TOPSIS method and the MCDA was created using the process followed by Chakraborty (2021a). Through the literature review, five criteria were preliminarily selected for the MCDA, preliminary indicators for these criteria were selected, and the interview questions were created.

Following that, interviews were conducted with four decision-makers from the project case study and 10 industry experts to gather their perspectives. These respondents were asked to rank the criteria and assign weights to demonstrate which criteria should have more influence on the score of the materials and thus the selection of circular innovations, with the answers by decision makers carrying double the influence. Once the criteria were ready, the full MCDA was set up in Excel.

Then came the next data collection phase, through which circular materials that were evaluated at the field labs of Amsterdam were selected and their data was collected under the guidance of indicators to measure the performance within the five criteria. This data was used in the Excel to study the performance of the materials and the utility of the tool itself. During this process, numerous assumptions and decisions were made for the set up of each criteria.

With the completion of the MCDA Excel tool and all the information gathered from the previous phases, the full process for the decision making framework was ready. This was created into a step wise manual with instructions for the Excel tool to help decision makers set it up, and use the tool for the selection of innovations, as well as the pre and post decision-making activities that were crucial to its success.

But this framework is most useful when combined with a circular flow of materials and a circular support system in the construction industry. To create this system, two components were required- the involvement of stakeholders, and circular strategies, specifically where they are positioned in the construction phases. Gerding et al. (2021) research of the multi-actor environment of the circular construction industry, helped determine the stakeholders who had to be involved and the circular strategies. The last step was to incorporate the R Ladder in the system, as a guide to represent the bigger objective of the construction phases, and how they enable the circular economy. The framework and the full system is seen in the figures.

Discussion and Conclusion

The process of creating the framework faced some challenges. Important criteria were not used for the MCDA due to the lack of data or indicators that represent the performance of the material. The MCDA method TOPSIS is sensitive to criteria weights, which was analysed to find the best approach for this project case, but decision makers must conduct the same analysis before finalizing the results. This is also a limitation of the framework itself. The circular system that enables the framework requires much higher collaboration between stakeholders from very different phases, and needs a higher level, longer, planning phase, evolving from months to years, which is a big change. The

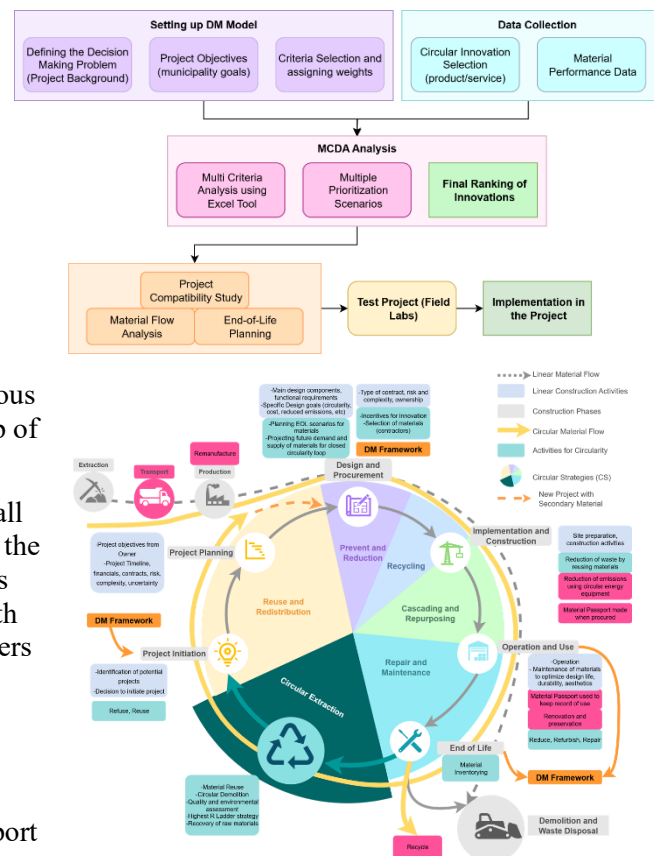


Figure 2- Decision-Making Framework and Circular

framework is useful on the project level and should be used to gradually bring about changes in the circular system through dedicated professionals in the construction industry all working towards the same goal: closing the material loop.

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List of Abbreviations

DM	Decision Maker
DMF	Decision-Making Framework
MCDA	Multi-Criteria Decision Analysis
BT	Betontegel

BSS	Betonstraatsteen
BAK	Baksteen
DT	Design Thinking
DTs	Digital Technologies

1. Introduction

1.1 Motivation for Research and Background

The critical role played by sustainable construction practices and materials in reducing global carbon emissions has been widely recognized and has fuelled countless innovations in every aspect of the industry. Based on the current trend, however, the global demand for construction materials is projected to reach 11.9 billion tons for concrete in 2050 (Deetman et al., 2019). The road infrastructure sector accounts for 25% of global greenhouse gas emissions (GHG) in 2021 (Liu & Kringos, 2024), with most of the global road infrastructure industry following the linear economy approach of “take, make, use and dispose” (“What is the linear economy?”, 2023., para 4), due to the nature of construction practices and the low reusability of materials, as well as the limited research conducted for the circularity of road pavements. Most road construction in the Netherlands consists of asphaltic and non-asphaltic pavements, with total production of hot and warm mix asphalt amounting to 6.2 million tonnes in 2022, and 18% of asphalt not being safe for recycling due to its carcinogenic properties (Oliveira et al., 2022).

In the EU, numerous governmental policies are being established to enable the transition to a circular economy. Organizations like the Ellen MacArthur Foundation work solely towards awareness and implementation of the circular economy, the government of the Netherlands has ministries who are assigned the responsibility of realizing sustainability and circularity in terms of waste, infrastructure, water, etc and numerous municipalities have their own circularity implementation timelines. Platform CB’23 was established in 2018 by the Central Government Real Estate Agency and Rijkswaterstraat, followed by the joining of numerous Dutch institutions and industry experts who collaborated together to create an exhaustive list of guidelines for circular design, reuse, criteria to evaluate the reusability potential, creating a circular economy network of professionals and supply chains. According to the Ellen MacArthur Foundation, the circular economy has three main principles that are driven by design, namely (“Circular Economy Introduction”, n.d., para 1) :

- Eliminate waste and pollution
- Circulate products and materials (at their highest value)
- Regenerate nature

Enabling the implementation of circular innovations applies all three principles, by designing materials and construction techniques that have longer lifetimes, reusability, lower environmental impacts during production and with reduced waste. Innovations also involve new technologies for circular demolition, refurbishment, processing and preparation for reuse. The innovations selected for testing at the field labs fulfill these requirements and criteria will be selected to evaluate innovations based on these three fundamental principles.

Road infrastructure increasingly uses recycled materials in material mixes, with more than 90% of secondary raw materials currently being used in road construction (Hendricks and Janssen, 2001). However, the lifespan road paving materials is limited even with periodic maintenance, and the material flows of asphalt and non-asphaltic construction materials following demolition/removal is unclear, thus proving challenging to map the circularity of the whole process. The Municipality of Amsterdam is thus working on over 200 road renovation projects in the city using circular and sustainable road construction materials and practices in accordance with the municipality’s objective to become a 100% circular city by 2050 (Policy: Circular Economy, n.d., para 2). The municipality aims to incorporate new technologies and research to achieve circular renovation with numerous field labs and private projects for testing and partnerships with research organizations like the AMS Institute.

1.2 Problem Analysis

In the search for circular solutions to the various issues with construction waste, emissions, low reusability and fragmentation of the circular network, many municipalities have initiatives that enable the circular economy in their towns and cities. Tapping into this circular network allows continuous interaction with industry experts and connecting them with the municipality as well. When collecting data about circular innovations and evaluating them, referring to the perspectives and advice of these experts allows a deeper understanding of the various issues faced by them and how they can be addressed when innovations are designed and introduced to the market. The complexities involved with gathering diverse perspectives can be systematically and delicately handled through the use of qualitative analysis methods like multi criteria decision making, that categorizes and prioritizes viewpoints to simulate the various trade-offs that the decision making problem requires. The various scenarios can represent changing objectives and priorities to bring suitable alternatives to the forefront when necessary.

It is important to recognize that the transition from the linear economy to a circular economy in road construction and the industry as a whole calls for an innovation-intensive process of systemic reconfiguration and adaption (De Jesus & Mendonça, 2017). The municipality of Amsterdam has taken great strides in their pursuit of circularity, enabling rapid technological advancement and a golden period of innovation fostered by the various initiatives to explore, identify, test and implement novel circular ideas in the construction and road industry. With the plan for hundreds of road renovation projects with similar requirements and objectives, there is a need for a scalable, standardised decision-making framework for the initial feasibility studies of new technologies, which can be applied simultaneously to multiple projects. This can encourage the closing of the circular material loop and realise circularity in several applications for these projects, through the rapid application of circular innovations which is aligned with the municipality's goals. Unlike the built environment, road construction follows a much more streamlined and standard process and material flow all over the Netherlands and creating a scalable framework can benefit the application of circularity in public spaces immensely.

The pavement industry is also victim to several lock-in mechanisms, which further contribute to energy demand (Z. Liu & Kringos, 2024). There are many factors responsible for this, including the long lifespan of the physical road assets, high sunk cost for asphalt production machinery, maintenance and rehabilitation, that determine the energy demand for the road system for many decades after their construction (Seto et al., 2016). Innovations like cold recycling technology has the potential to be much more environmentally sustainable than the conventionally used hot recycling technology, however, due to tradition, risk minimization, lack of investigation and guidelines and the road contractors' sunk cost in machinery for hot recycling, the adoption of this new technology is greatly restricted (Xiao et al., 2018). Many such barriers are prevalent in the process of innovation and the introduction of new technologies to established, structured industries like the construction industry, as explained by Thirumal et al. (2024, p. 22):

- slow uptake of new technologies in the construction industry,
- high implementation costs,
- resistance to change,
- lack of commitment from stakeholders,
- lack of built-environment-related data,
- data handling and management,
- lack of data interoperability,
- lack of CE regulations,
- lack of standardisation for digital technologies (DTs),

- sustaining the use of technology,
- lack of recognition for DTs,
- lack of skills, involvement of fragmented parties,
- lack of trained workforce,
- lack of proper information management systems,
- data security barriers,
- lack of circularity in product design,
- absence of sufficient technologies for reusable, recycled, and recovered materials, and
- lack of awareness

Thus, to convince decision makers of the imperative for a sustainable transition, research and innovation are vital to assess the life cycle impacts and costs of products, and to design products with reusable frameworks (Stahel, 2016). To assess the applicability of innovations, the main reason industry experts hesitate is the uncertainty of its performance, and this is most efficiently tested by comparing their properties to conventional road renovation technologies. There are many avenues to explore testing procedures for this objective, but a majority of methods do not accurately capture the trade-offs and comparisons between various criteria that are used to test the innovation. At the field labs for the Amsterdam road renovation projects, current testing processes are used to evaluate innovations primarily based on MKI or GWP impact performance, which test the environmental cost and the global warming potential. Thus, there is a need for a decision making framework that accounts for other critical indicators of performance including environmental, economic, mechanical properties, reusability potential, market availability, service life, maintenance requirements, etc and follows a systematic approach that allows the prioritization of criteria through weightage, a uniform scale for assigning scores, and the prioritization of the various opinions of stakeholders who have diverse objectives and perspectives on the important properties of these innovations.

The problem statement for this masters' thesis can thus be formulated as follows:

There is a need for a decision making framework for circular innovations that balances important properties through systematic trade-offs and captures the diverse expectations of the construction industry, in road construction.

1.3 Research Objectives and Research Questions

The primary aim of research for this thesis is to create a decision making framework using MCDA to compare circular innovations with the conventional industry materials and practices, and test the framework using the road renovation projects by the Municipality of Amsterdam. From the problem analysis and the literature review, the following research objectives can be formulated:

- To study the current state and capabilities of the testing process at the field labs and existing decision making frameworks in the industry, to learn about stakeholder trade-offs
- To create a quantitative decision-making tool that captures these trade-offs as a means to measure the performance and help select innovations
- To create a decision making framework with the tool that acts as a guideline for applying circularity in this context, and validate it using circular innovations

Based on the research objectives defined for this master's thesis, the following research questions can be formulated.

Main Research Question:

MRQ: “How can a decision making framework be developed based on the Amsterdam case study that balances trade-offs in circularity and is evaluated by stakeholder perspectives to rank circular innovations?”

The main research question is answered through the research avenues described by the following sub research questions:

Sub research Questions:

SRQ1: “What are the components of an innovation decision-making frameworks, and what is the industry standard for testing circular innovations in terms of the process and the trade-offs preferred by stakeholder categories?”

SRQ2: “What are the steps required to create a decision-making tool that captures trade-offs and scores innovations with a prioritization of diverse stakeholders?”

SRQ3: “How can the decision making tool and framework be validated using innovations from the project case study and feedback from the decision makers about its ability to improve the current decision-making process at the project?”

SRQ4: “How can the decision making framework be applied across construction phases, and what are the supporting circular activities that must be applied for the best use of this framework?”

Based on a detailed analysis of the current state of testing and circularity implementation in the road renovation projects, as well as the construction industry in the Netherlands, this research study aims to enhance the strengths and address the challenges of the system to optimise the process of selecting and applying circular innovations through various research methods.

1.4 Project Team- De Nieuwe Straat

This master thesis research study is conducted with guidance from the project team of De Nieuwe Straat, a joint research endeavour where the AMS Institute works and experiments with the municipality of Amsterdam, contractors, governments, and researchers like the team from TU Delft and from Wageningen University, to explore innovative solutions for infrastructure. Some of the main activities are as follows (AMS Institute, 2024):

1. Field Labs: Development of Innovations that are tested in real world environments in different parts of Amsterdam
2. Optimising the Reuse of paving stones and bricks, including the automation of cleaning and stacking.
3. Developing predictive maintenance tools using data, models and AI.
4. Testing materials of low emissions or recycled materials to reduce environmental impact

This research study is conducted as a part of De Nieuwe Straat, producing research insights and a decision making framework that can be used for testing innovations at the field labs. Data about the material innovations, indicators, and the current decision making process and its limitations is obtained through the thesis committee, who are active members of De Nieuwe Straat’s project team. The results of the study that are made public through the TU Delft repository may also be used by De Nieuwe Straat for their research projects.

1.5 Scope of Research

Circularity in the Design Phase of Construction

Circularity is a an incredible, innovative concept in the construction industry and a significant step forward to reduce emissions, construction waste and facilitate urban advancement through

infrastructure, in one of the most polluting industries of the world. This is especially essential in a country like the Netherlands where sustainability needs to be implemented with limited resources, overcrowding in the city centres, and with a mission to preserve historical and monumental construction while reinforcing the functionality of its expanding cities. There are numerous circularity strategies that can be applied across construction phases of initiation, preparation, design, build, financing, maintenance, and operational phase (Gerding et al., 2021) to enable the circular economy. Gerding et al. (2021) explains three fundamental circular strategies (CSs) obtained from the framework proposed by Ludeke-Freund et al.'s (2018) framework:

- 1) Maximising material and energy efficiency and dematerialization
- 2) Functionality with out ownership/product-service system (PSS)
- 3) Extending resource value and industrial symbiosis

Further elaborating CS (1), the paper explains that this strategy focuses on reducing waste from the outset, by reducing the amount of materials and resources utilized, and that value is created by reducing components, material input, and output. In terms of construction, this is translated into practice by evaluating the need for construction carefully, extending the lifetimes of products through innovative products, construction practices and maintenance. The decision making process in the planning and design phases of construction thus play a critical role in enabling circularity for the whole project, in terms of choosing products with longer lifetimes for better reuse, reusing materials from the same project site or other projects in the current project, planning for end of life scenarios, designing products that have higher reuse potential, etc. When applying circularity in a project, it is important to conduct a risk and uncertainty analysis to account for new technologies, required skillsets, contractors, risk premiums for uncertainty, reduced costs from changes in the future, and more, in the planning and design phases. Van Der Zwaag et al. (2023) used the MacLeamy curve to show that in the early design phase, the impact of circularity measurements is high, while the costs for circular design changes are relatively low, as seen below in Fig 1. The MacLeamy curve states that pulling the design effort to earlier design processes increases the flexibility of design changes while lowering the costs to implement changes (Construction Users Roundtable, 2004).

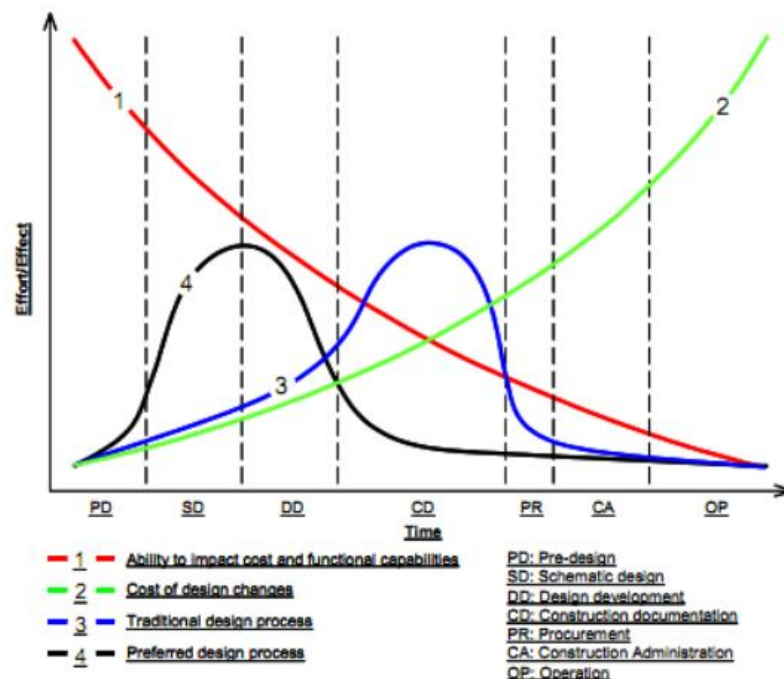


Figure 3 The MacLeamy Curve (2004). Ilozor and Kelly, (2012)

For this research study, the focus is on the planning phase where the municipality makes decision about which products to use to ensure the procurement of secondary materials in the present and the reuse of those materials in the future. The circularity objective to be explored is designing a decision making method to compare and select the most suitable circular material to be used in a given project.

Reuse: Two Opportunities in a Construction Project

Reuse is one of the core activities of circularity and it is primarily applied in two phases of a construction project. The first phase, that has been more commonly explored, is planning for the reuse of materials that are removed from a project at the end of life phase. Here, planning for its removal to ensure the best quality, storage, and the next destination or project where it can be reused, is the focus. The other phase is the procurement and utilization of reused materials in a new project, which is best realised during the planning and design phase. This phase is the focus of the current research project. When designers and clients have the decision making tools and circular network to plan for the use of secondary materials, the design of the construction project can be optimized for the implementation of circularity from the beginning, and arrangements can be made for their procurement, installation and removal, ensuring the highest quality at the end of life. The UK Green Building Council identified key activities in the construction process of the circular economy and created the diagram shown in Fig 2. The objectives of longevity, flexibility, adaptability, assembly, disassembly and recoverability are the guiding principles for the selection of innovative circular materials for the road renovation projects in Amsterdam and in the creation of the decision making framework (Fig 2).

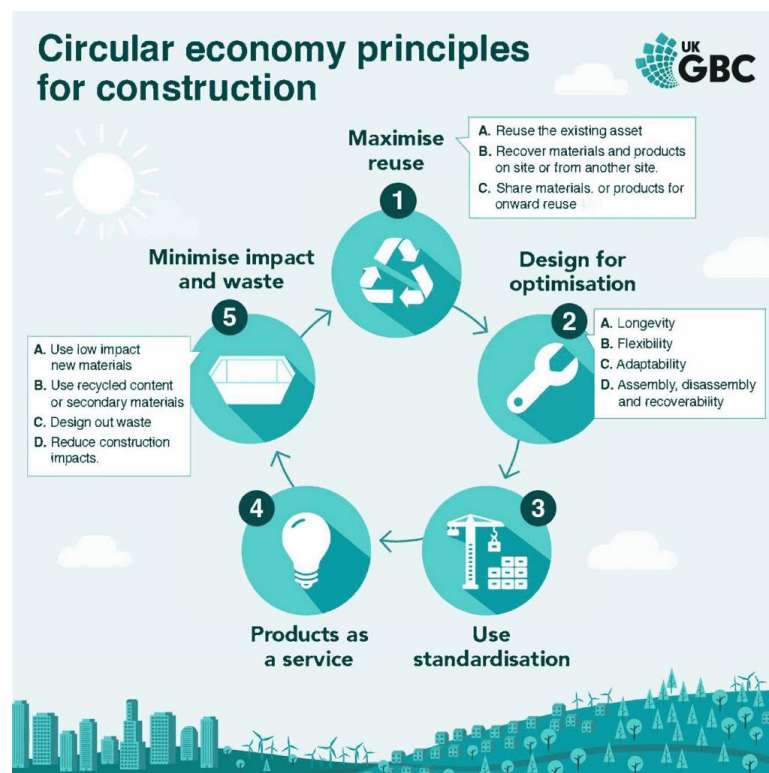


Figure 4 Circular Economy Principles for Construction. The UK Green Building Council, 2025.

Material Focus- Non-asphaltic Pavement Types

Material circularity in roads can be realized in terms of asphaltic pavements and non-asphaltic pavements, which are also called rigid and flexible pavements respectively. In the Netherlands, the road infrastructure is divided into two main types, the main road network (MRN) and the secondary

road network (SRN), as explained by Keijzer et al. (2015). The MRN includes all the national highways, is managed by the government body Rijkswaterstraat and is 95% composed of asphalt roads. The SRN consists of all the roads outside the MRN, is managed by regional governments and municipalities, and can be made of asphalt roads, brick roads and concrete pavement block roads.

Among non-asphaltic pavement types, the materials most relevant to the renovation projects in Amsterdam are concrete tiles (betontegels or BT), paving stones (betonstraatsteen or BSS), curbstones (banden) and clay bricks (Baksteen or BAK). The field labs at the municipality test for circular materials that have evolved from the above mentioned non-asphaltic materials, and they are the focus of this research study. Non asphaltic road materials contribute significantly to the total emissions from road infrastructure, for example, brick roads result in a carbon footprint of 10kg CO² per ton per year and concrete block roads to be 7kg CO² per ton per year. Thus, it is important to research the process of adopting innovative circular materials for non asphaltic road materials

R Ladder Strategy

The 10R ladder of circularity is one of the most fundamental tools to gain an understanding of circular economy processes and avenues for implementation. The R ladder shown in Fig 3, taken from the research paper by Foster (2019), shows the steps from R0 to R9 with descriptions.

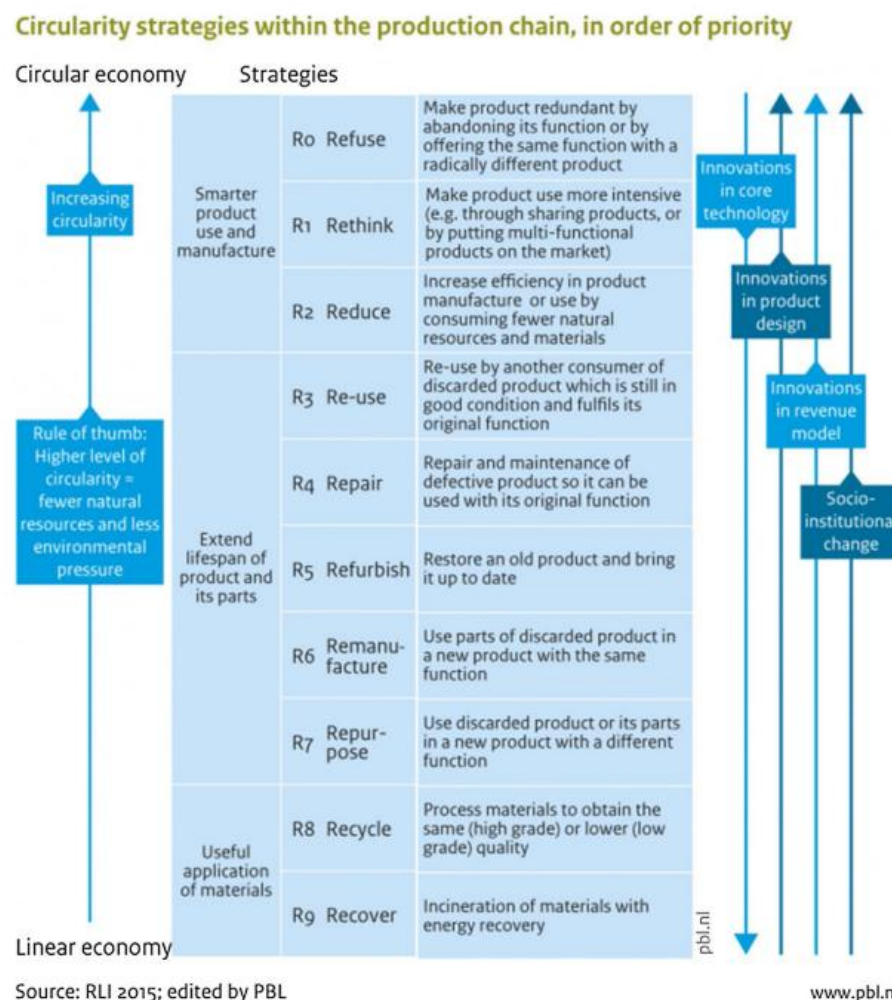


Fig. 3. Circularity strategies Employed for Adaptive Reuse of Cultural Heritage Buildings (reproduced with permission).

Figure 5 R Ladder Strategies in Circularity. Foster (2019).

Although the R Ladder is subjective and challenging to measure, it is seen as an effective guideline to strategize and create goals for circularity in an organization. The fundamental idea is that higher the outcome of the material on the R ladder, greater the amount of value retained at the end of life and lower the waste and emissions. For this research study, the outcomes of the materials that will be studied and optimized for, are from R3 to R7, that is Re-use, Repair, Refurbish, Remanufacture and Repurpose, although the objective remains to aim for the highest possible outcome, which is Re-use. The decision by the municipality of Amsterdam to renovate roads makes it impossible to achieve R0-R2.

1.6 Relevance of Research/Research Context

Circularity in the Netherlands

There are numerous resources and organizations dedicated to creating policies, guidelines and material passports to enable the circular economy in the Netherlands. As mentioned earlier, the Ellen McArthur foundation is a pioneer in propagating knowledge, with one of their most important contributions being the Butterfly Diagram as seen in Fig 4. This diagram provides a fundamental understanding of how the three main principles of the circular economy mentioned in the earlier section is visualized into value retention during use, maximum energy is extracted at the end of life, and how emissions are minimized at the manufacturing stage.

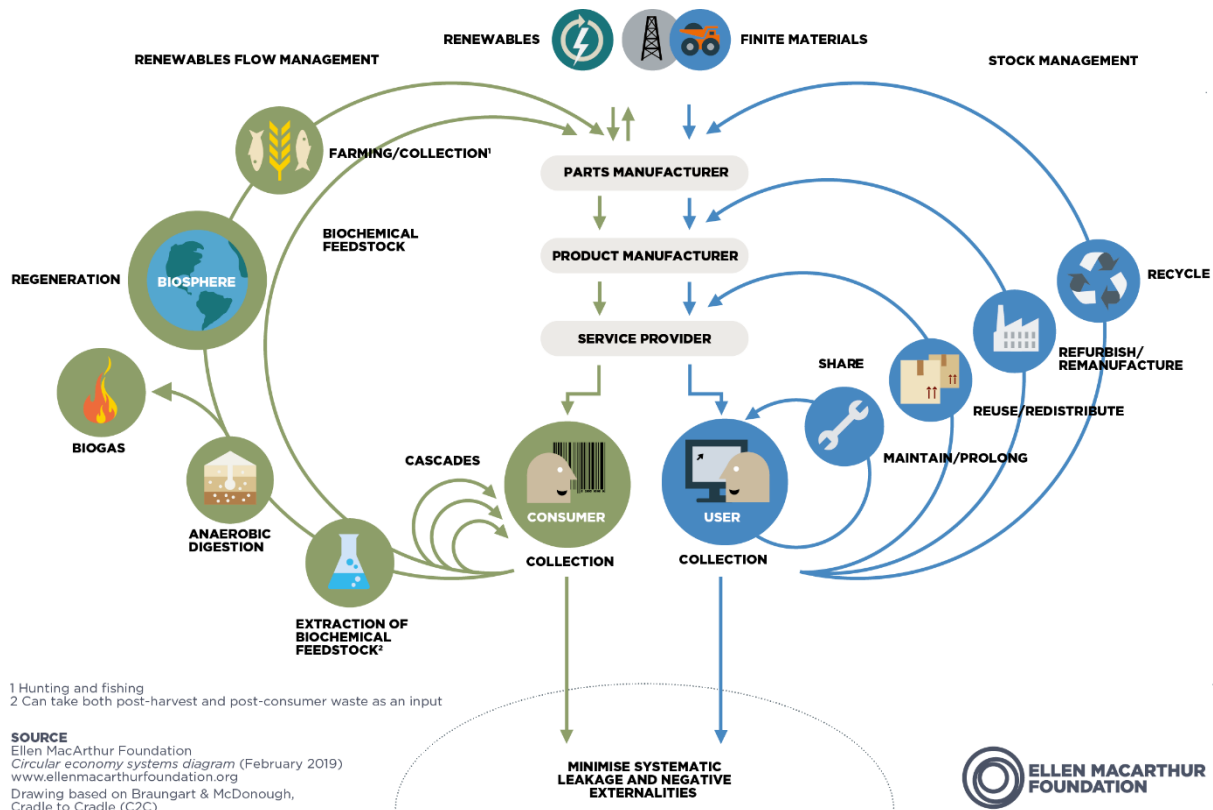


Figure 6 The Butterfly Diagram. (Ellen MacArthur Foundation, 2022)

The Butterfly Diagram shows the biological cycle on the left in green and the technical cycle on the right in blue, to represent the environmental activities and industrial activities for the circular economy, respectively. The construction industry is more connected to the technical cycle.

One of the most relevant resources for circularity in the construction industry is Platform CB'23. Through years of collaborative efforts between stakeholders across the industry, seven guidelines and two application tools as national, construction-wide agreements on circular construction have been developed, while creating an expansive network of members, to enable communication and

collaboration. Some widely used tools are the Lexicon for Circular Construction in English and Dutch, Circular Design strategies, Circular Procurement strategies and Passports for Construction. The Measuring Circularity Guide is one of the most important publications, with a list of indicators for protecting stocks of materials, environmental protection and value retention. They are accompanied by data collection and calculation methods for all the indicators. Combined with quantitative tools and decision-making processes, these indicators provide a practical method to conduct circularity assessments and apply circularity in projects at present and in the future, as seen in Fig 5 (Platform CB'23, 2022).

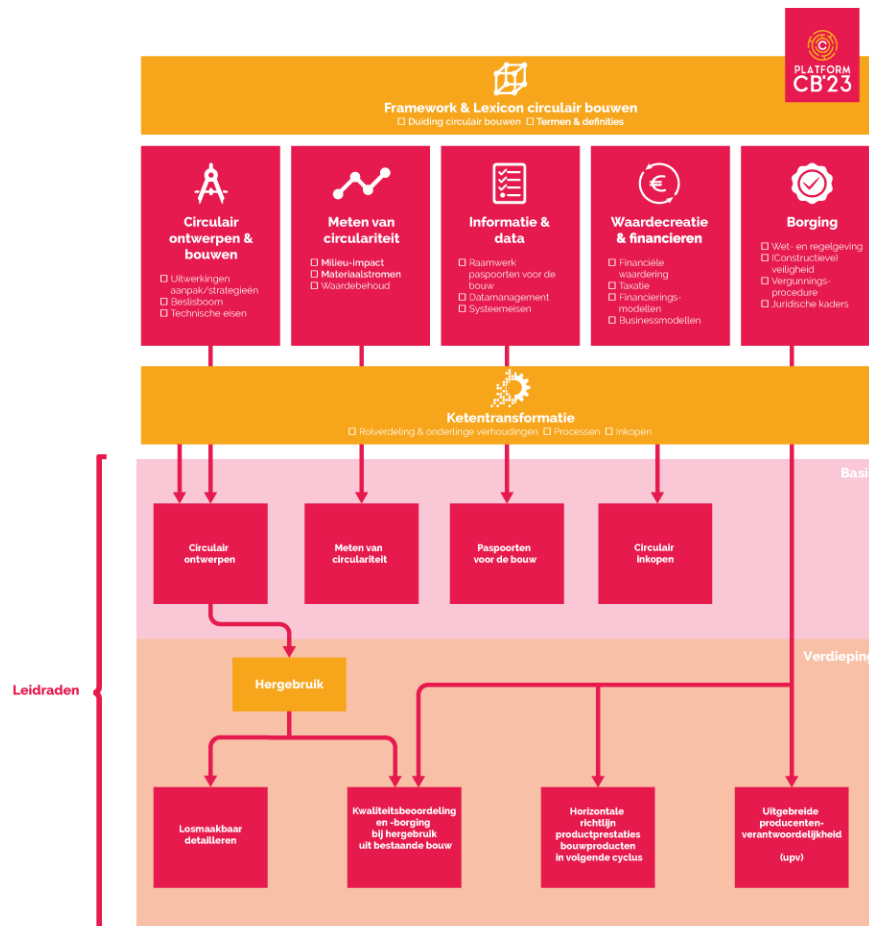


Figure 7 Samenhang Leidraden (Coherence Guidelines). Platform CB'23, 2022

The NEN Circular Construction Committee works as part of the NEN organization, which stands for the Stichting Koninklijk Nederlands Normalisatie Instituut, and is responsible for the creation of safety and construction standards in the Netherlands. With a dedicated department working to implement circularity in the construction industry, the NEN works to create guidelines for circular activities and connect them with existing material standards, and recognizes current relevant guidelines for sustainability and circularity like the Platform CB'23 Measuring Circularity Guideline, the Bouwbesluit en Bepalingsmethode Milieuprestatie Gebouwen (MPG), BCI Gebouw (2025), and many more.

Het Nieuwe Normaal Leidraden are The New Normal guidelines for sustainability that are used by numerous municipalities as reporting and measuring tools for circularity assessments. It consists of nine indicators divided into three themes derived for the three principles of Platform CB'23 Measuring Circularity Guideline. Stakeholders can request project evaluations for circularity from HNN and these are recognized across the Netherlands.

Alongside the HNN, the Nationaal Platform Duurzame Wegverharding, or the NPDW, is an organization that creates guidelines for circularity in road infrastructure specifically. They have created resources for circularity contracting, circular paving material passports and manuals, and are working to create programs for road circularity assessments and to expand guidelines from asphalt to non-asphaltic road materials too.

With numerous resources for circularity in the Netherlands, every organization stresses the importance of communication and joining the circular network to actually enable material reuse and close the material loop. Without collaboration, circularity is not possible in any country.

1.7 Overall Thesis Outline and Reading Guide

This report serves as a record of the research conducted for the master thesis, and is organized into eight primary sections, followed by the conclusion, references and appendices. Section 1 explains the motivation for research, project context, research questions and problem analysis. Section 2 details the research design undertaken for data collection and analysis. Section 3 details the theoretical background that is used to establish current knowledge and research gaps to provide the direction for research in this study. Section 4 contains the full research methodology that was developed based on the findings from Sections 2 and 3, to select research methods and the information required to answer the research questions.

Section 5 is the Results chapter. All the data collected and analyzed in this research study is provided in detail, with the full process, assumptions and research decisions that were made, to create the final decision-making framework. The current state of testing at the field labs and the results from the interviews are explained here, as well as the preliminary set up for the multi criteria decision analysis and details about the companies and innovations that have been selected for the analysis. The criteria weights, indicators and the normalization scale of the MCDA are also explained, followed by the full analysis. This section also explains the process of creating a decision making framework, the components of the framework that are derived from the process of collecting data, MCDA set up and the analysis itself.

Section 6 is the Discussions chapter, used to analyze the results of the research study, identify the strengths and limitations of the research process and the results themselves. Section 7 is the Conclusions chapter, which brings back the research questions to determine extent to which they have been answered and the research objectives have been met.

Following the main sections, supporting material like the references and appendices are detailed in the final sections. The appendices contain all supplementary data like interview transcripts, MCDA tables, etc.

2. Research Design

2.1 Research Philosophy and Approach

Based on the problem analysis, research questions and the objectives for creating the decision making framework, this research study takes inspiration from the interpretivist paradigm defined by Creswell (2009) and Denzin & Lincoln (2008), for qualitative research. It explains how reality is not a linear, objective experience and is rather multiple and constructed by individuals based on their past experiences, interactions, perceptions and the environmental context, internally and externally. Interpretivism is usually accompanied by Constructivism as an ontological and epistemological grounding:

1. **Ontological aspect (what is real):** Due to the novelty and volatility of the decision making and the circular industry, practitioners may have different perceptions for the meaning of circularity and innovations, and what they perceive as an ideal or preferred state of reality. Thus, reality consists of multiple lines of knowledge coexisting, explained as the subjectivity that must be accounted for during interactions.
2. **Epistemological aspect (how we know what is real):** While explaining methods used to create or shape the above reality, interpretivism/constructivism is founded in the belief that knowledge is not a single, objective truth waiting to be discovered, but it is created through interactions and discourse between the researcher, participants and artifacts. Subjectivity of the researcher and participants is embodied in the process of knowledge generation. To understand the complete nature of decision making in the industry, the perspectives of decision makers and those affected by decisions like contractors and operators must be researched extensively to observe patterns from groups based on their past experiences. The researcher then draws conclusions about potential causes from their prior knowledge about barriers and challenges in the construction industry.

This paradigm helps justify why qualitative inquiry, stakeholder interviews and design reflections are central to this research. The process of selecting criteria with weights to prioritise them, selecting alternatives, and determining the most suitable alternative does not yield an objective result, but is shaped by institutional constraints and human experiences. The result is unique to the project being studied, and is subjective to knowledge from the participants, researcher and scientific literature. The sensitivity of the process is also studied at length in this thesis to document more influential aspects that affect the final result.

Alongside the above qualitative methods, a quantitative analysis is introduced in this study through the criteria selection, criteria weights, and assigning weights to the stakeholders involve, to map patterns in the data collected. Thus, a mix methods research design is adopted for this study, using qualitative methods to create a discourse of the strengths and weaknesses, challenges and opportunities of decision making in various themes related to the case study, then creating a quantitative model to embody the decision making process that can be used as an aid for improved decision making In the future. Mixed-methods designs allow for breadth and depth in the study, since quantitative weight elicitation provides structure and comparability, while qualitative trade-off discussions and reflections provide meaning, context, and validation of those weights (Creswell & Plano Clark, 2018, p. 5). This is embodied in the Research through Design strategy adopted for this thesis as explained in the next sections.

2.2 Research Strategy: Research through Design (RtD)

Through this research study, an iterative process of learning through each step of creating the framework is necessary, to gain a deeper understanding of the applicability and limitations of the

framework itself, as well as the research process used. Thus, the aim is to also test and validate the research process to check if it is replicable for future research and to create a transparent account about the research decisions taken at every step. It is important to explain how different decisions might yield different results, with the whole research practice aimed at optimising the framework for future applications and scalability, if it is outside the scope of the current study. This is especially valuable to explore decision making and the creation of frameworks that act as a guideline, considering the vastness and embedded uncertainty of both, and to encourage continued research in the same field.

Research through Design (RtD) is an approach that extracts insights from the design practice to gain a deeper understanding of complex issues in the design field, by developing iterative prototypes and models (Godin & Zahedi, 2014; Sauerwein, 2020). The term was first coined by Christopher Frayling in 1993 where he proposed three forms of interaction between research and design or art- research for art and design, research into art and design and research through art and design. Over time, the term art was used less to describe the same relationship as the approach was increasingly applied in scientific disciplines, and Findelli (2004) redefined the three forms of design research, to describe “Research through design” as the closest to the actual design practice, recasting the design aspect of creation as research (Godin & Zahedi, 2014, p.3).

In Research through Design, knowledge is produced through the act of designing and reflecting on artifacts (Stappers & Giaccardi, 2017). Stappers and Giaccardi (2017) define “artifact” as “object (often material) created during a design process” and “prototype” as “artifact used in research that can realize the (inter)action that is studied” (Stappers & Giaccardi, 2017, table 2.3). Giaccardi (2019) explains how prototypes as research products can be used to enable reflection on the design outcome and the activity, so that the process of designing prototypes is integral to developing knowledge through the research study. RtD is then used to develop insights since the research tool is now the prototyping process and the prototype serves as the proof-of-concept (Sauerwein, 2020). In pursuit of creating a decision-making framework, the research process must be documented and analysed alongside the creation of the framework and tool itself to create a replicable study that can be used in future research to expand its scope and improve on its limitations. Thus, the tool and framework will be developed through a process of prototyping in this research study with documentation of the research decisions taken, empirical data used, and differences in theoretical expectations and observations from the case study.

2.3 Applying the RtD Philosophy to the Thesis

Godin & Zahedi (2014) conducted an extensive literature review of publications that studied RtD to determine the main aspects of this research approach. These dimensions are detailed below and can be adapted to the current research study as follows (Godin & Zahedi, 2014, p.5):

- **Ontological Aspects- What reality can be perceived using RtD?**

RtD can be used to envision how the current process or design can be transformed into a preferred reality, or state of being. Wolfgang Jonas (2006) proposes three steps to enable this transformation through design inquiry:

1. Analysis, which is concerned with how things are currently (the truth);
2. Projection, which is concerned with how things could be (the ideal); and
3. Synthesis, which is concerned with how things will be (the real).

In this study, the preferred state is a more transparent, evidence based circular innovation selection process, that can be scaled up from road infrastructure to the construction industry as a whole. This research study must work towards improving the process of decision making through the case study selected using these three steps, to transform the current state into a preferred state. This is detailed more in the Research Methodology section.

- **Epistemological Aspect- What makes an observation valid?**

Jonas (2007a) proposes the methods of action research and grounded theory, where action research aims to “modify reality, while observing and processing theoretical modifications” and grounded theory aims at theory building, while accepting the modification of its subject matter” (Jonas, 2007a, p. 192). For this study, where one of the goals is to create a replicable research process for the further development of the framework in the future, the epistemology of action research is more suitable, since its validity criterion for replicability is recoverability (Godin & Zahedi, 2014). Godin & Zahedi (2014) further explain that “a rigorous process leads to valid outcomes and therefore recovering the process and establishing its rigor would lead to granting validity to the outcomes of the research” (Godin & Zahedi, 2014, p. 7). For this study, the rigor of the research process is realised by gathering knowledge from reflection-in-action, through designing and testing prototypes (Schön, 1983).

- **Expected Contributions- What type of results can be expected from RtD?**

Godin & Zahedi (2014) suggest reflexive practice to improve design methodology and shape the contributions from RtD, derived from Schön (1983), which can occur through reflection-in-action and reflection-on-action (Schön, 1983). For this study, many decisions are made in selecting components, methods and tools for the framework, through reflections and comparisons with many options. The rigor of research is also strengthened through this practice, thus reflection-in-action is applied during the research study and reflection-on-action is applied towards the end of the study. Zimmerman et al (2007) propose four criteria to evaluate the contribution of research:

1. Process: The research contributes to the “rigor applied to the methods and the rationale for the selection of specific methods” (Zimmerman et al., 2007, p. 499);
2. Invention: The research situates its contributions in the current state of knowledge and provides “significant advancement” (Zimmerman et al., 2007, p. 499);
3. Relevance: The research contributions lead to, or support, a preferred state of the world. Also, the research must explain why the state is preferred (Zimmerman et al., 2007, p. 500).
4. Extensibility: The research contribution must be usable as a basis for new research, i.e. it must be “described and documented in a way that the community can leverage the knowledge derived from the work” (Zimmerman et al., 2007, p. 500). These are also used to create the research objectives and research questions for the study to steer the direction of research and methods used.

- **Methodological Aspect- What “process of research are associated with RtD?**

Three dynamics are explained by Godin & Zahedi (2014) that appear in sequence for an RtD project- coupling, interweaving and decoupling- as explained by Basballe and Halskov (2012). Coupling occurs in initial stages to combine research and design interests. Interweaving occurs during the middle when research and design interests influence each other. Decoupling occurs in later stages when the success of the research and design processes are evaluated separately. These three dynamics also form part of the basis for the research flow to be observed in this study, which is explained in the methodology section.

- **Limits- What issues commonly come up in RtD and what can’t it do?**

The focus on the knowledge and not the product limits the utility of RtD in producing tangible research products, which are integral to the contribution of research to the industry. It

also emphasizes tacit knowledge, with limited frames of reference for the researcher. RtD also requires a larger time frame compared to other philosophies to offset the previous two limitations. By testing RtD, these limitations will also be revisited at the end of the study to analyse their implications and propose solutions.

2.4 Research Methodology Based on RtD (Research Process Overview)

Based on the above theories, and the decision making theories explained in the Theoretical Background chapter, the below methodological choices followed:

Table 1 Methodology Decisions for Research Process

Methodological Choice	Reason based on RtD+Action Research Theory
Qualitative Engagement through Interviews	To understand goals, preferences, hesitations and constraints faced- mapping multiple realities
Criteria Weightage	To quantitatively trace trade-offs/ tendencies of stakeholder groups, but interpreted through qualitative observations. Used to map stakeholder trends and simultaneous coexisting perceptions
Criteria Selection	First from literature, validated by interviews, knowledge is constructed through interactions
Iterations and Reflection-in-Action (recoverability)	Prototypes are created in each iteration with reflection on research choices. Design process and research process are thus documented together
Validation of Research and Results	Verifying theory with empirical, testing numerical model with experimental data, rigorously documented research process, cross-checking quantitative results with qualitative narratives

There are two primary steps to creating a decision making framework:

1. Observation of the decision making process (qualitative)
2. Creating a decision making tool to support the process (quantitative)

Based on the research by Bolompe et al. (2022), Van Der Meer et al. (2019) and Parolin et al. (2025), the following process has been adopted to create the decision making framework in this research study:

1. Selection of Case Study: The road renovation projects and field labs in Amsterdam have been selected as the project case study for this thesis, to observe the process of decision making in the testing and selection of circular innovations. The framework to be created aims to improve on this process with more efficiency in decision making, to include more criteria, be more customizable with applications in diverse projects, and more accessible with simple digital tools.
2. Interviews: For qualitative data about the decision making process, interviews with decision makers and other process stakeholders have been selected as the most suitable research method. It allows the collection of expert opinions and experiences of stakeholders from other projects, alongside specific rankings and weights of criteria. This facilitates more inclusion in the construction industry with the combination of results from the decision makers with the

most power and influence and expert stakeholders who have participated in numerous projects and can provide a holistic view of the circular innovation process.

3. Multi Criteria Decision Analysis: For the quantitative analysis, an MCDA approach has been selected to combine all the information from the interviews, literature review and project case study and balance trade-offs. The specifics about the MCDA and the MCDA method selected are explained in the next section.

2.4.1 Interviews as a Research Methodology

The interviews for this study have been designed as three parts;

- a. Part 1- Specific question about the process of circularity and selecting circular innovations that they have observed in other projects and their experiences. The respondents are also asked to share the main challenges they have faced for the implementation of circularity in the projects they were a part of.
- b. Part 2- Ranking and assigning weights to criteria. The respondents will be asked to rank five criteria that are presented to them during the interview, which were selected by the researcher based on the literature review. They will also be asked to add to the list if they think any criteria are missing
- c. Part 3- Conclusion and future scope. The respondents will be asked their opinion on the MCDA and if it is a suitable method for testing and selecting circular innovations.

These three parts are designed such that the interview can paint a complete picture of the current state and potential future state of decision making processes in the industry. The questions may be modified slightly during the interview to gain additional insight based on the background of the respondents and their responses.

2.4.2 Multi Criteria Decision Analysis

Based on the literature mentioned in the Theoretical Background section of this report, the quantitative component of the decision making framework is designed using a multi criteria decision analysis, or MCDA. The steps to conduct an MCDA for this research study and project case are as follows. The complete process of the MCDA setup is explained in later sections.

1. Selection of the MCDA Method: With over 200 unique methods to conduct MCDA (Cinelli et al., 2022), a thorough literature study will be conducted to choose the method most suitable for this study based on the requirements of the municipality, the current testing process and the objectives of the decision making framework.
2. Choosing Criteria and Assigning Weights: Based on the interviews and the literature study, criteria are selected and weights are assigned. This process varies slightly depending on the MCDA method selected.
3. Choosing Indicators: Within criteria, indicators will be used to measure the performance of the innovations. For this study it is required that all the indicators measure performance on numerical scales, thus the methods, criteria and indicators will be chosen to enable this aspect.
4. Choosing alternatives: Circular innovations from the project case study will be chosen for the MCDA and data will be collected using the indicators. More details about the selected innovations has been provided in the later sections.

The MCDA has been selected as the quantitative method of choice for this decision making framework due to its ability to incorporate complex, conflicting project objectives and stakeholder perspectives. It allows the decision maker to balance trade-offs, and offers a structured approach for complexity. Many methods allow flexibility in data and scales by allowing data of different units to be compared without the need for normalization. It also allows the researcher to conduct a robustness or

sensitivity analysis to evaluate the reliability of the results and observe how changes in parameters affect the results in different scenarios.

Various research methods have been used to gather the information required for the set up and conducting the multi criteria decision analysis. The full research flow and the research methods that have been employed for this research study, have been divided into two phases for the creation of the decision making framework, as explained in the next section.

2.5 Research Phases for this Thesis and Research Flow Diagram

The research design follows the simple process of data collection, creation of the framework, demonstration of the framework and testing.

The full process is explained in detail in the next sections. The research flow diagram is given in Fig 8.

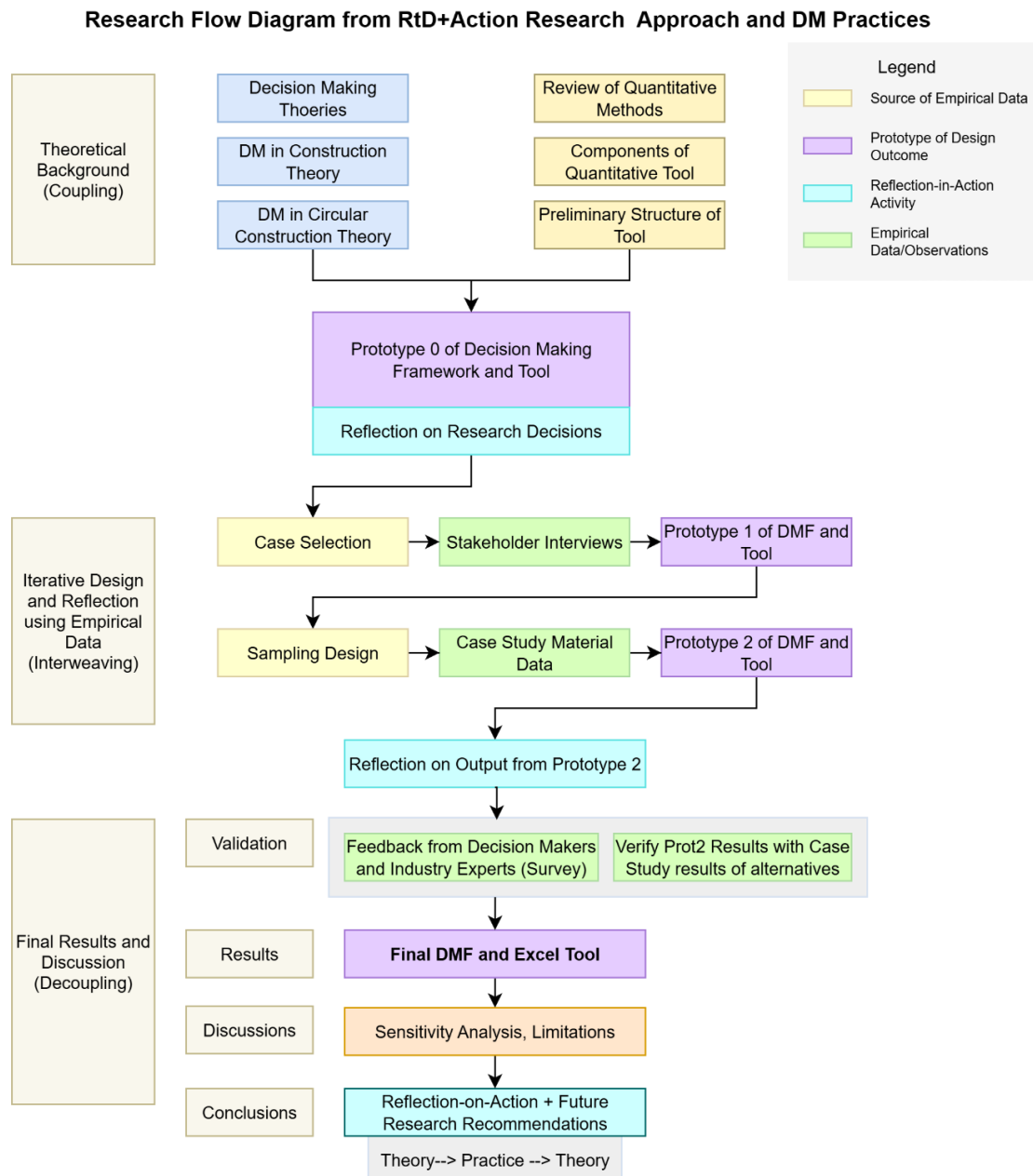


Figure 8 Research Flow Diagram (author)

2.6 Phase 1: Theoretical Background (Coupling)

Data is collected through a literature review to assess theories of decision making, methods of designing a decision making framework, and creating Prototype 0 of the framework and tool. The aim is to understand current knowledge in the industry and in academic research to form a preliminary basis for information. This is followed by a reflection of the research decisions made to select theories and methods to create Prototype 0.

From the RtD+Action Research point-of-view, the coupling of design and research interests occurs in this phase, through emphasis on the design activity and research reflection.

The research questions below are the focus in Phase 1:

SRQ1: “What are the components of innovation decision making frameworks, and what is the industry standard for testing circular innovations in terms of the process and the trade-offs preferred by stakeholder categories?”

SRQ2: “What are the steps required to create a decision-making tool that captures criteria trade-offs and scores innovations with a prioritization of diverse stakeholder perspectives?”

Sub-phase 1 Literature review

The first part of data collection is a systematic literature review which will contribute a significant portion of the required information for Prototype 0. Criteria are used as a means to define stakeholder tendencies, preferences and constraints, of which preliminary criteria are obtained through literature. The literature review seeks to answer most of SRQ1, as we understand current practices of testing and decision making in the industry through research papers and other literature, as well as the documented challenges. The first part of SRQ2 is also answered through the selection of the DM (Decision-making) theory and method. It will be carried out according to the following goals:

- To assess existing DM theories and methods and choose the most suitable based on the properties of the DMP (based on the research by Marco Cinelli et al (2022))
- To complete the preliminary selection of criteria and indicators
- To determine types of interview respondents through purposive sampling
- To create interview structure and questions

The following are the main results from the Literature Review and where they are used:

- Final DM Method and Structure of Prototype 0 (SRQ2): This is and modified through the interviews where decision makers are asked for feedback about the feasibility of the DMF (Decision-making Framework) structure, and it is used as input for the prototype.
- Final Decision Criteria (SRQ2): Criteria are the primary requirements that circular innovations need to be checked on, to compare them with traditional road renovation materials, including structural properties, lifecycle properties, maintenance properties, circularity properties, cost properties, logistics properties, emissions properties, etc.
- Categories of interview respondents and interview questions (SRQ1 and SRQ2): These will be used to select the respondents, and both will be used as input for the Interviews.
- Preliminary set of indicators: The indicators within the criteria which will be used to collect data for the performance of materials will be selected through the literature review. During the collection of test data, the feasibility of indicators will be checked, and they will be finalized depending on whether data is available for them or not. After test data is collected, the final indicators will be used as input in the MCDA analysis.
- Process limitations (SRQ1): A preliminary set of limitations in the decision making process for circular innovations in the industry as a whole will be obtained from the literature review

and the theoretical background. This is input to determine the requirements of the decision making model. Verification and finalization of these, and limitations from the process at the field labs will be obtained from the interviews.

- Reflection 1: The research process of this phase and the decisions for selection of the theories, method, and overall structure are documented.

All the results from the literature review are detailed in the Theoretical Background chapter.

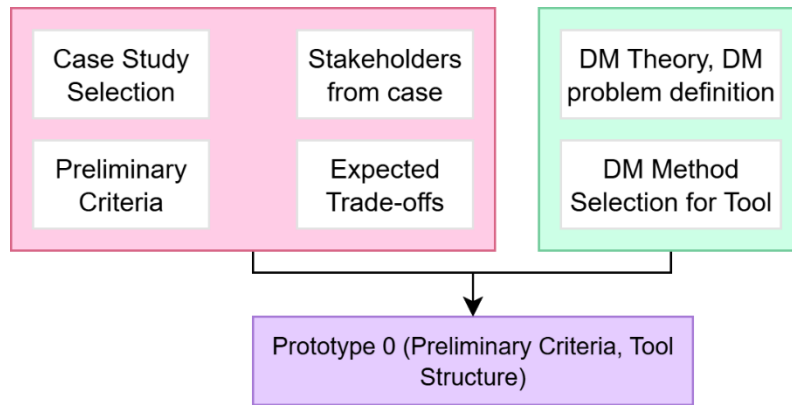


Figure 9 Components of Prototype 0

2.7 Phase 2: Iterative Design and Reflection using Empirical Data (Interweaving)

In the second phase, research and design activities are entwined in cycles of data collection, creating prototypes, testing and reflection. Within each cycle, the prototype is validated against empirical data, results are recorded, and the output is analysed to guide decisions for the design of the next prototype.

During the literature review, the case study project is also selected, and the respondents to be interviewed are categorized into groups through purposive sampling. For the first cycle, Prototype 0 is tested through different types of interviews with stakeholder groups, where the respondents are presented with the criteria selected and asked to assign weights to the criteria, based on their experiences with circular projects in the field. They are also asked if they find the list complete or if there are criteria missing, and what those criteria are. The stakeholders are also assigned weights based on their influence level as project decision makers on the final selection of criteria, for the case study.

Prototype 1 is then created using the criteria weights, stakeholder weights and requirements for the DMF based on constraints. The next cycle starts by selecting alternatives from the project case study through **sampling design**. The empirical data about alternatives is collected from the decision makers, and it is used to validate the selected indicators, since only those indicators can be used for which data was collected during the case study. Prototype 2 is then created with all the data about alternatives with a final, most suitable alternative result. The second Reflection is carried out at the end of Phase 2 to track all the research and design decisions that were undertaken, and that resulted in Prototype 2. The full process is explained below.

Cycle 1: Case Study Selection, Semi-structured Interviews, Prototype 1

This cycle starts with Prototype 0, that is tested through interviews, and the results are compiled into Prototype 1 of the DMF. The interviews bring to light the current state of testing and the challenges of the process at the field labs, thus providing answers for SRQ1. Industry experts are also asked about

the challenges they have observed from their experience in the field of circularity. The diverse perspectives of stakeholders from SRQ2 are captured through the criteria weightage and ranking, thus allowing them to demonstrate their priorities and needs in the characteristics of circular innovations.

Figure 10 Components of Prototype 1

Following the literature review and selection of indicators and criteria, semi structured interviews will be conducted to collect information about the perspectives of stakeholders. There will be two sets of respondents:

- Industry Experts, Circular Innovators and Researchers (SRQ1 and SRQ2): Perspective about challenges in circularity from their experiences in other projects and research, their prioritization of important criteria, and adding more criteria if needed.
- Project Decision Makers for SRQ1: Primary stakeholders to be interviewed from the project case, i.e., project managers and decision makers from field labs to understand the current testing procedure, understand limitations, and gain their input for ranking MCDA criteria

The interviews thus take place in three steps:

- Planning of interview questions based on the perspectives that need to be captured from each stakeholder
- Set up of interviews and conducting them
- Analysis of results

The interviews will be semi structured, to understand the stakeholders' perspectives by first asking them for a direct answer and then asking for their reasoning behind their answer. The questions will be centred around the themes of circularity and road renovation, where the stakeholders will first be asked to describe the main challenges they have observed with the implementation of circularity from their experience in the field. They will also be asked to assign weights to the criteria in their category. For the stakeholders in the field labs, the interviews will also focus on the current processes of testing, challenges faced, characteristics of innovations that were selected after testing, and the barriers to implementing these circular innovations in the road renovation projects. The interviewees will also be presented with different scenarios based on the various objectives that are usually prioritized in projects, and asked if the weights for the criteria might change.

In the research project by Van Der Meer et al. (2019), the researchers conducted semi structured interviews to collect information from stakeholders for the purpose of understanding their decision making and their perspective regarding the multi criteria decision making process in a graphical representation through the Conceptual Content Cognitive Map, or 3CM method developed by Kearney and Kaplan (1997). They used a single longitudinal case study approach on an infrastructure tender, and conducted 25 interviews with 10 individuals, that were strategically conducted with the first phase halfway through the tender and the second phase after the tender was completed. The approach is similar to the planning for the interviews of this thesis and can be adopted for the interview sub phase. The key individuals that will be selected for this thesis are as follows:

- from the primary case study of the field labs for the road renovation projects
- from other road renovation projects in Amsterdam, to gain diverse perspectives.
- from the involved departments of the Municipality of Amsterdam, for the client perspective.
- from the companies creating circular innovations that are tested at the field labs, whose innovations will also be evaluated as alternatives

Following the interviews, there will be an analysis phase to decide the weightage to be assigned to each of the stakeholder categories, based on which the circular properties of the innovations will be prioritized. This will contribute to defining the trade-offs between properties. During interviews with stakeholders from the municipality, the questions will also enquire about the various municipality objectives that take lead for projects, to capture multiple scenarios for the DMF and test how the results for the same alternatives might vary depending on the prioritized objective. The primary stakeholders from the project case will be asked for their opinion when assigning weights to the categories, and existing literature will also form the input for this step.

The following are the results from the Interviews:

- Final criteria and weights
- Primary limitations of the process that need to be improved on when creating the new framework- translated to requirements of the decision making framework
- Project objectives and municipality interests
- Existing testing framework including indicators and criteria used in the field labs, and methods of testing
- Successful tests, analysing factors of success and failure, understanding challenges of testing and implementation

The criteria weights will then be compiled along with the weights assigned to stakeholders, to calculate the final weights. This can be done through a weighted average matrix, finding the average weight of the criteria per stakeholder group, or through simple compounding of criteria weights for certain groups.

With the final criteria weights and input from the respondents about the choice of DM method and their perspectives, Prototype 1 is created, as a template of the tool that is ready to be tested using the data of the alternatives. The final structure of the DM tool is now ready to be tested. The qualitative guidelines of the DMF are condensed into the final document at this stage as well.

Cycle 2: Alternatives Selection, Analysis in the DMF, Prototype 2

This cycle starts with selection of alternatives through sampling design and collecting data for them, from the project case study. The final indicators are then decided, since the availability of data will determine which indicators can be used. All this information is then used in Prototype 1 to get the final experimental results from the DMF, and the qualitative portion of the DMF with the guidelines

for decision making are detailed in the document. The DM tool is also subjected to sensitivity analysis to test the robustness of the tool through the weights of the criteria and how they influence the results.

The first full DMF is created at the end of Cycle 2, called Prototype 2.

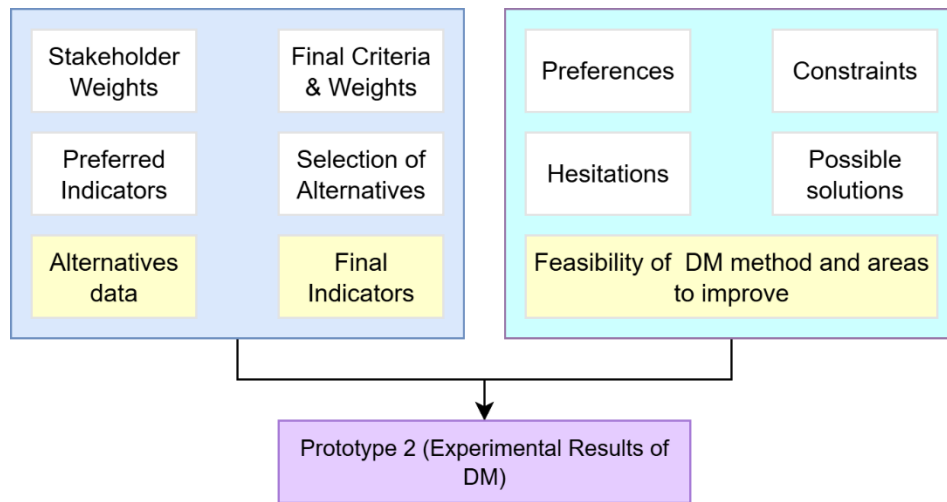


Figure 11 Components of Prototype of 2

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Data analysis is conducted to map the diverse information that is collected from the previous cycle, to determine how it will be used, and to find patterns in the database. The results of data analysis will form the input for the MCDA analysis and to build the final decision making framework.

Phase 2 aims to answer the following research questions stated at the start of the research study:

SRQ3: “How can the decision making tool and framework be validated using innovations from the project case study and feedback from the decision makers about its ability to improve the current decision-making process at the project?”

SRQ4: “How can the decision making framework be applied across construction phases, and what are the supporting circular activities that must be applied for the best use of this framework?”

The activities of collecting test data, verifying indicators in the process, testing the DM tool and obtaining feedback from the stakeholders for the framework, are motivated by SRQ3. Explaining the practical application of the framework and required activities, answers SRQ4.

Cycle 2 starts with a secondary data collection process to collect test data about the innovative materials that need to be used in the MCDA, through which the following information is acquired:

- Selection of materials to be assessed in the DM tool (SRQ3)
- Secondary data collection to gather data about materials to be tested in the DM tool, and which ones need to be selected, through collaborations with the project team of Nieuwe Straat.
- Secondary data collection to gather test data about materials to be assessed in the DM tool through indicators, and which ones need to be selected, through collaborations with the project team of Nieuwe Straat. (information will be anonymized in the report and data will be shared based on licensing agreements of companies)
- Final selection of indicators based on data that is available from the field labs about the materials

As explained in the Introduction chapter, this thesis has been guided by the members of the thesis committee who form a part of the project research team of Nieuwe Straat, where circular road materials are being studied for a few years through field labs and more. The material innovations for the MCDA are selected in consultation with them, and data is obtained through them. This data is anonymized for this report and only used as testing data to check the feasibility of the DM tool.

The next activities in Cycle 2 are for the experimental results themselves:

1. Creating the Model: Set up of the DM tool through the Method, Structure (formulae), Criteria, Indicators
2. Testing the Model: With material data and criteria from interviews
3. Multiple scenarios are defined based on changing client objectives to test performance of the same alternatives with different weights for criteria

After the results of the DM tool are available the DM process will be presented to the municipality to obtain their suggestions and understand its limitations. They will also be requested to test it out for their own use, and improvements will be incorporated from their experiences.

Following the data analysis with the DM tool and testing with the municipality, the whole process will be condensed into a practical decision making framework to answer SRQ3, which is the second to last step in the research study. It will contain the following elements:

1. The various criteria, indicators and weights assigned to them, as well as the scoring scale and different scenarios, that is used in the DM tool. The method used will also be explained in detail.
2. Method of selection of stakeholders and their organization into categories with corresponding criteria.
3. List of information that needs to be collected about the alternatives that need to be used.
4. Method of selection of alternatives and defining the decision making problem (which is standardized for diverse applications)

Once the framework is ready, the application of the framework in the industry is analysed as well as the stakeholders that need to be involved, which answers SRQ4. This can be visualised through the activities that need to be performed for the best use of the framework, when, where and how it should be used.

Reflection 2: At the end of Cycle 2, the second reflection-in-action is performed to track the decisions made as new information was obtained. Numerous decisions were taken by the researcher based on the practices from current literature and from their own experience through comparative analyses, and capturing these details transparently adds to the rigor of the academic process and its recoverability.

2.8 Phase 3: Final Results and Discussion (Decoupling)

The final step is to gain feedback from decision makers about the proposed framework, and to test the results of the alternatives in the DM tool against the actual results from the case study. These two components are consolidated to form the final DMF and DM tool for this study.

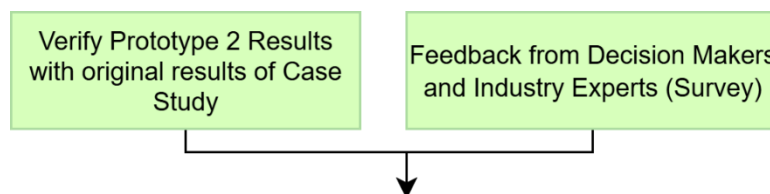


Figure 12 Components of Final DMF and DM Tool

The main activities of this phase are:

- Testing the finalized framework with a smaller group of end users through an online questionnaire
- Comparing the final framework with the success criteria prescribed at the start of the study
- Analysing the documentation of the research process for process validity and theoretical contributions

Decoupling: In this stage, decoupling of the research and design process is carried out with reflection-on-action to evaluate the rigor, recoverability and contribution of the RtD process, and the feedback for the DMF and DM tool to evaluate the strengths and limitations of the design process and designed tool.

Process rigor- The research process and decisions must be recoverable and replicable by other researchers attempting to conduct similar research. This has been described by McNiff (2013) as “the process is recoverable by anyone interested in subjecting the research to critical scrutiny” (McNiff, 2013, p. 18). Action research “puts the burden of validity on anyone who would challenge it.” (Godin and Zahedi, 2014, p.7)

The success criteria to determine the extent to which the decision making framework performs can be taken from Zimmerman et al. (2007), who proposed a set of four criteria to evaluate the contributions of research:

- Process: The research contributes to the “rigor applied to the methods and the rationale for the selection of specific methods” (Zimmerman et al., 2007, p. 499);
- Invention: The research situates its contributions in the current state of knowledge and provides “significant advancement” (Zimmerman et al., 2007, p. 499);
- Relevance: The research contributions lead to, or support, a preferred state of the world. Also, the research must explain why the state is preferred (Zimmerman et al., 2007, p. 500).
- Extensibility: The research contribution must be usable as a basis for new research, i.e. it must be “described and documented in a way that the community can leverage the knowledge derived from the work” (Zimmerman et al., 2007, p. 500).

This has been converted to the below success criteria for the DMF of this study:

1. Inclusion of all important properties to test circular innovations
2. Accurately capturing stakeholder opinions through interviews and analysis, well represented in the final framework
3. Ease of use by many, by creating it on widely accessible software and with simple, clear process to get the results
4. Flexibility and scalability to be customized by project decision makers for diverse projects

The success criteria for the RtD+Action research process can be taken as the research contributions from Chiapello (2012):

- Means: Any tools that can be used by the practitioner to articulate his thoughts, such as plans ((Godin and Zahedi, 2014, p.8)
- Language: All means of communications (oral or not) and terms used by a professional community (Godin and Zahedi, 2014, p.8)
- Repertoire: Any inspirational solutions and experiments that were either performed by the practitioner or that are known to her or him (Godin and Zahedi, 2014, p.8)
- Appreciative system: A system of values or criteria by which the practitioner judges a solution or work accomplished (Godin and Zahedi, 2014, p.8)

- Global theories: Theory that can guide the practitioner in her or his actions, reflection or understanding of a situation (Godin and Zahedi, 2014, p.8)
- Role: The role a practitioner sees herself or himself as occupying in a project and which has an influence on the type of solutions or scope of action she or he is allowed to take. (Godin and Zahedi, 2014, p.9)

The DM tool will be compared with the decision making process currently being used at the field labs to create the final framework. This is done to ensure the limitations of both are accounted for and managed, to create the most efficient decision making process for testing circular innovations.

3.Theoretical Background

3.1 Introduction to Decision-Making in Complex Systems

With the high complexity, uncertainty and risk of the current world's socio-technical systems, the need for advanced decision-making techniques and protocols on the project, organizational and national level has been realized throughout the industry. Extensive scientific research is published every year to optimize decision-making (DM) process, develop decision support tools and study barriers to decision making to stay ahead of the issues that arise across industries. This section explores various decision-making theories from current literature in a systematic analysis to determine the most useful in the context of this research study and potential solutions, to be included in the decision-making framework and tool.

When decision problems consist of multiple actors, multiple categories and conflicting priorities, robust decision making tools are combined with decision-making theories to navigate spaces of deep uncertainty and diverse possible outcomes. A decision-making framework is a structured process that integrates problem definition and evaluation of alternatives with the inclusion of stakeholder experiences and values, to support transparent, consistent, justifiable choices under uncertainty (Cinelli et al., 2020). It provides a systematic foundation to align technical, economic, and social considerations for complex, real-world problems (Belton & Stewart, 2023). The creation of decision-making frameworks is initiated through the definition of the decision problem, which forms the basis for the selection of decision techniques and theories.

A decision problem is a structured representation of a situation where a decision maker must choose between alternatives based on available information, preferences and possible outcomes (Colorni & Tsoukiàs, 2024). Li (2008) explains that decision problems can be categorized as bounded and unbounded, where bounded problems are easily defined and separated from the context in which they exist, and unbounded problems are much more difficult to define and cannot be separated from their context. This research study is focused on unbounded problems in the context of circular construction, which is explained further in the next sections.

3.2 Framing of the Decision Problem

To start the process of framing the problem, the dimensions of the decision making framework selected for this study are:

- Construction
- Circularity
- Innovation

The decision environments that can be used to categorize decision problems are based on (Taherdoost & Madanchian, 2023):

- Nature of information: Certainty, Risk, Uncertainty, Deep Uncertainty
- Types of actors and their involvement: Individual, Group Decision, Competitive Decision Making
- Type of decision-making process: Programmed and Un-programmed
- Parameters: Single Criterion Decision Making and Multi-Criteria Decision Making
- Time: Static, Dynamic and Adaptive DM
- Purpose of the DM Process and Result: Prescriptive, Descriptive, Hybrid

With the expansive theoretical basis for decision-making in research literature, the exploration of theories is limited to the three dimensions explained above. The construction industry can be

described as a decision environment with high risk and medium to high certainty, due to the standardization. It is usually a group decision, programmed, single or multi criteria decision process with policies and strict protocols to reduce the risks of safety, high costs, time extensions and losses.

When it comes to circularity, the decision environment pivots in a different direction. It poses a highly uncertain, risky decision space with group decisions, un-programmed and multi-criteria decision making. To reduce the risks and uncertainty, and due to the lack of knowledge, single criterion decision making is adopted in many cases, but numerous studies suggest multi-criteria decision-making is crucial to decisions about circularity, as seen in Coelho et al. (2016), Siksnyte et al. (2018). When circularity is applied to construction, the resulting sustainability transition is a socio-technical process where decisions are embedded in multi-level systems, and single-actor optimizations can produce lock-in mechanisms or failure to scale sustainable options (Geels, 2019).

Decision-making for innovations involves high uncertainty, high risk and conflicting multi-actor solution spaces, where decision-makers must balance novelty with established processes using limited knowledge. Trade-offs between costs, risks and long-term benefits must be modelled into the DM process (Goulart Coelho et al., 2017). The combination of innovation with circularity and in the construction industry introduces deep uncertainty in the problem space, with the involvement of a network of practitioners, impactful consequences and navigated by multiple criteria simultaneously.

3.3 Comparative Study of Decision Problems and Solution Theories

From the previous section, it is evident that the solution space for circular innovations in the construction industry, the following characteristics of decision problems apply:

- Decision-making under Deep Uncertainty (DMDU)
- Group, Strategic Decision-Making
- Multi-criteria Decision-making
- Dynamic or Adaptive Decision-Making

Table 2 compares the various theories that can be used to create a decision-making framework for the given decision problem.

Table 2 Decision Making Theories and their Relevance

Name of the Theory	Description	Relevant Aspects to DMF	Relevant Aspects to Circular Construction	Source	Relevance in Current research context
Robust Decision Making/ DMDU	Testing decision strategies under stress across plausible preferred states (futures), for results in deep uncertainty	Supports adaptive learning with focus on robustness over optimization	Improving the resilience of circular infrastructure and enables long term policy planning with scalability	Lempert, 2019	High
Multi-Criteria Decision Analysis (MCDA)	Evaluating alternatives against multiple quantitative and qualitative criteria	Balancing diverse conflicting criteria like environmental with cost and time	Enables trade-off analysis in circular procurement for materials, technologies or designs	Cinelli et al., 2020	High
Behavioural Decision Theory (BDT)	Examines how cognitive biases and bounded	Identifies behavioural and perceptual limits	Improves adoption and participation in	Kahneman, 2011	Medium

	rationality affect decision outcomes.	in stakeholder decisions.	circular innovation processes.		
Value-Focused Thinking (VFT)	Ensuring long term objectives are defined first (values) to create decisions aligned with them	Clear definition of evaluation criteria and objectives, supports dynamic innovation strategies	Guides early-stage circular design decisions to align innovation with sustainability values.	Keeney, 2022	High
Socio-Technical Transitions Theory (Multi-Level Perspective – MLP)	Describing interactions between niche innovations, socio-technical regimes, and broader landscapes.	Identifies pathways for the diffusion of innovation, institutional factors	Enables analysis of circular transitions in constructions on various levels	Geels, 2019	Medium
Institutional Theory	Explains how standards and structures influence organizational decisions.	Constraints of construction industry affecting innovation adoption	Barriers to circular construction	Scott, 2014	High
Open Innovation Theory	External collaboration, knowledge-sharing, innovation process across boundaries	Enables the co-creation of alternatives and cross-sectoral DMFs	Collaborative circular construction processes between public clients, researchers and private firms	Chesbrough, 2003; Chesbrough, 2020	High
Systems thinking	Models interdependencies and feedback loops within complex systems.	Cross-sectoral and long term impacts of decisions	Used for circular flow modelling, lifecycle impact analysis, and scenario planning.	Sterman, 2018	High

With the objective to create a decision-making framework and tool that can accommodate numerous conflicting criteria (eg circularity, cost, time, etc) to evaluate alternatives in a robust tool, that captures stakeholder perspectives through trade-offs, multi-criteria decision analysis (MCDA) has been selected as the theoretical basis and decision making method for this study. It is important to ensure that stakeholder and institutional values are prioritized for the selection of criteria through VFT, and BDT can help understand cognitive biases and bounded rationality that affect decision outcomes. Systems Thinking (ST) is applied through the modeling of material flows and long term impacts of circular decision in the construction ecosystem. The full idea for the framework is detailed in the Conceptual Framework section.

3.4 Decision-Making Frameworks in Scientific Literature and Learnings

In Teigiserova and Schraven (2024), a “circular innovation framework” was built in five layers combining client, circularity and sustainability strategies, an analysis of the network and barriers, and a PSS model and performance indicators on the bottom level, that enables a multi-stakeholder co-creation process, include organizational issues, and includes the lifecycle perspectives in circularity and the R Ladder strategies. In Guzzo et al. (2019) the circular innovation framework is composed of three perspectives- the conceptual perspective for resource efficiency to conserve embodied energy in artifacts and skilled labour, the strategic perspective with 21 circular strategies to develop circular

business models, and the practical perspective with 77 strategies to operationalise circular strategies. Most holistic and strategic circular frameworks focus on incorporating multiple phases and aspects of circularity, with strategies for implementation on an organizational level, but not to compare different circular innovations in the market for specific projects.

In the paper by Bolomope et al. (2022), the research study utilized interviews as the qualitative method to engage decision makers in a dialogue to learn about the current decision making process and identify the subjectivity of opinions and experience biases that may affect the process. Following interviews, the researchers adopted the multi-objective optimization (MOO) as the quantitative method to create a decision making chart, where construction clients assigned utility scores from 0-100 to numerically assign the significance of project factors, and follow decision routes to choose procurement methods. The study by Van Der Meer et al. (2019) uses two rounds of interviews with stakeholders to study the role of MCDA in the decision making of the tendering process for a project (the case study), and used content analysis to extract data, thus demonstrating how the MCDA was used to make a trade off matrix (ToM) and the weighted sum method was used to choose between alternatives for the tender. The research by Parolin et al. (2025) utilizes a multi narrative decision analysis (MNDA) which is using MCDA to leverage narratives. Opinions shared by stakeholders about the prioritization of decision making criteria in different scenarios, during these interviews, were converted into weights for the criteria, which were then divided into personas and scenarios for the tool's sensitivity analysis.

The research by Santos et al (2018b) uses multi criteria decision making methods to create a sustainability based decision support tool for road pavements, by selecting indicators that covered a large spectrum of aspects related to the three wellbeing dimensions of environmental, economic and social sustainability, and employs the PROMETHEE-II method for ranking alternatives, which is explained as an “outranking MADA method”.

It is thus crucial to analyse the decision making objectives, input parameters and criteria accurately to achieve a robust analysis of alternatives in this problem case. Cinelli et al. (2022) have conducted extensive research to create tools and support systems for the selection of MCDA methods and to build an MCDA assessment as a whole.

3.5 Selection of Methods for Decision Making: MCDA

The first crucial step in creating the quantitative part of the decision making framework is selecting the MCDA method to be used. To determine the most suitable method, the Decision Making Problem needs to be framed, considering the requirements and desired output from the MCDA. The method selection for this study has been conducted through in two steps:

1. MCDA-MSS by Cinelli et al. (2022): This study has analysed over 200 MCDA methods from literature in the industry and matched it with taxonomy to create a user-centric Methods Selection Software, to determine the most suitable method for the given parameters of the DMP. For this study, this approach was adopted as the first step, since it helped define the requirements of the DMP using the standard taxonomy explained by Cinelli et al. (2022), which then helped understand the types of MCDA methods, various aspects of the construction industry and objectives that they fulfil, and gain an understanding of the academic discourse surrounding MCDA in the current research climate.
2. Study of literature that has used MCDA for Decision Making in Road Infrastructure and Construction: After gaining an understanding of the scientific potential of MCDA methods and a preliminary definition of decision making problem parameters, it was necessary to study practical applications of the MCDA in case studies similar to the selected project case of circular road renovations in Amsterdam. The various literature considered covers the aspects of circular decision making, innovation frameworks and road infrastructure to learn

about the efficiency of these methods, limitations, and observing which methods may suit the project case study best.

The results from Step 1 were compared with the MCDA methods used in existing decision-making frameworks to select the most suitable method out of all the options available. The first step also grants a much better understanding of the taxonomy of defining the decision making problem, and is an important introduction to the categories of methods that are available, which motivated the final choice. Thus, the theoretical basis of MCDA methods was granted by the first step, and the practical application of MCDA methods was explored in the second step, to make the final decision of the MCDA method.

Step 1: MCDA-MSS by Cinelli et al. (2022)

The research by Cinelli et al. (2022) consists of an extensive analysis and compilation of 205 MCDA methods and their divergent forms methods that were used in existing literature, to represent the three families of MCDA methods: scoring functions, binary relations and decision rules. These methods were then mapped to a defined taxonomy by evaluating which characteristics are supported by each specific MCDA method. Taxonomy v.2 contained 156 characteristics that were mapped to 205 MCDA methods and thus serves as the information table for the software's rule-based modelling. Using all the information and mapping, the MCDA-MSS decision support tool (Multi Criteria Decision Analysis- Methods Selection Software) was created in an online format, available for public use by professionals, researchers and educators to learn about the potential of MCDA and its incredible diversity.

It is structured into four main sections in the MCDA-MSS to select the MCDA method as well:

- A. **Problem typology:** This section serves to help the user define the Decision Making Problem by selecting the kind of decision recommendation, characteristics of the alternatives, relation between criteria, and more.
- B. **Preference Model:** This section helps the user decide the type of model for their analysis, by selecting the measurement scale, how alternatives are compared, the relationship between criteria and their weights, aggregation method, etc.
- C. **Elicitation of preferences:** In this section, the user decides how the preferences of decision makers are categorized and implemented in the model, including direct and indirect preference elicitation and the level of confidence.
- D. **Exploitation of the preference relation induced by the preference model:** This section is the final step to defining the decision recommendation based on the preference relation, by enriching the strategy used to derive it. It helps the user decide whether a single recommendation is sufficient or whether an output variability analysis is required for a range of outcomes resulting from uncertainty, as well as prioritising certain results over others.

The MCDA-MSS also contains taxonomy and models that account for incomplete information and uncertainty, to select models that can numerically include these in the final results. Based on the taxonomy explained in the paper and other scientific literature that employed an MCDA for decision making frameworks, the characteristics were selected for this thesis and the road renovation projects, resulting in the option between two suitable methods- the ELECTRE III-H method and the EVAMIX method.

To create the decision making framework that is intended for the road renovation projects, a ranking type of model is the most suitable so that the performance of alternatives are compared to each other to rank from best to worst with the inclusion of conventional methods, and a complete order is needed to ensure all their properties are accounted for, as well as each alternative's performance. The selection of the remaining properties is detailed below:

Table 3 Selection of MCDA Method through the MCDA-MSS Software

Section	Question	Choice	Reason for Selection
Section 1- Problem Typology	Problem Statement	Ranking	Alternatives from best to worst in comparison with conventional methods
	Order of Alternatives	Complete	No ties or incomparability
	Scale leading the recommendation	Ordinal	Only the rank matters, not the distance between alternatives' scores
	Set of alternatives	Stable	Predetermined set of alternatives for one analysis
	Criteria Structure	Flat	All criteria at the same level of detail (weights assigned)
	Evaluation of alternatives on the criteria	Deterministic	Information for each criteria and alternative measured through indicators (mostly numerical)
	Type of deterministic performances	Per alternative	Each alternative is measured with the same indicator and scale for each criterion
	Criteria preference direction	Known	
	Type of the known order of preference direction	Monotonic	Indicators or values will be entered so that "more" means "better" (or "worse") for all
	Criteria set completeness	Complete	
Section 2- Preference model	Scale used by the method(s)	I don't know	Is it purely quantitative or purely qualitative?
	Comparison of performances	I don't know	Does the DM benefit from a normalized approach or is the comparison of raw data sufficient?
	Weights of the criteria	Yes	
	Per-criterion pairwise comparison thresholds	No	Small differences within criteria do not require a strong veto
	Interactions between criteria	No	Impact of criteria is solely measured by the weights assigned
	Criteria profiles	No	Conventional methods are the control but are considered equal to all alternatives
	Compensation between criteria	Null Compensation	

	Aggregation of multiple criteria evaluations	Yes	Performances on multiple criteria are aggregated to provide the decision recommendation
	Type of aggregation of multiple criteria evaluations	I don't know	Is a simple weighted sum sufficient or should there be binary comparisons?
	MCDA method(s) inconsistency management	No	Not required
Section 3- Elicitation of Preferences	Type of preferences elicitation	Direct	
	Specify criteria weights	Yes	
	Type of Weights	Precise	
	Type of precise weights	Trade-offs	
	Frequency of preference input	One time	
	Confidence level of preferences	No	Not required
Section 4- Exploitation of the preference relation induced by the preference model:	Type of exploitation of the preference relation induced by the preference model	Univocal recommendation	Output should be a precise "best option"

At this stage, two MCDA methods are suitable for the analysis, EVAMIX and IDRA. If an output variability analysis is required, EVAMIX is the only option, if not, both methods are equally suitable. Thus, further studies are required to understand the benefits and limitations of the two methods and select the most suitable for this project case. The defining characteristics that determined this final recommendation of the two models were the assignment of weights for criteria, the lack of pairwise comparison thresholds for criteria and null compensation. The MCDA-MSS is shown in Fig 11.

1 Problem typology
 2 Preference model
 3 Elicitation of preferences
 4 Exploitation of the preference relation induced by the preference model

Section 1: Here you can define how the problem is framed by (i) choosing the type of decision-making challenge under consideration and (ii) describing the criteria used to assess the alternatives.

Problem statement
What type of decision recommendation is requested? ranking (2)

Order of alternatives
What order of alternatives is requested? complete (2)

Scale leading the recommendation
What scale leading the recommendation is requested? ordinal (2)

Set of alternatives
What is the nature of the problem in relation to the alternatives that constitute the set? stable (2)

Criteria structure
What is the structure of the criteria used for the assessment? flat (2)

Evaluation of alternatives on the criteria
What is the type of performance of the criteria? deterministic (2)

Type of deterministic performances
What is the type of exact performances? per alternative (2)

Criteria preference direction
What is the knowledge of the preference for the values of each criterion? known (2)

Type of the known order of preference direction
What is the type of the known order of preference for the criteria? monotonic (2)

Criteria set completeness
What is the completeness status of the criteria set? complete (2)

Section 2: Here you can define what type of model you would like to apply, accounting for (i) how the input data is used by the method, (ii) comparison of criteria performances, (iii) compensation between the criteria performances, (iv) aggregation of the criteria evaluations, and (v) the capacity of the MCDA methods to deal with inconsistent preference information.

Scale used by the method(s)
How should the input information/performance data be used by the method(s)? I don't know (2)

Comparison of performances
How should the comparison of the performances on the criteria be performed? I don't know (2)

Weights of the criteria
Should weights be used to differentiate the role of criteria in the aggregation procedure? yes (2)

Per-criterion pairwise comparison thresholds
Should pairwise comparison thresholds be used to model the imperfect knowledge of criteria performances and/or to characterize the preference sensitivity of the DM when comparing two alternatives on a single criterion? no (3)

Interactions between criteria
Should interactions between criteria be considered to reflect a non-additive nature of preferences? no (2)

Criteria profiles
Should criteria profiles not corresponding to the considered alternatives be used to derive a decision recommendation? no (2)

Compensation between criteria
How much can the good performance on a criterion compensate for the bad performance on another criterion? null (3)

Aggregation of multiple criteria evaluations
Should the performances on multiple criteria be aggregated by the method(s) to provide the decision recommendation? I don't know (2)

MCDA method(s) inconsistency management
Should the MCDA method(s) be capable to handle inconsistent preference information? I don't know (2)

1 Problem typology
 2 Preference model
 3 Elicitation of preferences
 4 Exploitation of the preference relation induced by the preference model

Section 3: Here you can define what type of preferences information you can provide, how and with what frequency.

Type of preferences elicitation
What type of preference information is provided? direct (2)

Specify criteria weights
Do you want to specify the weights of the criteria? yes (2)

Type of weights
What type of weights should be used? precise (2)

Type of precise weights
What type of precise weights should be used? tradeoffs (2)

Specify per-criterion pairwise comparison thresholds
Do you want to specify the per-criterion pairwise comparison thresholds? no (2)

Specify interactions between criteria
Do you want to specify the information on the criteria interactions? no (2)

Specify criteria profiles
Do you want to specify the criteria profiles? no (2)

Frequency of preference input
With what frequency would you like to provide the preference information? one time (2)

Confidence level of preferences
Would you like to include a level of confidence when providing the preferences? no (2)

Most selective questions

Most selective questions in this section

Reset section

Reset all

Previous

Next

1 Problem typology
 2 Preference model
 3 Elicitation of preferences
 4 Exploitation of the preference relation induced by the preference model

Section 4: Here you can decide how the preference relation induced by the preference model can be exploited to derive or enhance the decision recommendation.

Type of exploitation of the preference relation induced by the preference model
 What type of exploitation of the preference relation induced by the preference model would you like to be performed?
 univocal recommendation (2)

Type of exploitation of the preference model with a univocal recommendation
 Would you like the univocal recommendation to be driven by an output variability analysis or not?
 I don't know (2)

Most selective questions

Most selective questions in this section

Reset section

Reset all

Previous

MCDA methods

Once you answer a part or all questions from the four Sections, the method(s) recommended for your decision-making problem will automatically appear in the list below.

If you click on the ⓘ you will see a description of each method with the answers that you chose in bold.

When present, the column "Missed features" shows the decision-making features that you selected and which are not supported by the recommended methods.

Number of MCDA methods suitable for this decision-making problem = 2

Method name	Reference
EVAMIX ⓘ	Click here
IDRA ⓘ	Click here

Figure 13 (a to e): Screenshots of the MCDA-MSS Tool by Cinelli et al. (2022) used to get MCDA Method Recommendations (author)

At the end of the MCDA-MSS survey, the tool also provides links to the recommended methods. These research papers have been included in the references of this report as well, for the EVAMIX and IDRA methods.

Step 2: Review of MCDA Methods from Construction Literature

The following methods are thus being reviewed in pursuit of selecting the most suitable method for this thesis from decision making frameworks in road infrastructure and the construction industry:

1. **PROMETHEE-II** - Santos et al (2018b) explored numerous methods to build the decision support tool that can be used to choose the most preferable alternative of asphalt mixtures based on indicators chosen to represent the three pillars of sustainability- environmental, economical and social sustainability. The SUP&R DSS (Sustainable Pavements and Railways DSS) was developed using the PROMETHEE-II method for ranking alternatives and an AHP based survey for the weighting of criteria. PROMETHEE-II stands for Preference Ranking Organisation Method for Enrichment of Evaluations, and is an outranking method like the ELECTRE family, and utilises a pairwise comparison of alternatives by considering a function representing the difference between the scores for each criterion, with predetermined preference and indifference thresholds. The Analytic Hierarchy Process is a value-based method that also evaluates alternatives using pairwise comparisons, but it asks the DM to for her preference on a scale from 1-9 on a multilevel structure where the goal is at the highest level, the criteria and sub criteria are

at the middle levels and the alternatives are located at the lowest level. This structure is used to determine the criteria weights and alternatives scores a linear additive model is used to determine the overall score of the alternatives with the weights representing the trade-offs between the criteria.

2. **EVAMIX:** The Evaluation of Mixed Data method is an outranking method that addresses problems involving a mix of cardinal and ordinal data (Darji & Rao, 2013). Through EVAMIX, dominance scores for the alternatives are calculated through pairwise comparisons for both ordinal and cardinal criteria, that are standardized and converted to an overall dominance measure, thus ranking alternatives. For criteria weighting, it is often combined with AHP, similar to PROMETHEE. In the research by Darji & Rao (2013), AHP was used to identify unique pairs of alternatives (criterion-to-criterion), and interview respondents were asked to compare attributes in pairs using Saaty's fundamental scale, where numerical values like 3, 5, 7, and 9 corresponded to verbal judgments such as "moderate importance" to "absolute importance". After that, the priorities for attributes and alternatives were calculated by the maximum eigenvector method in EVAMIX, and the degree of pairwise dominance was calculated as the difference in score between a higher performing alternative and lower performing alternative.
The complexity of input data, however, and the limitations of pairwise alternatives that necessitates advanced software, makes EVAMIX a less ideal method for this thesis.
3. **IDRA:** The Intercriteria Decision Rules Approach uses pairwise criterion comparison and is based on two core hypotheses: a "mixed utility function" (considering both trade-off and importance weights) and "bounded consistency" (allowing flexible input without strict consistency checks) as described in the research by Greco (1997). One of the main advantages of this method is that it supports decision making with partial information and it considers all intercriteria information from the decision maker, even if other methods consider it inconsistent. However, the main drawback stems from its advantage, making the requirements of input data fairly complex compared to TOPSIS and AHP, due to its ability to account for and accommodate partial data.
4. **ELECTRE Family:** The Elimination and Choice Expressing the Reality family is a group of outranking methods particularly used in cases where criteria might conflict with each other. They also function through pairwise comparisons to determine if one alternative "outranks" another, and their characteristic feature is their non-compensatory nature, meaning poor performance on one criterion cannot be fully offset by strong performance on another (Corrente et al., 2012). From this binary relation, situations of weak or strict preference, indifference, and incomparability can be derived. The research by Corrente et al. (2012) explains the ELECTRE family with a focus on hierarchical setups of this method. Hierarchy can be establish in criteria and sub criteria with a partitioned structure where each sub criterion belongs to only one criterion in the level immediately above it, and preference relations are positioned at the each node of the hierarchy, which allows a decision maker to understand why an overall preference exists by seeing how preferences decompose at lower levels.
One main drawback of ELECTRE is the large number of parameters that the decision maker is required to set up at the beginning of the analysis, which makes it highly complex, even more so than EVAMIX and PROMETHEE. It is thus not preferred unless non-compensatory analysis is an absolute necessity.
5. **TOPSIS:** The Technique for Order Preference by Similarity to Ideal Solution is a widely adopted MCDA method designed to solve complex problems with a fundamental idea of the preferred alternative being the closest to the ideal solution and the farthest from the anti ideal solution. It involves the comparison of numerous alternatives simultaneously, allowing the decision maker to

get a comprehensive result of trade-offs from a single analysis, based on their weighted attributes (Arioz et al., 2025). Following the determination of criteria weights and the data for alternatives, data normalization is conducted to place data points on the same scale. The ideal solution is then the data from the alternatives that performs the best among all alternatives and the anti-ideal solution is the data from the worst performing alternative, within that criteria. The final ranking of alternatives is determined through the aggregated performance of each alternative across all criteria.

6. **VIKOR:** VIKOR stands for ViseKriterijumska Optimizacija Kompromisno Resenje from Serbian, meaning Multicriteria Optimization and Compromise Solution (Opricovic and Tzeng, 2003). It is a popularly used method, using the compromise solution, which is a feasible solution closest to the ideal through an agreement established by mutual concessions. It also considers the relative importance of these distances. The relative importance is calculated under weight-stability intervals for the preference stability of the compromise solution obtained with the initial weights (Opricovic and Tzeng, 2003). It is effective in selecting optimum alternatives in complex systems, taking a balance between different decision variables to reduce subjectivity (Ruiz et al., 2022). Further comparison of the methods is given in Table 4.

Table 4 Comparison of various MCDA methods from existing circularity DM frameworks

MCDA Method	Comparison of Alternatives	Complexity of Input Data (user friendly)	Criteria Organization
EVAMIX	Degree of pairwise dominance to calculate overall dominance measure of an alternative	Advanced software, not widely usable	Hierarchical
IDRA	Pairwise; using mixed utility function (it is a pairwise criterion comparison approach-based method) (PCCA)	Complex since formulae were created to account for partial information	Hierarchical
PROMETHEE-II	Pairwise comparison of alternatives	Concept is not familiar to general audience, thus challenging to circulate a tool widely	Hierarchical, DM gives preferences to goal, criteria, sub-criteria, alternatives and order of the preference is used to rank alternatives
ELECTRE family	Pairwise comparison to check if one alternative “outranks” the other	Complex software needed to program continuous outranking loops	Hierarchical and non-hierarchical variants found
TOPSIS	Group comparison; any number of alternatives compared simultaneously to find distances from reference points	Simple formulae, simple software is sufficient	Non-hierarchical
VIKOR	Group comparison; distances from ideal solution is calculated along with weight stability intervals	Simple software is sufficient, but additional steps from DMs to determine	Non-hierarchical.

		weight stability intervals	
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The following inferences are derived from the above comparison:

1. EVAMIX, IDRA, PROMETHEE and ELECTRE methods all use pairwise comparisons, which require programmed loops for continuous comparisons of alternatives and to determine the best performing alternative, which cannot be done on commonly used software like Excel. This makes them less suitable for the success criteria of this DMF.
2. EVAMIX, IDRA, PROMETHEE and ELECTRE also use hierarchical criteria systems, which further complicates how the DMs assign criteria weights to represent their trade-offs. This extends the decisions made during MCDA setup and requires much more collaboration from DMs, rather than a straightforward assignment of weights. This also makes them less suitable.
3. TOPSIS and VIKOR are better suited due to its straightforward computational procedure. They also allow group comparisons which makes it easier for DMs since it can be easily modelled in spreadsheet based software.
4. VIKOR uses distances from ideal solutions to compute the scores of alternatives. It is important for complex systems since it also counts the importance of these distances by assigning weight stability intervals within which the performance of an alternative is actually viable. Defining these intervals takes an additional process from DMs, and given the objective to increase the simplicity of the decision-making process, VIKOR is also less suitable than TOPSIS.

Thus, TOPSIS is the preferred method due to its logical principle of choosing the alternative closest to the ideal and furthest from the anti-ideal solution, and its applicability in various fields with easily interpretable results. It is also preferred due to its sensitivity to emphasized criteria weighting which is particularly beneficial when project objectives are defined and there are specific requirements for the performance of alternatives, which makes it suitable for circularity programs. Another advantage of TOPSIS is its scalability with simple software, as other methods require complex coding and algorithms for diverse applicability. Considering these advantages, TOPSIS is the preferred method for this research study, and the MCDA structure is created using the formulae and model described by Arioiz et al. (2025), Chakraborty (2021a), and Theilig et al. (2025a), as explained in the following sections.

3.6 Conceptual Framework

A preliminary literature review of existing research papers that employ MCDM methods for decision making in road pavements like Santos et al (2018) reveals similar research methodologies to conduct the analysis, defined by the five primary milestones for an MCDA, namely:

- the selection of indicators and criteria,
- defining the alternatives and formulating the matrix,
- specifying weights for each indicator,
- ranking the alternatives and
- conducting a sensitivity analysis of input parameters to determine their impact on the ranking of alternatives.

The components of the conceptual framework are thus as follows:

1. Decision Alternatives and Criteria: The Value-Focused Theory and MCDA theory guide the selection of important criteria and when selecting alternatives from the project case study.

2. Specifying weights for criteria and stakeholders: Through semi-structured interviews, weights for criteria are determined by stakeholders from the project case study and from the industry as a whole. Weights are also assigned to stakeholder categories based on their influence on decision-making for the case study.
3. MCDA Structure: Using the TOPSIS method, the actual tool and structure is created, where criteria weights and alternatives with their data are input.
4. Ranking alternatives: The results from the MCDA are compared with the original results from the project case study, and a sensitivity analysis conducted to check the robustness of the tool.
5. Application of the DMF across the construction ecosystem: The “how” and “when” for the use of the tool and the DMF is mapped across construction processes, using System Dynamics to understand material flows and long term impacts, to avoid unintended consequences from circularity.
6. Stakeholder Behaviour and Adoption: Online questionnaires are used to test the utility of the final framework. Behavioural Decision Theory is used to understand cognitive biases in the second component and in the last component.

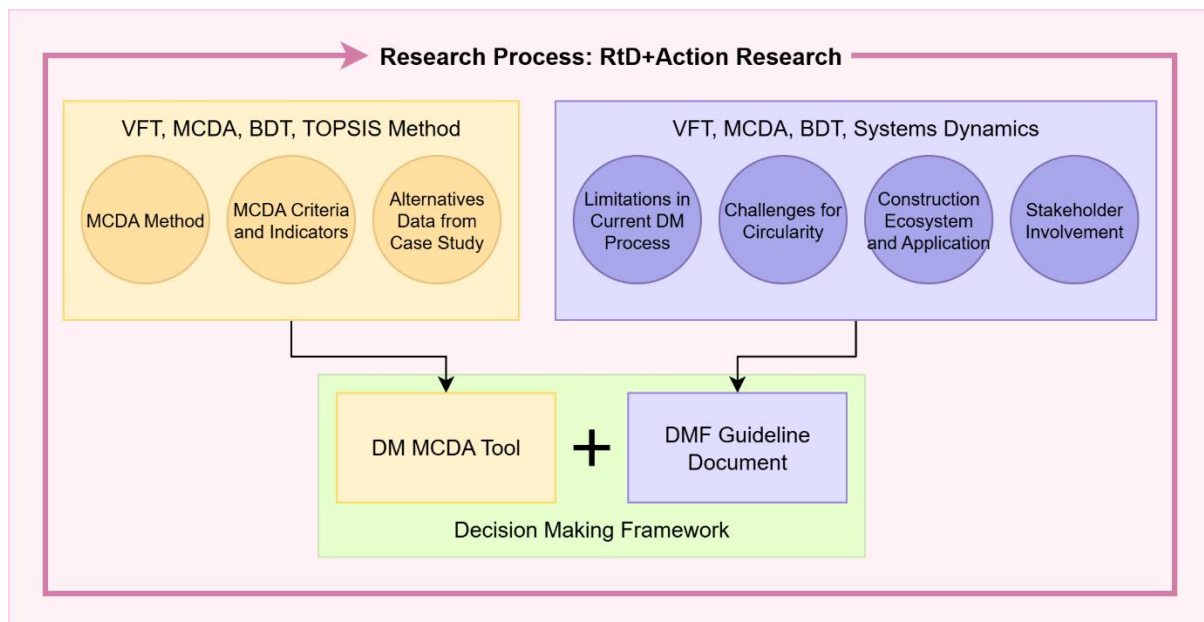


Figure 14 Conceptual Framework combining Design and Research Process

For each component, the RtD+Action research process is used to guide data collection and interpretation, with reflection-in-action at many stages throughout the development of the framework. Thus, it is possible for future researchers to study the impacts of different research decisions on the creation of the framework as a means to improve it.

3.7 Circular Innovations in Road Construction in the Netherlands

The diversity and supply of circular products in the Netherlands is the result of decades of research and innovation in circularity, enabled by the efforts of public and private stakeholders. The following are some of the most popularly used circular road materials of the non-asphaltic courses and secondary roads that are in use today.

1. Reused clay bricks (Baksteen in Dutch): Numerous market players are experienced in circular demolition, storage, cleaning and quality inspection of reclaimed bricks from roads, taking the role of material suppliers in the industry. Clay bricks have high emissions, and a very long lifespan, and by using the right binder, their quality can be preserved for up to 135 years on average (KNB, 2025). Thus, it is necessary to reuse these bricks as they are released from older roads or removed and put back during renovation.

2. **Biobound:** Biobound is a circular alternative for traditional concrete, by using recycled concrete and biobased concrete to create products with much lower lifespans but adhering to the technical standards of traditional materials. One of their products, the Biobound Betontegel, is a concrete paving tile with one side made from concrete containing recycled concrete aggregates, and the other side being biobased concrete containing elephant grass, which grows abundantly in the Netherlands near airports. Both sides of the tile are made usable, which extends the lifetime and thus the value retention (Biobound, 2017).
3. **PlasticRoad:** PlasticRoad is a technology developed through a collaboration between KWS, Wavin and Total, and is an innovative road material made from recycled plastics. Their pilot project is the PlasticRoad cycle path in Zwolle, with reduced emissions and better drainage. This is a type of sustainable, recycled asphalt material which serves as an alternative to high emissions asphaltic courses, and fulfills all NEN road standards for functionality.
4. **Geopolymer concrete bricks:** Geopolymer concrete is an innovative road materials where concrete is made from alkaline activators instead of cement, and mineral by-products like slag and fly ash. By refusing the use of cement, this material eliminates the huge emissions that are generated from cement production, and is widely considered one of the best alternatives. One major drawback of this technology is that since geopolymer concrete does not involve the process of hydration for binding, it is not considered concrete in some NEN and EN standards (European specifications for road materials), due to which clients are hesitant to use it, although it fulfills the structural and road performance requirements stated for traditional concrete tiles (Yilmaz, 2023). Road materials using geopolymer concrete are CERO from Struykverwo which is concrete tiles using geopolymer concrete (geopolymer betontegel).
5. **Cement-free concrete paving bricks (betonstraatsteen, or BSS):** Cement free concrete is also used to make concrete paving blocks by many suppliers to provide the options and properties of cement blocks with low emissions, as they have a higher dimensional stability (increased thickness over smaller area and higher density due to concrete) which allows them to withstand heavier traffic loads (Struyk Verwo Infra., 2025).
6. **Georetron Baksteen:** Georetron is a product offering by the MBI that acts as an alternative to traditional clay bricks. It performs like a clay brick, but is made from concrete, which reduces the large emissions released from the manufacturing process of clay bricks. It also fulfills the NEN and EN standards for clay bricks and fulfills the aesthetic requirements that are needed for the installation of clay bricks (MBI, 2025).

The construction industry in the Netherlands has yielded many circular alternatives, a slight majority being circular processes that reduce emissions and enable reuse, but also numerous circular materials that can replace traditional materials. Since there is not much room for diversity in road infrastructure, there are not as many circular alternatives yet, but the options described above are being selected by more designers and clients due to their reliability. Projects like the field labs that keep pilot projects for these materials significantly improve the confidence of contractors to choose circular alternatives and are an important part of the circular economy. It is also thus important to enhance the testing process so that the field labs can be applied in more municipalities.

3.8 Challenges of Innovation in Construction Industry

There has been a multitude of research to explore the response of the industry to innovations and how this process can be streamlined by managing challenges and optimising opportunities. The concept of environmental turbulence was first explained by Ansoff and McDonnell (1990), where they define environmental turbulence as the combined measurement of the “changeability, instability, and predictability which is reflected in the complexity and novelty of change in the environment.” (Dan Kipley et al., 2018, p. 2, para 4). Five levels can describe global industries and how they respond to innovation, which are Stable, Reactive, Anticipatory, Exploratory and Creative ((Ansoff and McDonnell, 1990). According to Wamelink et al (2007), “Large parts of the building industry can be placed in turbulence level 2 (adjustment to its environment, efficiency driven by existing and known

processes).” (Wamelink et al., 2007, p. 4, para 3). These concepts have been popularly adapted for the circular economy to study the receptivity of the market to products and services as the construction industry pivots from a linear to a circular economy. In their book “Strategic Management and the Circular Economy”, Tonelli et al (2018) build on the concept of the “strategic gap” explained by Ansoff (1965) which refers to the disparity between an organization and the external environment (Tonelli et al, 2018), and they argue that the organizational-environmental gap tends to get larger in the circular economy if the organization does not change in adaptation to the new requirements. This happens since adopting circular thinking presents enterprises with emerging prospects for innovation and competitiveness within their sectors, while simultaneously confronting them with uncertainties and expanded accountability. Thus, there is a need for a streamlined decision making framework in the industry to enable the testing and selection of circular innovations in the construction industry, to seek out innovations, manage risks and to narrow strategic gap faced by organizations while transitioning to the circular economy. The main ideas obtained from these research papers has also been mentioned in Table 1.

3.9 Identifying Research Gaps

However, the literature review has also highlighted research gaps that need further study. Within the sphere of circularity, there is extensive research for the use of MCDA based decision making frameworks in construction, but most have been devised for a procurement perspective and not for the testing process, which is the next step. Based on the above literature review, there are numerous studies conducted to study the incorporation of circular innovations in the construction industry, and research about the application of MCDA based decision making frameworks for the selection of innovations, but there is a lack of research conducted to study circular innovations in road infrastructure using an MCDA based decision making framework. Majority of existing literature for decision making frameworks has incorporated LCA, economic and mechanical indicators at the most, with ways to combine them, but very few have considered other important properties like structural properties, lifecycle properties, maintenance properties, circularity properties, cost properties, logistics properties and emissions properties, and sufficiently designed a method to capture the trade-offs between seemingly unrelated properties.

Thus, this master’s thesis aims to design a decision making framework by including the perspectives of diverse stakeholders across diverse criteria that can be scaled up for application in numerous other projects in the Netherlands.

The most relevant literature for the research method, components of MCDA and fundamental concepts of circular innovation are detailed in the table below. The remaining literature and citations have been listed in the References section of this proposal.

Table 5 List of Relevant Literature for Masters Thesis

Sl No.	Year	Author	Title	Research Significance	Key Ideas for Research Study
1	1965	Ansoff, H. Igor	Corporate Strategy: An Analytical Approach to Business Policy for Growth and Expansion.	Innovation and Barriers, Strategic Gap	Organizational development through innovation and transitional challenges
2	2018	Tonelli, Marcello & Cristoni, Nicolò.	Strategic Management and the Circular Economy	Strategic Gap in Circular Economy, Need for Innovation	Strategic gap between the organization’s current capabilities and what the industry demands, how innovation is required to shorten the gap

3	2014	A. Sanchez et al	Evaluation framework for green procurement in road construction	Evaluation Framework	Linking the phases of road construction with incentive mechanisms for proactively motivating behavioural change; seven procurement stages
4	2024	Dominika A. Teigiserova, Daan F.J. Schraven	A comprehensive framework for circular product-service systems in infrastructure: Enhancing customer-contractor collaboration	Decision Making Framework	Components of this framework are structured in five layers, and all layers are intended to address co-creation elements with iteration to arrive at the final PSS model
5	2019	Guzzo, D., Trevisan, A. H., Echeveste, M., & Costa, J. M. H.	Circular Innovation Framework: Verifying Conceptual to Practical Decisions in Sustainability-Oriented Product-Service System Cases.	Circular innovation framework	Three levels- conceptual, strategic and practical- to execute circular innovation in the organization
6	2018	Santos, J., Bressi, S., Cerezo, V., & Lo Presti, D.	A sustainability-based decision support system for road pavements.	MCDA Decision Making	Sustainability based decision making, using outranking MCDA method, PROMETHEE-II method
7	2024	Barrak, E., Rodrigues, C., Antunes, C. H., Freire, F., & Dias, L. C.	Applying multi-criteria decision analysis to combine life cycle assessment with circularity indicators.	MCDA Decision Making	Combining LCA and Circularity through MCDA, outranking Electre method
8	2024	Liu, Z., & Kringos, N.	Transition from linear to circular economy in pavement engineering: A historical review.	MCDA Decision Making	Combining LCIA with mechanical and economic criteria using VIKOR method
9	2022	Cinelli, M., Kadziński, M., Miebs, G., Gonzalez, M., & Słowiński, R.	Recommending multiple criteria decision analysis methods with a new taxonomy-based decision support system.	MCDA Decision Making	MCDA-MSS; software to select best suited MCDA method by defining DMP requirements
10	2019	van der Meer, J., Hartmann, A., van der Horst, A., & Dewulf, G.	Multi-criteria decision analysis and quality of design decisions in infrastructure tenders: a contractor's perspective.	MCDA Decision Making with Interview	MCDA with input from interviews with contractors who participated in a tender
11	2024	Liu, S.	Mapping the road to sustainability: A critical assessment of circularity indicators	Circularity Indicators	Comparing 6 indicators and listing their limitations to choose the most suitable

			in pavement infrastructure		
12	2020	Suprayoga, G. B., Bakker, M., Witte, P., & Spit, T.	A systematic review of indicators to assess the sustainability of road infrastructure projects.	Sustainability Indicators	Extracting indicators from 31 road infrastructure literature and categorization based on Gibson et al
13	2005	Gibson, R. B., Hassan, S., Holtz, S., Tansey, J., Whitelaw, G., & Whitelaw, G.	Sustainability assessment: Criteria, process and applications	Categorization of Indicators	Minimum requirements for sustainability

3.10 Reflection from Theoretical Background

Key Moments of Adaptation:

1. There are numerous decision theories in literature, but MCDA is the most suitable for the requirements of the current decision-making tool and framework, due to the ability to define criteria weights and navigate the trade-offs. It should be complemented by theories like VFT, BDT and Systems Thinking to account for all other aspects.
2. Selection of the MCDA Method: Multiple MCDA methods may be suitable for the tool, but TOPSIS has been selected due to its simplicity and transparency. It does have significant limitations, but increasing the sample size for data collection (in interview respondents) and careful selection of alternatives (with instructions for this in the guideline), as well as its ability to simultaneously compare an infinite number of alternatives, are three measures used to improve on its limitations.
3. It is evident from the literature that some of the barriers to innovation, presented as challenges in the implementation of circularity, can be alleviated through the creation of an optimized approach to decision making, which is built on the perspectives of stakeholders. Involving diverse stakeholders in the creation of the decision making framework improves their confidence in the process through participation, and captures their uncertainties and concerns to improve on them.
4. Interviews serve as the most personal and inclusive data collection method to capture stakeholder perspectives. It cultivates a greater sense of participation and involvement which garners more commitment to the research process and the implementation of circularity in the industry, more than other methods like surveys or workshops, which feel less personal.

Challenges:

Selecting theories and the MCDA method was not a straightforward activity from existing literature, and required extensive critical thinking. The final choices still have limitations, but are the most suitable, and the limitations are recorded and incorporated in the next iterations. The performances of these methods will be observed.

Adjustments:

The learnings from the theoretical background form part of the components of Prototype 0, giving the research approach and decision-making basis for the framework. The criteria and respondents selection are detailed in the Results chapter.

4. Results

Phase 1- Theoretical Background (Coupling)

From this phase, Prototype 0 is to be created. The components of the Prototype 0 are:

1. Decision Problem Definition, Decision Theory and Method Selection: MCDA, TOPSIS, VFT, BDT, Systems Thinking (Theoretical Background)
2. Preliminary MCDA Criteria and indicators

Remaining Research information for Phase 2 that is discovered in Phase 1 is:

1. Selection of stakeholders and categorization from case study

The activities to be performed in Phase 2 are:

1. Case Study Selection
2. Interviews with stakeholders and categorization from case study
3. Actual trade-offs made by stakeholders
4. Creation of Prototype 1
5. Selection of alternatives from Case Study
6. Final MCDA Analysis
7. Creation of Prototype 2 (First complete draft of DMF)

4.1 Case Study Selection- Project Nieuwe Straat

The selection of the road construction industry and Project Nieuwe Straat as the case study for this project has been made for the following reasons:

1. Open Innovation: The field labs allow open collaboration between the municipality, innovators and circularity experts from around the industry to proactively work towards the implementation of circularity, from their own capacities.
2. The field labs create pilot projects for the rapid testing of innovations, which is a huge leap forward in the circularity transition, and improving the process can have a great positive impact in the transition that can be potentially adopted by other municipalities.
3. As a relatively new endeavour, the testing and selection process in the field labs has iteratively evolved exponentially. With more inclusion of scientifically tested decision-making theories and methods, in the form of a framework that can be applied at multiple points of the construction cycle, the functionality of the field labs can be scaled up with well defined information and material flows. This in turn accelerates the circular transition greatly.
4. The project currently uses limited criteria to assess material performance. To balance environmental criteria with project constraints like cost and distance, the MCDA based tool can be used, alongside analysing stakeholder trade-offs. From a research standpoint, the project is the best opportunity to test these theories.

The purposive sampling and selection of stakeholders from the project for the interviews is detailed in the next section.

4.1.1 Interviews

The respondents for the interviews were selected from two broad categories: decision makers from the field labs at the municipality of Amsterdam and other experts from construction projects with a focus

on circularity. The decision makers were mainly asked about the testing process at the field labs and the challenges observed, and their rankings and weightage for the criteria has the most significance for this MCDA. The experts were asked to share their experience about circularity implementation and innovation selection process in other projects. Their opinions about the ranking and weighting of criteria are crucial to the framework to understand the priorities of the market as a whole, which improves its adaptability. The interviews were 45-60 minutes long, and were conducted in English.

4.1.2 Data Protection

Prior to the start of the interviews, approval was obtained from the Human Research Ethics Committee, where details about the protection of identifiable information about the respondents and the data management plan were mentioned. The participants were informed about data protection before the start of each interview, and were sent informed consent forms with all data protection information for their signature. The interviews were recorded and transcribed for the purpose of obtaining data, but the recordings were deleted after the study was completed and all identifiable information in the transcripts was either removed or pseudonymized.

4.1.3 Purposive Sampling and Representation of the Industry and Municipality

The stakeholders and decision makers for the interviews were selected through purposive sampling, based on specific criteria, to ensure diverse expertise on the subject and adequate representation of those involved in the process of circularity from the construction industry. The research by Arioiz et al. (2025b) used the TOPSIS method to identify stakeholders' level of interest and power in the solar PV supply chain to assess the applicability of the circular economy's 10R targets. The study concluded that although reverse supply chain stakeholders like recyclers and landfill-related collaborators play the leading role in advancing circularity, stronger contribution from forward (suppliers, manufacturers, installers) and external stakeholders (researchers and NGOs) is essential to achieve an effective circular transition (Arioiz et al., 2025b). Another point to note is that when it comes to applying MCDA in a project to evaluate its options, the decision makers should have the most influence in selecting criteria weights and the MCDA set up as a whole. Thus, these two ideas were applied to select interview respondents through purposive sampling.

To represent the diversity in professional backgrounds in the construction industry and circularity, the stakeholders were divided into four categories to explain their experience with circularity.

- Municipality respondents who work in circulatory departments are the most connected to the circular economy as upholders of the circularity ambitions of the country. Their efforts are directed towards researching the market, creating more frameworks and taking steps toward creating policies that can be developed into standards in the future, and are responsible for strategically planning for the future of circularity. They are likely to pursue circularity as the priority and plan projects centred around the same objectives.
- The innovation teams of the municipality and researchers from academic institutions are more aligned towards the theoretical study of circularity in terms of their professional experience. They can advise on new products and processes that improve the application of circularity and are usually more connected with public clients, but may not be fully aware of the actual levels of implementation in projects.
- Circularity consultants and circular innovators from the industry have the most knowledge of the applications of circularity in actual projects, due to their extensive professional experience in the specific field. They are usually tasked with recommending feasible solutions that fulfil the circularity objectives of the municipality within the constraints of actual projects, and find a best possible solution.
- Process managers from the industry have worked extensively with circularity projects, but also work on traditional construction projects. They may not have the awareness about the various circular options available that circularity consultants do, but they have an extensive knowledge about project constraints, and how they have observed the application of

circularity within those constraints. It is interesting to compare their opinions with those of circularity consultants.

The position of the above categories in terms of the connection to circular ambition and objectives versus project implementation can be implemented as seen in Fig 9.

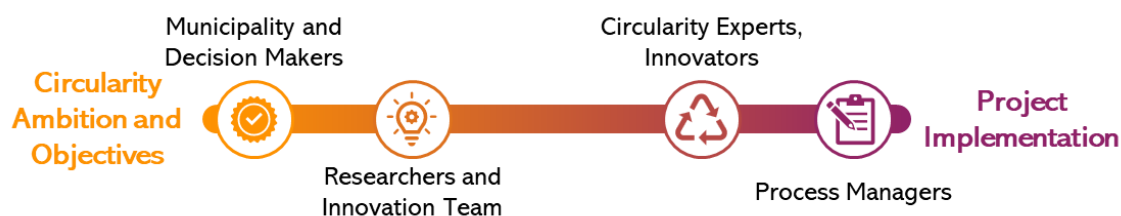


Figure 15 Position of Stakeholder Categories for the implementation of circularity

To use the MCDA for a project, the criteria weights assigned by the project's decision makers are the most important, as they create the project objectives. The stakeholders were thus categorized into the following:

- Project Decision Makers (Field Labs): Decision makers from the municipality of Amsterdam, the AMS Institute and circularity consultants, and they are given more influence in assigning the criteria weights
- Professionals in Circularity: Stakeholders from the municipality that are not decision makers or connected to the field labs, researchers, industry experts and circular innovators who do not work at the field labs.

In order to further understand the trade-offs, the stakeholders were also categorized into the following:

- Municipality+: All respondents who work at the municipality, and contractors working on municipality projects
- Industry experts: Stakeholders who are not working in municipality projects at present.

The trade-offs made by the stakeholders are thus captured under three systems of categorization, to map the preferences across different groups in the industry and circular economy, as seen in Fig 10.



Figure 16 List of Stakeholders and their categories for this study

The ranks and weights assigned to criteria by the respondents will be aggregated to determine the final weights of criteria for the MCDA, once all the required interviews are conducted. The respondents were informed about privacy and data protection and were sent informed consent forms. The interviews were recorded and transcribed, and the video recordings were deleted after the results were gathered. The transcripts are attached as supplementary material and the informed consent forms are provided to the thesis committee for record keeping.

4.1.4 Expected Decisions and Trade-offs made by Stakeholder Categories

The decisions to be made for decision makers from the MCDA analysis can be explained in terms of compromises that they are willing to make for the best possible outcome. These are termed trade-offs in MCDA nomenclature, that can be explored by decision makers with this decision making framework. They can be fundamentally defined as maximizing the benefit criteria and minimizing the cost criteria, to find the best performing alternative. The best performing alternative is thus the one that can achieve the highest possible benefits for the lowest possible costs.

In this MCDA, this is represented by:

1. Obtaining the highest reductions in emissions, for the lowest product cost:

Municipality, innovation team, researchers might choose higher reductions for higher costs, while process managers might express that a lower cost is preferable even if it means slightly lower reductions.

2. Obtaining the highest reductions in emissions for the shortest distance between the supplier and the project site:

Municipality, innovation team might choose higher reductions in spite of a larger distance, the same can be expected from circularity consultants, but process managers might still choose a shorter distance for slightly lower reductions.

3. Decision between a Higher Upfront Cost (Circularity) for Greater Circularity and Reuse (that is, lower emissions and lower costs in the future) versus Lower Upfront Costs and Lower Reuse (traditional material, higher maintenance and new material costs):

This might be divided. The municipality and decision makers might go either way depending on their professional responsibilities. As decision makers in the project they have the responsibility to ensure as much circularity as possible, but as owners of the project they might still choose lower upfront costs due to the pressure of utilizing public funding. Circularity consultants will probably recommend higher upfront costs for greater circularity, process managers may also be divided, depending on the critical objectives of the projects they have worked in.

4. Greater distance for circular materials (higher transport emissions, lower manufacturing emissions due to reuse) vs Shorter distance for traditional materials (lower transport emissions, higher manufacturing emissions):

Most probably, a majority of the respondents will choose a greater distance for circularity, since circular materials are usually treated in specialized facilities that are not commonly found.

5. Less aesthetic and less durable bricks (reused bricks that have lower emissions, no construction waste) vs more aesthetic and more durable bricks (new bricks that have higher emissions, higher construction waste):

The municipality has strong standards of aesthetics and materials that can be used to comply with them. This might thus be a limiting factor, in the sense that they would not choose secondary materials that are less aesthetic if it is slightly more circular than another option, if the other option is more aesthetic. Circularity consultants might choose more durable bricks, process managers will choose more durable bricks as well.

These are a small number of trade-offs that can be observed from the MCDA tool, among many others. The MCDA Excel tool serves to assign criteria weights to model these trade-offs by giving more importance and a higher weight to the characteristics that decision makers are willing to make compromises for, and giving lower weights to criteria that decision makers consider non-negotiable and basic necessities to be fulfilled by the materials.

4.1.5 Anonymization of Interview Respondents and Summary of their Responses

The following sub categories of respondents were contacted and the categories were assigned these identifiers:

1. Project managers at field labs in Amsterdam- PMM (Decision Makers)
2. Process managers at field labs in Amsterdam- ProcMM (Decision Makers)
3. Members from the innovation team and living labs in the municipality of Amsterdam- InTM
4. Contractors/ companies with innovations from the field labs (any role)- InCM (Decision Makers)
5. Circular Innovators from industry- InCI
6. Interviews with the AMS Institute- AMS
7. Circularity experts from the industry (specialist advisors)- CExI
8. Process managers with experiences in circular projects from the industry- ProcMI
9. Researchers from TU Delft with expertise in circularity- TU

There are contractors and consultants who help source materials for the field labs and advise on their properties and whether the innovations have performed successfully in the field labs. They are also categorized as InCM, and are thus assigned as Decision Makers. The respondents interviewed may fit into multiple categories at once, and this is the preferred quality when selecting who to interview, as it improves the efficiency and quality of results.

The following table provides a summary of the results from the interviews:

Table 6 Summary of Results from Interviews

Sl No.	Name	Categories	Key Information Gathered
1	Respondent 1	ProcMI 1	Projects with circularity objectives discard this goal when materials or processes turnout to be expensive. Conventional methods are preferred mainly due to cost and time, and stakeholders in these projects are not obligated to report on how sustainable the project is
2	Respondent 2	RTU	Important to look at durability, lifetimes and reusability for circularity, currently municipality only checks EPDs (environmental impact) of these bricks. Decision makers opinions about the criteria is most important.
3	Respondent 3	InTM (Municipality)	Circularity is most important criteria and cost is not a defining criteria since it is a given. Municipality is prepared to adopt innovations that are more circular and is prepared to support the cost.
4	Respondent 4	CExI 1	Information about indicators and criteria that are most important in innovative projects, where circular solutions have to be adopted.
5	Respondent 5	ProcMI 2	As process managers they are only asked to measure and report on the time, cost and progress of projects, not

			mandatory to report on sustainability. Thus all circularity objectives are excluded if they don't fit in with time and cost. This is a big limitation and frameworks/policies are needed to ensure this is applied in projects.
6	Respondent 6	ProcMM, AMS (Decision Makers 1)	Decision maker from the field labs. Insight into the current testing process from a process perspective, what is important for selecting innovations.
7	Respondent 7	CExI 2	Time, cost and accessibility to circular innovations is important as it is common for projects to discard innovations if they do not fulfill these requirements. They are almost considered boundary criteria and chance criteria are sustainability and circularity.
8	Respondent 8	CExI 3	Government mandates should be put in place for circularity and to incentivize the industry through competition to innovate and develop more solutions, with mandates there will also be a greater supply of circular services
9	Respondent 9	InCM (Decision Maker 2)	How quality of bricks is determined, through visual inspection and environmental inspection. It is necessary to measure the structural performance and durability of secondary materials as well, but that does not exist in the market currently
10	Respondent 10	PMM, AMS (Decision Maker 3)	Full process of testing innovations in the field labs. Since the innovations are in the pilot projects for 5 years, the testing process must be started 5 years before a project is supposed to begin. The municipality has visibility about roads that need to be renovated or reconstructed in the near future, and using this they should define requirements to suppliers and start testing materials in advance. They should create the demand for the material and not wait for suppliers to approach them.
11	Respondent 11	InCI	The cost is still the most important aspect in selecting materials. The organization follows its own process for assigning quality to reclaimed bricks, and there should be a standard from the municipality for assigning quality scores
12	Respondent 12	ProcMI 3	Refuse is implemented by reviewing the client's objectives and project specifications, and finding out if the client's requirement can be fulfilled using lesser resources like less land, less materials, less labour, etc. MKI and GWP is a big debate, but MKI indicators are vulnerable to data manipulation and suppliers can make their products seem to perform better on paper while having high GWPs. Thus, GWO is preferred.

13	Respondent 13	ProcMM (Decision Maker 4)	Space (land) is one of the biggest challenges in Amsterdam for construction. Information sheet with indicators for testing the quality of bricks in the field labs in Amsterdam. The municipality needs to create the demand and standards for designing for circularity.
14	Respondent 14	CExI 4, InCI	Quality inspector, working on a national circularity database. The municipality is testing products and this is a big step forward for the circular economy, but the first contact is currently made by suppliers with innovations. IT is very important for the municipality to use its knowledge to make standards and policies for circularity, or release official information about the requirements that should be fulfilled by circular materials. It is then easier to get more optimized materials that can be compared better, and since there are more suppliers there are competitive prices also.

The criteria weights and additional criteria collected from respondents are provided in Appendix 5.

4.2 Multi Criteria Decision Analysis

This section details the procedure and method selection of the Multi Criteria Decision Analysis used for this thesis. It also contains information about the current testing process at the municipality field labs in Amsterdam, the structure of the MCDA, the flow of information to determine the parameters and the various MCDA methods considered that leads to the selection of the TOPSIS method.

4.2.1 Current State of Testing at Municipality Field Labs

The field labs are one of the only projects in the Netherlands that offers a solution to test circular materials in an efficient manner so that they are declared ready or not ready for actual implementation in projects. One of the biggest barriers to circular innovation is the uncertainty in the performance of materials and this initiative by the municipality of Amsterdam works to improve this situation. During the interviews, the members of the municipality and decision makers of the field labs were asked about the current process of testing, which is as follows:

1. Suppliers who want to release their material for use in projects and improve visibility through municipality approval, reach out to the field labs managers.
2. The managers then set up an innovation sheet, where the properties of the material are detailed and the progress and results from the field labs are entered during the field labs milestones.
3. The field labs conduct a preliminary assessment to determine if the material is useful, only after which is it approved for testing in the field labs.
4. The material is applied in a specified section of road that is in use for approximately 4 to 5 years, and its performance is recorded through periodic inspections from the managers and surveys from residents for aesthetics and utility.
5. For circularity, the field labs most base their decision on the environment product declaration data alone, which details the environmental impact of the material through emissions and impact on the quality of life for its users.
6. If the material performs well and fulfills conditions for circularity and emissions, it is approved from the field labs, and it can be used in the road renovation projects Amsterdam.

Currently only one material has successfully been released from the field labs and is due to be used for road renovations, which is the Geopolymer Betontegel. The MCDA Excel Tool result will be validated using this result from the field labs.

This is an excellent initiative adopted by the municipality in a crucial time to fulfill the circularity target of 2030, but the process faces major limitations. The main performance parameter is the EPDs of the material alone, and does not include other important characteristics like the cost, availability, reuse potential, mechanical performance, and more. The process of tracking the results from the pilot projects is also not standardized, thus the reports for different materials show different aspects. There is also no end-of-life planning for the materials that are approved from the pilot projects, and the knowledge of current projects they can be applied in is limited to the road renovation projects from the municipality only. If the field labs can be improved on these limitations, the potential impact on the circular economy is highly beneficial and turn the tides for circularity in construction.

4.2.2 Procedure to Set up MCDA

As explained in the Research Methodology, the MCDA has been set up in four steps:

1. Selection of the MCDA method
2. Selection of Criteria and Assigning weights
3. Selection of Indicators
4. Selection of alternatives and obtaining their data

The results of each step have been explained along with the assumptions and data gathered to make the final decisions for the setup of the MCDA.

4.3 MCDA Structure

4.3.1 Introduction to the Method

The Technique for Order of Preference by Similarity to Ideal Solution method, or TOPSIS Method, is a widely adopted multi criteria decision making method that facilitates the selection of the best alternative by evaluating its closeness to the positive ideal solution and distance from the negative ideal solution. With over 13,000 citations (Chakraborty, 2021), it employs a simple procedure that can be effectively programmed into spreadsheets like Excel to yield objective results through mathematical computations. Numerous literature explains TOPSIS to be an ideal method for decision making, including the paper by Theilig et al. (2025) that compares the results of multiple MCDA methods for the same project case study, namely . According to their research, TOPSIS is a favourable decision making method for this thesis due to the following reasons:

- **Transparency and Wide Applicability:** TOPSIS is described as having a “transparent and traceable decision-making process” due to its “straightforward computational procedure and logical principle” (Theilig et al., 2025). The two primary steps are data normalization and weighted criteria application, following which the positive ideal and negative ideal solutions are determined. The best alternative is then the one closest to the positive ideal and furthest from the negative ideal. TOPSIS is easily programmed into Excel or an Integrated Development Environment (IDE) like Python that use spreadsheets for data organization, while other methods require more complex software like SuperDecisions. The decision making framework to be created through this thesis should be available to diverse stakeholders in the industry and easily applied to diverse projects, thus TOPSIS is more suitable.
- **Numerical objectivity:** TOPSIS requires that all data input is numerical, thus qualitative characteristics of alternatives are also assigned numerical values and can be normalized using a sum-based method or a vector method, which was further elaborated in the paper. Other

methods like AHP (analytical hierarchy process) and ANP (analytic network process) can handle qualitative data directly through verbal scales, which introduces a level of subjectivity that is not required for this thesis.

- **Group Comparisons:** One of the main reasons TOPSIS has been selected for this thesis as compared to AHP and ANP is its ability to compare a large number of alternatives simultaneously, which AHP and ANP employ pairwise comparisons to ultimately determine the ideal alternative. To enable efficiency in the process of testing and comparing circular innovations in the field labs of the municipality, it is critical to have a decision making method and framework that allows the input of numerous alternatives at the same time, and understand how their performances compare under the assigned criteria weights.
- **Less time-consuming data input:** Especially observed when a large number of alternatives need to be studied, it consumes less time to have all the data input in the MCDA when using TOPSIS since all data points are normalized on the same scale with predetermined criteria weights and their performance is measured in terms of the distance from the same positive and negative ideal solutions. In AHP and ANP, additional steps are required to set up pair wise comparisons.
- **Sensitivity to Emphasized Criteria Weighting:** The results produced by TOPSIS are directly influenced by the criteria weights that are assigned, based on the objectives and priorities of the decision makers involved in the analysis. This is an important factor to represent the goals of the municipality and of each project, while granting decision makers the flexibility to define the most important criteria based on the priorities defined for each specific project. This property also enables the framework to capture the diverse perspectives of stakeholders and their collective experiences in circularity. In other methods where hierarchies of categories and criteria correlations are included in the analysis, the weights assigned to individual criteria and the priorities that are specified may be disproportionately diminished as they get buried as sub categories.

The procedure of TOPSIS and the MCDA as a whole for this thesis is adopted from the research by Chakraborty (2021) which explains the methodology and procedure of TOPSIS alongside its applications, the processes and mathematical functions defined by Theilig et al. (2025) and the alternative recommendations provided by Arioiz et al. (2025). All three research papers follow the fundamental concepts of TOPSIS for decision making but have modified certain steps to best fit their research focus, which serves as a holistic view to curate the most suitable format for the MCDA in this thesis, as explained in the following sections.

5.3.2 Potential Formats for MCDA

The main procedure for the MCDA was derived from process used by Chakraborty (2021b) and Theilig et al. (2025) and is defined for this thesis as follows:

1. **Defining problem structure-** This step involves goal definition, selection of criteria, data collection, and choosing circular innovations as alternatives.
2. **Assigning criteria weights-** In Theilig et al. (2025)'s research, an elaborate process of AHP with subjective pairwise comparisons was used to determine criteria weights. For this research study, interviews with stakeholders were conducted where respondents were asked to rank criteria from the most to least important and assigning weights to them on a scale from 0-100%. The interview respondents were assigned weights based on their influence as decision makers for the selected case study and the significance described in the research by Arioiz et al. (2025) to calculate the final score of each criteria.
3. **Selection of indicators and assigning numerical values to all-** The indicators used to quantify the properties of circular innovations are selected. In case of qualitative properties, a numerical scale is defined and numerical scores are assigned.

4. Normalization of Data- Theilig et al. (2025) used an aggregate of the sum based and vector based normalization results to derive the final normalized matrix. For this study the sum based normalization is sufficient, and the formulae used is as follows:
Sum Based method N1:
For every alternative i and criteria j , where x_{ij} is the original value, the normalized data value r_{ij} is given by:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}}, \quad \text{for all benefit criteria,} \quad (1)$$

and

$$r_{ij} = \frac{1/x_{ij}}{\sum_{i=1}^m 1/x_{ij}}, \quad \text{for all cost criteria.} \quad (2)$$

The normalized matrix is thus given as:

$$[r_{ij}] = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}$$

The weighted normalized matrix is derived by multiplying each criteria's weight w_{ij} with the normalized matrix:

$$[v_{ij}] = w_{ij} * [r_{ij}]$$

5. Distance from ideal and anti ideal solution: The distance of each alternative from the ideal solution d_i^+ and anti ideal solution d_i^- is computed using the Euclidean distances:

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}$$

The relative closeness coefficient C_i is then calculated as the final score for each alternative:

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-}$$

C_i gives a value between 0 and 1 with the most preferred alternative being ranked 1 and the least preferred alternative being ranked 0.

The research by Chakraborty (2021b) detailed a comparative study between TOPSIS and Modified TOPSIS, with the full procedure for both methods. Modified TOPSIS varies from TOPSIS due to one critical change: the inclusion of weighted Euclidean distance calculations. The formulae and detailed explanation are presented in the Phase 2- Data Analysis chapter, where the choice between Theilig et al. (2025)'s method and Chakraborty (2021b)'s method is explained. The data, calculations and full MCDA is also provided in the same section.

Definition of the Ideal and Anti-Ideal Solution

In the TOPSIS method, alternatives receive their scores based on the distance from the ideal and anti ideal solution. In the study by Theilig et al. (2025), the ideal solution is determined as the maximum

value found within the weighted normalization matrix within each criterion, and the anti ideal solution is the minimum value found within the weighted normalization matrix within the same criterion.

For this study, the ideal and anti ideal solution are defined as the highest scoring alternative and lowest scoring alternative, and the remaining alternatives receive final scores based on their distances from these two extremes, within each criterion. There is also no limit in the TOPSIS method to the number of alternatives that can be compared in one analysis, thus a large number of innovations and data can be compared in one analysis simultaneously.

This framework thus provides a decision making method of comparing existing innovations and circular materials from the industry to each other, and finding the best innovation between them. The criteria for the best alternative is defined by the decision makers for each project and changing objectives, before the start of the analysis. This allows decision makers to compare the performance of various innovations with the flexibility to define criteria weights from project objectives, and choose the most suitable alternative for the given project.

An important point of discussion is thus the scope of this decision making framework. From a national and continental perspective, it is most beneficial to include national standards, sustainability ambitions and policies in the decision making process. They can thus be included in the MCDA as the ideal solution, and the anti ideal solution will be conventionally used material that is not innovative in terms of circularity or sustainability. There are challenges to realizing this requirements in this study, as follows:

1. Non-uniform units of measurement and scales: Many national standards and policies define requirements in qualitative terms, or in larger units when they are defined in quantitative terms, as national statistics. However, the performance of innovations in the field labs and in circularity projects is in much smaller scales in terms of square meters or kilometers, within the project area. It is challenging to accurately define a normalization scale or conversion scale to represent national policies in smaller units, especially for requirements that qualitatively measure performance. Only a few that are translated into indicators for some of the criteria, for example, Platform CB'23 defines indicators for circularity alone, but not all, and thus it cannot be applied for the MCDA and framework as a whole.
2. Broad ambitions for the future: On the EU level, many policies for sustainability like the Paris Agreement, define goals for countries to reach certain sustainability targets within a time period, but do not contain specifications on how this translates into the performance of circular innovations and products.

This is thus a limitation of the current research study. Further research is required to explore methods to translate these ambitions into measurable KPIs for materials and projects, through which this decision making framework can evolve into a national level standard that can be utilized to create policies. At the moment, the framework is most required on the municipality level to choose from available innovations, which is a critical activity to visualizing and implementing circularity in as many projects as planned. In line with this requirement, the current method of determining the ideal and anti-ideal solutions for TOPSIS has been selected.

4.3.2 Criteria Selection

Based on the review of existing literature, circularity policies in the Netherlands, current state of testing at the municipality field labs and interviews with stakeholders, the six primary criteria for this study have been selected as follows:

1. Mechanical Properties (Durability/Design Life): The selected alternatives are compared with the conventional material used for pavements to ensure they fit the minimum standards of performance in terms of structural soundness, wear and tear, and durability.
2. Global Emissions (Sustainability): The total emissions from the lifecycles of alternatives is measured through the MKI (Milieu Kosten Indicator, Dutch for Environmental Cost

Indicator) and EPDs (Environmental Product Declarations) measured through a Lifecycle Analysis (LCA). This data is obtained from the municipality and the AMS Institute directly.

3. **Circularity Properties:** The circularity of alternatives measures the extent to which secondary material is incorporated in its composition and the extent to which this material can be reused at the end of its first design life. The research by Theilig et al. (2025) describes the Urban Mining Index as a method to measure the circularity potential, which can be used for this study if adequate information is available.
4. **Cost:** As the industry advances in technology and circular innovations, the implementation of circularity is still largely inhibited by cost as a decision making property. For this study, the cost is a sum of the selling price of the circular innovation and the supplementary costs of transport, storage, and application.
5. **Logistics:** For innovations, one of the most challenging properties is the availability of these new materials. It is determined by the number of suppliers, the location of these materials (which in turn informs the requirements for transportation) and the ease of storage near the project site.
6. **Time for implementation:** This property measures the amount of time required to apply the selected alternative in practice. Scores will be affected if the material requires highly specialized labour or training, and measures the duration between the start of application till the material is ready for use.

4.3.3 Selection of Indicators for Each Criteria

Initial literature review revealed numerous international standards that dictate criteria and KPIs to be used for road infrastructure and road construction. The research by S. Liu (2024) compares twelve existing circular economy indicators to understand their use in evaluating pavement infrastructure, of which 6 were shortlisted and analysed, namely the MCI, CEI, CB'23, ESCi, CEIP, and MRS. Each indicator has its own advantages and disadvantages, and a choice should be made based on the context of circularity that needs to be checked. Suprayoga et al. (2020) conducted a systematic literature analysis with an initial set of 490 papers from which 31 were finalized as the most relevant in terms of sustainability in road infrastructure, and all the indicators from these papers were included in the final list. These indicators were then categorized into 10 criteria based on the work of Gibson et al. (2005) that refers to them as “a minimal set of core [sustainability] requirements” across the environmental, economic and social dimensions. Thus, the most relevant sustainability indicators for this research could potentially be adopted from this exhaustive list. As for indicators measuring the current performance standards of road construction, ISO 13472 and ISO 13473 specify testing for different materials and characterizations.

Following the literature review, extensive information in the form of project documentation and interviews was collected from the field labs in Amsterdam to determine how materials are currently being tested and which aspects are not yet included, to determine the final criteria and indicators that will be used for the MCDA. Each criteria is measured by one or more indicators which have wide applications for diverse projects and innovations, contributing to the increased usability of the decision making framework.

The European Emissions Council and SMEs Executive Agency (EISMEA) proposed a model for the circular economy with the recommended indicators for the recommended indicators per value chain, as seen in Fig 12. In addition, the initial plan for the indicators to be used for the MCDA were as follows:

- For LCA indicators: ISO 14040 (2006) en
- For pavement quality: <https://www.iso.org/obp/ui/#search>

- For circularity indicators: Literature by Liu, S. (2024) comparing 6 circularity indicators and listing their limitations to choose the most suitable.
- Additional Sustainability Indicators: Literature by Suprayoga et al (2020) titled “A systematic review of indicators to assess the sustainability of road infrastructure projects” with a list of indicators in the appendix.
- For mechanical properties: Information from project documentation of the field labs in Amsterdam
- For cost indicators: Information from project documentation of the field labs in Amsterdam

EXAMPLES OF RECOMMENDED INDICATORS PER VALUE CHAIN STAGE

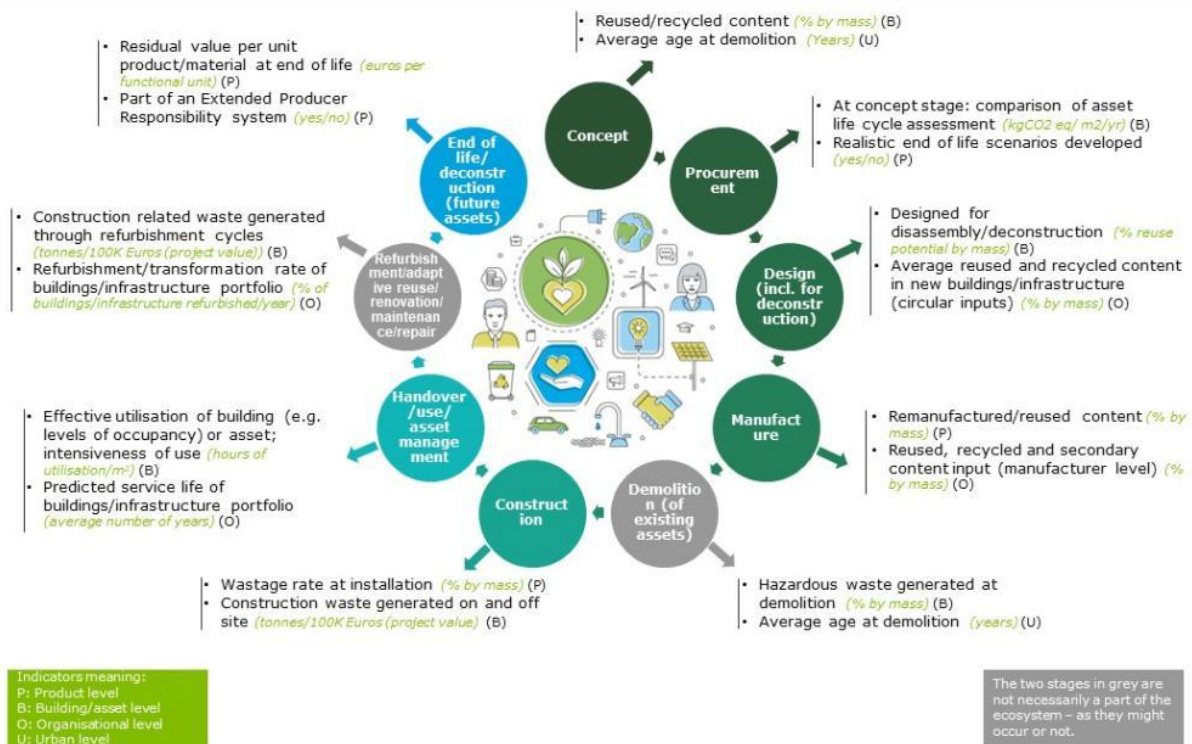


Figure 17 Examples of Recommended Indicators per Value Chain Stage. (European Innovation Council and SMEs Executive Agency (EISMEA), 2023)

Challenges in Selection of Indicators

A significant hurdle in the process of selecting indicators, is that although there are numerous resources from public organizations in the Netherlands with indicators for circularity, sustainability and more, with many being discussed in the previous sections that are highly relevant to this study, these indicators could not be selected for the test model. It was determined through multiple discussion with the decision makers that most of the data required for these indicators was not acquired during the field labs pilot projects, or pre and post the field labs. This is an important limitation in the decision making process of the field labs. More structure and planning is required to determine further aspects of testing for circularity from resources and organizations like the indicators from Platform CB'23, HNN, and the NEN.

Through the discussions with decision makers at the municipality of Amsterdam, AMS Institute and the project team of the Nieuwe Straat, data for the innovative materials was acquired. The various indicators to be selected for the analysis was also verified by checking what data was available and

considered in the current process of selecting innovations at the field labs. The following feedback was obtained from them:

1. There is currently no applied process for evaluating the mechanical and structural performance of the materials in the field labs. The quality of reused materials is determined by the circularity consultant of the field labs based on an environmental inspection and visual quality inspection, and the structural performance is assumed to be the same as conventional material. Stakeholders from circularity consultant company agree that this is a necessary criteria and data should be collected for this, and they are in the process of developing this capability in their organization.
2. The cost of the materials is obtained from many different activities involved in acquiring the material, including the manufacturing cost, transport cost, storage and cost of labour in applying the material in a project (some materials need specific skilled labour or training to apply them, which significantly increases the labour cost). There is currently no definitive overview of this data with the decision makers. The quotation given by suppliers is also volatile and is based on negotiation, which stems from the amount requested by the municipality. When deciding what material to use for the pilot projects, the cost is not part of the decision making process, but even if the material performs well for circularity reduces the embodied carbon footprint, it is disregarded later in the project if it is too expensive. This was discussed with Respondent 10 in the interview, who is a decision maker in the field labs, and they agreed that it is important to include this parameter in decision making. This is also an important parameter as seen in the interviews with Respondents 1 and 5, who are both process managers from the industry.
3. There are numerous indicators to measure the circularity potential of a material, but almost no data to check the reusability potential. It is a challenging criteria to define, and thus challenging to choose indicators for the same. The decision makers were consulted about this challenge and agreed that they had not yet considered reusability as an indicator for circularity and used EPD data alone, but that it was necessary. This study aims to detail the possible approaches to measure circularity for this decision making framework as well.

Components of Prototype 1

The components of Prototype 1 for the MCDA tool are:

- Final Criteria for MCDA
- Final criteria weights and stakeholder weights for MCDA
- MCDA Method programmed into the Excel tool
- Preferred Indicators for the MCDA

The components of Prototype 1 for the Decision Making Framework (qualitative) are:

- Current state of testing at the field labs
- Stakeholder Preferences (final trade-offs), constraints, hesitations in adopting circularity
- Possible solutions put forward by stakeholders to improve on the challenges
- Stakeholder opinion about the choice of method and theories, and the applicability of the DMF

4.3.4 Finalization of Criteria, Indicators, Materials and Material Data

Further exploration allowed the collection of data from the research team that the thesis is created in collaboration with at TU Delft, named the Nieuwe Straat, a research project which is a collaboration between the AMS Institute, the municipality of Amsterdam, contractors and researchers from TU Delft and Wageningen University.

Considering the options from literature research and by speaking to industry experts, the following criteria and indicators were finalized for the analysis:

1. Embodied Carbon (previously Global Emissions (Sustainability)) is measured by the MKI (Milieukosten Indicator) values of the materials, obtained from EPD data (Environmental Product Declaration).
2. Lifetime (previously Mechanical Properties (Durability/Design Life)) is measured by the design lifetimes of the materials and historic maintenance records of the municipality for data about when roads are renovated or replaced.
3. Availability is measured by calculating the distance of the storage warehouse of the material to Amsterdam.
4. Cost is calculated as a sum of the cost of the product and the cost of transporting it to the project site.
5. Circularity is calculated by measuring the number of times a material can be reused in 100 years using its functional lifetime, and the emissions from a material in the time period of 100 years.

4.3.5 Companies and Innovations Selected for Analysis

The materials selected for this study are all brick or concrete based blocks, and this decision for uniformity was made to demonstrate that the MCDA and decision making framework should be formulated with alternatives belonging to the same category. Thus, asphaltic materials and innovations have been excluded from the research for this study, owing to the differences in how circularity is expressed in such materials, compared to pavements made with brick and concrete block based materials.

Owing to the flexibility and transparency of the MCDA, it is important to compare the performance of innovations with reused traditional materials to study the improvements or reduced performances under the selected criteria. Thus, materials for the MCDA are chosen under the reused traditional and circular innovation categories. This provides insights about whether it is sufficient to just reuse traditional materials, or if innovative materials are also important in enabling circularity. By comparing their performance, the costs and resources used for innovation are being questioned, to observe whether a significant change is brought about by using these innovations in new construction for the future, or if it is sufficient to continue the use of traditional material as long as they are properly reused. The traditional materials are also being compared to each other by their performance to further explore this idea.

Three main traditional materials are used for road pavements that are non-asphaltic in the Netherlands, namely the betontegel (concrete tile), Baksteen (clay bricks) and the betonstraatsteen or BSS (concrete paving blocks). At least one circular alternative must be compared to these materials. For betontegel, Biobound and geopolymer concrete variants are popularly used (as explained in the theoretical background). For Baksteen and BSS, innovations incorporating recycled materials in the composition are more commonly seen in the Netherlands.

The field labs in Amsterdam have analyzed the performance of a few of these products in the field labs, which can be selected for the MCDA to compare the results and validate the functioning of the MCDA Excel tool. Based on the circular materials that have already been tested in the field labs, the preliminary selection of companies and innovations for circular alternatives is:

- Traditional Betontegel
- BioBound Betontegel
- Geopolymer Betontegel
- Traditional Baksteen 2
- Georeton Baksteen

- Traditional Red BSS

Data for these companies is obtained through official company websites, public national databases in the Netherlands and by collaborating with the project team of De Nieuwe Straat. Detailed explanations about the selected materials can be found in the Phase 2- Data Analysis section.

Thus, traditional betontegel is being compared with Biobound and Geopolymer betontegel alternatives, traditional Baksteen is being compared with georetron Baksteen which creates bricks that have the properties of clay bricks but from concrete, and traditional red BSS is compared with the other traditional materials to check their lifetime and reusability potentials.

A total of 6 materials have been chosen across 5 criteria, which provides 30 data points for analysis. These materials have been selected to represent the options available in the market for non-asphaltic road paving materials and their diversity reduces the risk of bias in the results. Given the limited number of materials that have been tested in the field labs, this array of materials is the largest possible dataset with proportional comparisons. Ideally, more criteria must be included and more materials should be used for comparisons in the MCDA, which is an important development of the proposed model from this study, that should be explored for further applications.

The purpose of the MCDA is a comparative evaluation of the existing, pre-tested alternatives from the field labs, and the test materials have been selected to demonstrate those purposes. The MCDA tool can be scaled up further to function as a mapping tool for the market, which will bring out the best potential of the method, and this can be done in future applications of this tool.

4.3.6 Final Multi Criteria Decision Analysis- Calculations

Structure and Formulae:

The final MCDA model has been created using the method by Chakraborty (2021b) for the following advantages:

- Data normalization leads to representing each raw data point as a fraction of the sum total of all the data points within each category. This allows the comparison between alternatives exclusively within the criteria, and removes the risk of repetition that may occur between the various criteria. For example, the Transport criteria also affects the total emissions, which is repetitive due to the Embodied Carbon criteria. But in the MCDA, the relative performance of alternatives to each other within each criteria is considered for the final score and not the raw data, so a numerical value (the fraction) is used to measure the difference in performance to the total.
- The formulae used are simple while offering all the required data calculations to account for the trade-offs between the criteria.
- Chakraborty (2021b) proposes the TOPSIS method and the Modified TOPSIS method, which result in slightly varying outputs for the alternatives. It is interesting to observe the change and analyse a different approach.

The data for the MCDA innovations has been obtained through discussions with the project team of the Nieuwe Straat, specifically their Environmental Product Declarations. The final criteria being used are Embodied Carbon, Lifetime, Distance, Cost, Circularity, and the various decisions made for all of them are explained in this section. The full manual for using the MCDA tool is attached in the supplementary material with screenshots and steps.

Steps of the MCDA and Formulae:

Step 1- Normalized Data. i refers to the material, j refers to the criteria

After the innovations are input on the left and the raw data is also input, the first step is to normalize the data, through the formula:

$$y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^I x_{ij}^2}$$

where x_{ij} is each data point corresponding to a material, within one criteria and y_{ij} is the normalized value (normalized performance rating). Thus, each data point is normalized to express a fraction of the sum of the squared values. For the Excel, the raw data is first squared in a separate column and the sum of the squares is calculated to be the denominator from the formula. The raw data point is then divided by the square root of the sum of squares.

Step 2- Integrate Weight with Normalized Performance Rating

Simple multiplication. The weight for each criterion is obtained from the interviews with stakeholders that have diverse circularity experience, and decision makers from the municipality are giving double the influence as the other respondents. The weighted normalized data is given by:

$$v_{ij} = W_j * y_{ij}; (i = 1, 2, \dots, I; j = 1, 2, \dots, J)$$

where W_j is the weight of the criteria and y_{ij} is the normalized data from the previous step.

Step 3- Find the positive and negative ideal solutions.

The ideal and anti-ideal solutions are determined by slightly different formulae for cost and benefit criteria. Cost criteria are where having higher values are a negative outcome for the decision maker and benefit criteria are where high values are a positive outcome. The formulae are given by:

A^* and A^- are denoted as the positive and negative ideal solution sets respectively which can be detected from Eq. (7) as

$$A^* = [v_1^*, v_2^*, \dots, v_J^*] \quad (8)$$

$$A^- = [v_1^-, v_2^-, \dots, v_J^-] \quad (9)$$

Where,

$$v_j^* = \begin{cases} \max v_{ij}, & \text{if } j \text{ is a benefit attribute} \\ \min v_{ij}, & \text{if } j \text{ is a cost attribute} \end{cases}$$

$$v_j^- = \begin{cases} \min v_{ij}, & \text{if } j \text{ is a benefit attribute} \\ \max v_{ij}, & \text{if } j \text{ is a cost attribute} \end{cases}$$

In the Excel, the MIN/MAX formulae are used to determine the ideal and anti ideal solutions. These formulae are thus modified according to whether the criterion is a cost or benefit criterion.

Step 4- Finding the separation values

Separation Values are calculated from the distance of each performance rating from the positive and negative ideal solution, within criteria. Separation values are calculated **for each material, to represent its performance across all the criteria.**

$$S_i^* = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^*)^2}$$

$$S_i^- = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^-)^2}$$

where S_i^* is the overall performance of the material in relation to the positive ideal solution in each criteria, and S_i^- is the overall performance in relation to the negative ideal solution.

In the Excel, after the distances from the ideal and anti-ideal solutions are calculated, they are squared in the next column. The squared values are then carried to the “Alternatives Final Score” sheet, where they are used in a table with all the values across the criteria for each alternative. A separate table is used for the Ideal and Anti-ideal distances, and the sum of the squared values from each criteria is then calculated. The square root for each alternative is then calculated, which yields the separation value for each alternative.

Step 5- Calculate the overall preference score

$$V_i = \frac{S_i^-}{S_i^- + S_i^*}$$

The overall preference score is V_i for each alternative i . It is the relation of the distance from the anti-ideal solution to the sum of both distances for each alternative. This is the final score of the alternative, to represent its performance. This is a straightforward formula, and the higher the score for the material, higher the ranking, and the more preferred it is.

Materials and Data:

Material data from the innovations tested at Project Nieuwe Straat has been used to test the MCDA Excel tool in this framework. This called for a secondary data collection process in Phase 2 of the research methodology, as explained in Chapter 4. The following are the materials selected for the analysis and their key characteristics.

Table 7: Materials Selected for MCDA

Sl No.	Material Name	Type of Material	Level of Reuse (new, reused, circular new)	Description
1	Traditional Betontegel	Concrete Tile	Reused	Measurements (in mm) 300x300x45, thickness 0.045. 50 years functional lifetime
2	BioBound Betontegel	Concrete tile with biobased material	New (circular)	Same properties as traditional; circular concrete top layer and biobased concrete base from recycled elephant grass combined with concrete aggregate. Both sides can be used, thus infinite reuse

3	Geopolymer Betontegel	Concrete Tile using geopolymer as alternative for cement	New or Recycled concrete (circular)	Same properties as traditional, geopolymer used to substitute cement. Base concrete geopolymer concrete, top layer is aesthetically unchanged. Reduced emissions
4	Traditional Baksteen	Baked clay bricks, masonry	Reused	High functional lifetime, lower shrinkage and expansion, withstand frost and high pressure, retains heat
5	Georetron Baksteen	Concrete bricks, alternative to traditional Baksteen. Embody best properties of clay brick with reduced emissions of concrete	New (circular)	Made of concrete with coloured top layer (kleurvaste) to resemble bricks, natural aggregates. Lower emissions than Baksteen, 50 years functional life, top layer erosion occurs since it is concrete. Premium protection treatment to preserve top layer
6	Traditional Red Betonstraatstenen (BSS)	Concrete paving stones with red colour	Reused	Natural or mineral aggregates with kleurvaste top layer, durability and functional life of 40 years

Activities:

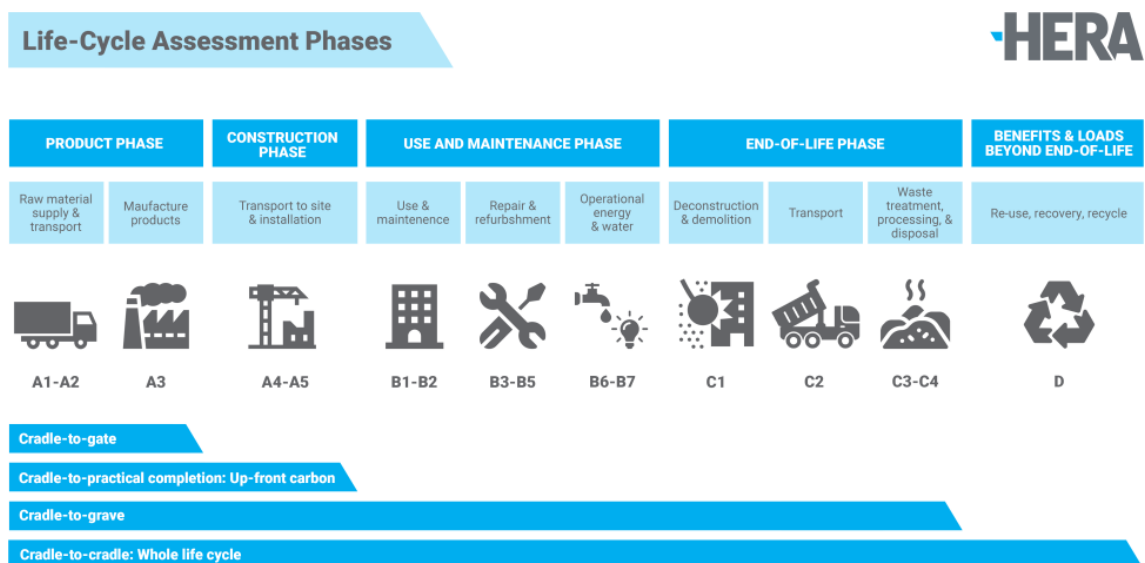


Figure 18 Lifecycle Assessment Phases (Coyle, Hera, 2024)

The EPD data contains the emissions for the materials within the categories of activities as shown in Fig 13, which are obtained from a lifecycle analysis. A1 refers to the raw material supply, A2 refers to the transport of raw material and A3 refers to the manufacture of the construction material. For this study, only the emissions in the Product phase (A1-A3) are considered since the decision making framework is focused on testing materials. When testing services and conducting circularity assessments for entire projects, emissions from the remaining phase must be included in the analysis as well. The materials used in the current analyses are traditional materials (new) as well as reused materials, thus the consideration of emissions changes based on the level of use.

Considerations for the Criteria

It is important to note that Embodied Emissions, Availability, Lifetime and Cost are singular data points, occurring from one type of activity. Measuring Circularity means measuring the impact of a material from a combination of activities, and these will be listed and explained clearly in the corresponding sections.

Embodied Emissions

The EPD data for the innovations is used as the main source of information, and the indicator used for the MCDA is the MKI for the first analyses. The second iteration of the MCDA used the GWP as the indicator to compare the change in results, which has been discussed in detail in the next section and the Discussion chapter.

The MKI or the Milieukosten Indicator is the outcome of a lifecycle assessment (LCA) that expresses the environmental impact of a product or project in monetary terms. This value represents the expected social costs if the environmental effects were reversed, and are thus termed “Shadow costs” for society. The lower the MKI value, the more sustainable the solution, and it is thus categorized as a cost criterion. It has been standardized by the Nationale Milieu Database in the Netherlands, and many municipalities mandate projects and organizations to report on the MKI, and comply to pre specified levels.

Although the MKI is widely used and provides a standard representation of the perceived costs to society from environmental impacts, it conflicts with the actual financials that are calculated using the lifecycle analysis or lifecycle cost calculations, that actually include the expenditure connected to a product or service due to its related activities. It should thus be seen as a complementary perspective alongside LCA and LCC.

The MKI is calculated as the sum of the weighted values of 11 indicators, the data for which is obtained through an LCA. The indicators are assigned weights from the Nationale Milieu Database (NMD). Some of these indicators are not actual costs and a monetary value is used to represent their impact. A few of the indicators are emissions values, like the Global Warming Potential that calculates carbon emissions in kg CO₂ equivalent units, and others like Human Toxicity Potential are measured in kg 1,4-dB equivalent units, that is in amounts equivalent to 1,4-dichlorobenzene as a reference to measure the impact on human health through ecotoxicity. Some of these indicators measure the negative impact to the quality of life and are represented in numerical values although they are conceptually qualitative, which allows decision makers to visualize slightly uncertain effects of the construction process on residents.

Each MKI indicator is also assigned weights to measure its influence, which are specified by NMD Bepalingsmethode, which is the Dutch standard for calculating the environmental impact of construction materials and processes (Ecochain, 2025). NMD stands for the Nationale Milieu Database, the governing body and policy maker for circularity assessments and standards in the Netherlands. Although the indicators use different units of measurement, the weighting factors are assigned to them in euros, as seen in Fig 14.

Impact category	Unit	Weighing Factor (€/unit)
Global warming	kg CO ₂ -eq	0.05 €
Ozone layer depletion	kg CFC-11-eq	30.00 €
Acidification	kg SO ₂ -eq	4.00 €
Eutrophication	kg PO ₄ ³⁻ -eq	9.00 €
Depletion of abiotic raw materials	kg Sb-eq	0.16 €
Depletion of fossil energy carriers	kg Sb-eq	0.16 €
Human toxicity potential	kg 1,4 DB-eq	0.09 €
Ecotoxicological effects, aquatic (freshwater)	kg 1,4 DB-eq	0.03€
Ecotoxicological effects, aquatic (marine)	kg 1,4 DB-eq	0.0001 €
Ecotoxicological effects, terrestrial	kg 1,4 DB-eq	0.06 €
Photochemical oxidant formation (Smog)	kg C ₂ H ₄ -eq	2.00 €

Figure 19 Old ECI/MKI Weighting Factors (Ecochain, 2025)

For this study, the above weighting factors have been used, since the data for the materials have been obtained this way. In the newest documents, GWP is termed climate change and measured as the sum of three types of emissions- climate change fossil, climate change biogenic and climate change land use and land use change. The number of units emitted by a certain material or product changes depending on the indicator as well, thus, although some factors have extremely high weights, the MKI is balanced.

Impact category	Unit	Weighing Factor (€/unit)
Climate change - total*	kg CO ₂ -eq	
Climate change - fossil	kg CO ₂ -eq	0.116
Climate change - biogenic	kg CO ₂ -eq	0.116
Climate change - land use and land use change	kg CO ₂ -eq	0.116
Ozone depletion	kg CFC-11-eq	32.00
Acidification	mol H ⁺ -eq	0.39
Eutrophication aquatic freshwater	kg P-eq	1.96
Eutrophication aquatic marine	kg N-eq	3.28
Eutrophication aquatic terrestrial	mol N-eq	0.36
Photochemical ozone formation	kg NMVOC-eq	1.22
Depletion of abiotic raw materials, minerals and metals	kg Sb-eq	0.30
Depletion of abiotic raw materials, fossil fuels	MJ net cal value	0.00033
Water use	m ³ water, world eq. deprived	0.00506
Particulate matter emissions	Health problems - incidence	549750.00
Ionising radiation, human health	kBq U235-eq	0.049
Ecotoxicity freshwater	CTUe	0.00013
Human toxicity, cancer effects	CTUh	1096368.00
Human toxicity, non-cancer effects	CTUh	147588.00
Land use related impact / Soil quality	Pt/m ² *year	0.000087

Figure 20 New ECI/MKI Weighting Factors (Ecochain, 2025)

The MKI value used for each innovation in the MCDA is the MKI/m², which is calculated by multiplying the thickness in meters into the MKI/m³. This is done since the innovations in the field labs are tested a section of the road, and the performance per squared meter is used for comparisons. It is first checked as the MKI/m² for one lifetime for all the materials, then calculated to the MKI/m² for 100 years, since materials have different lifetimes and to keep the duration a fixed variable. Depending on the lifetime of the material, some activities have to occur multiple times within the span of 100 years. If the material is durable with a longer functional lifetime, it can be reused more times and not need to be replaced as frequently, whereas if a material has a short functional lifetime, it has to be replaced with new material more than once in 100 years, which leads to increased emissions. These emissions were calculated from the activities from A1 to A3, which is extraction, transport and manufacturing.

Since the embodied emissions is a cost criteria, the minimum MKI weighted normalized value is the ideal solution and the maximum MKI weighted normalized value is the anti-ideal solution.

Another approach is using the GWP as the sole indicator to measure the performance of innovations, which has been explored in the Discussions chapter as a secondary approach and the change in results is also mentioned there.

Process for Embodied Emissions:

1. The materials and their suppliers are filled in the spreadsheet.
2. The MKI/m² values for all materials is filled in the excel, for one lifetime.
3. Using the functional lifetime, the MKI/m² values for 100 years is extrapolated (eg if functional life is 50 years, MKI/m² is multiplied by 2 to get the MKI/m² for 100 years).
4. The normalized values and weighted normalized values are obtained. The weight for this criteria from the interviews is 0.20, and the normalization formula for cost criteria is used.

Lifetime

For this criteria, there are two data points to be used. One is the design lifetime or the time period till which a road is defined as functional until it has to be replaced, and two is the functional lifetime of the material. Both data points were obtained in consultations from the municipality. For this study, the functional lifetimes of the innovations were considered to compare their performances, since it is a better indicator of the material's durability and retained quality or value after the first, second, and sometimes even the third time it is reused. A second approach using the road design life is used to observe whether the results change, which has been explored in the Discussions chapter.

The functional lifetime is measured in years, and since it is a benefit criteria, the approach normalization formula and ideal and anti-ideal solutions are calculated.

Distance (Availability)

For this criteria, there has been a lot of consideration for the best way to measure the availability of a material. The following indicators were considered:

1. Scalability or supply of the material at least until 2030
2. Number of suppliers for this material at present, for projects
3. Distance from the supplier's warehouse to the project site

The scalability or supply can be measured by first projecting the required demand of the material until the next milestone, which is currently 2030. It is assumed that traditional materials will fulfil 100% of the demand, but this is not the case for innovative, circular materials. Once the projected demand is available, suppliers can be asked about their ability to fulfil that demand, in simple estimates or in exact production and manufacturing values. Although many suppliers obtain their reused bricks from other projects and it may be challenging to determine when and where these projects may release materials, it is crucial to collect this data and consider the supply when choosing a material. Upon long discussions with the municipality it was discovered that this was not yet considered and data is currently unavailable to measure this, but the interview respondents agreed that this is a necessity.

Similarly, there is limited information about the total number of suppliers who can supply a certain material. At the field labs, the municipality does not seek suppliers, rather they are approached by suppliers who have an innovative material that they would like to test in the pilot projects. The municipality then tests the material and approves or rejects it. There is still no exploration to seek other suppliers if a material is approved, which is a challenging task if a supplier has approached the municipality with a unique material, it is assumed that the material is unique to them. Two respondents from the interviews explained this flow of information and process of circularity and suggested an alternate, much more efficient method to improve this process, which has been explained in the Discussions chapter. For this analysis, this information was also not available.

Thus, the only data considered for the availability is the distance of the supplier's warehouse to the project site, which was obtained from the Nieuwe Straat project team. The criteria weight has been calculated as 0.14, and since it is a cost criteria, the appropriate formulae have been used.

Cost

For this criteria, there are two main approaches that can be taken:

1. Total of all costs associated with the material like transport, manufacturing, cost of labour for implementation in the project, cost of the product itself, cost of storage, etc.
2. Combination of costs from some activities only, like cost of material, transport to project site, storage costs
3. Only considering the cost of the material in the quotation provided by the supplier (after negotiations)

At present, the cost of transport and storage can be calculated from the distances, but the defining characteristic cost is the cost of the material itself, that has to be paid by the municipality, and plays a large role in decision making. In the current process, one of the limitations is that the cost of the material is only discussed with the supplier if the innovation performs well in the field labs. Even at that point, if the cost is accepted by the municipality, majority of the time the material is the first cost-saving aspect and it gets rejected at later stages in the project if financials are being considered, since traditional materials have lower upfront costs. Insurers are unwilling to pay higher upfront costs even if there is higher cost saving in the future from using circular materials. This has been expressed by multiple respondents in the interviews and has been explained further in the Discussions chapter. Due to this factor, the municipality currently does not have cost data for the materials used for the MCDA, but efforts are still underway to retrieve these costs. The criteria sheet has been kept in the MCDA model and if the data is available, it will be included and the final results for the alternatives will get automatically recalculated.

Circularity

Circularity is perhaps one of the most important criteria for this analysis and the field labs, and the most challenging to calculate. The approaches that can be taken are as follows:

1. Estimating the number of times a material can be reused in 100 years based on its functional lifetime, which represents its quality
2. Using data about existing roads and their quality, to estimate the percentage of material in those roads that can be reused, recycled or disposed.
3. The amount of reused material in a certain material
4. Designing for reusability- measuring the extent to which a material can be reused from the way it has been designed.

All of these methods represent various aspects of circularity and can be used in combination or by themselves to represent this criteria. For the second approach, the municipality has collected data about different roads in the region, their materials and the percentage of the road in good, moderate and poor quality. The challenge with this approach is that these roads have been laid decades ago, and only contain traditional materials. There is thus no data for innovative circular materials in this method.

The third approach uses the percentage composition of reused or circular (biobased, low emissions) materials in a given road material, to determine how circular it is. This is an approach taken by many circular innovators when designing materials, but the municipality has not collected this data from suppliers in this project yet. This method can also measure the reduction in emissions from the material, and would prove effective for decision making in choosing innovations.

The final approach is a critical method that has a significant influence in shaping the circular economy in construction if it is used in decision making. Modularity and reusability are interconnected aspects of materials, and should be used in decision making. Even concrete tiles (betontegels) are sometimes designed in a way that both sides can be used, which means the wear and tear from one side is compensated by the other side, which is 100% in quality and performance. Some materials are modular (easily removed and reinstalled in project sites) while accessory materials like the mortar can be created to cause minimal damage to the material in installation, operation and extraction. Suppliers must be incentivized and encouraged to create materials like these for the future. There is currently no method to numerically calculate the design for reusability aspect, and the materials selected for this MCDA are traditional materials that are gaining a second life, thus this approach is not relevant to measure their performance

The selected approach to measure the circularity of the materials is then the calculation of reusability in terms of the quality of the material remaining after one use or lifetime, which is represented by the functional lifetime, and thus the number of times it can be reused in 100 years. The steps to represent this data in the Excel are as follows:

5. The Functional Lifetime of the materials are input in the Excel
6. The Road replacement period (average lifetime of roads that use this material) is obtained from the records of the municipality and past data of road maintenance and replacement activities, which are planned based on the location of the road, traffic (pedestrian and automotive), weather and drainage, installation year, design life of the material, mechanical properties like porosity, durability, wearing course strength, and more. This information is input in the column adjacent to the functional lifetime.
7. To calculate the number of times it can be reused in 100 years, the functional lifetime is divided by the road replacement period. This number indicates the number of times the material can be reused until its quality is too poor to be reused and it might have to be recycled or downcycled. In that case, new material has to be put in its place. For this criteria, only reuse is the lowest level of the R Ladder that is considered, since that is selected objective.
8. This marks the end of this indicator. The normalized and weighted values are then found, to obtain the ideal and anti-ideal solution.
9. The next indicator is the emissions. Based on the above value, the number of times new material is required in 100 years is calculated, by dividing 100 by the functional lifetime.
10. This number is multiplied by the amount of emissions that result from new materials, which is specified in the EPDs from the activities A1- A3. The emissions for 1 new material is first input, then multiplied with the number of new materials required in 100 years, which results in the emissions for 100 years.
11. This indicator is now complete. The weighted normalized values are calculated to obtain the ideal and anti ideal solutions
12. Following the completion of both indicators, the average ideal and anti ideal distances for each material across both indicators are taken as the overall scores of the material in this criteria. These are then squared for the final calculation.

For the reusability, the number of times a material can be reused is measured assuming 100% quality for a new material and 0% at the end of functional lifetime, with reuse allowed for all levels of quality in between. At 0% it is assumed it can only recycled or downcycled.

The Global Warming Potential is used here to measure emissions since it is the primary output from the A1-A3 activities, which are sufficient to represent the emissions from new materials. Other indicators like MKI are not as relevant when it comes to measuring the reduction in carbon emissions

from reuse. It is measured in kg CO2 equivalent units, since the amount of new material overall is considered and not the emissions from a specific area of the road.

Once the criteria are specified and distances for the ideal and anti-ideal solutions for the alternatives within each criterion are calculated, their squared values are obtained in preparation for the final score calculations of the alternatives. This is the process followed in the Excel:

1. Separate tables are made for the distance from the ideal solution and the distance from the anti-ideal solution, in the sheet termed “Alternatives-Final Scores”.
2. The squared values of the distances are put in for each alternative from each criteria, and their sum is calculate in the end.
3. The formula used is as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^*)^2}$$

$$S_i^- = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^-)^2}$$

where S_i^+ is the overall performance of the material in relation to the positive ideal solution in each criteria, and S_i^- is the overall performance in relation to the negative ideal solution.

4. Once these separation values are obtained, the overall preference score is calculated for each alternative in a separate table using the formula:

$$V_i = \frac{S_i^-}{S_i^- + S_i^+}$$

The higher the V_i value, the higher the score of the alternative and thus the better its performance ranking.

The results from the MCDA are discussed in the next section

4.3.7 Final Ranking of Alternatives from the MCDA

The results of the alternatives per criteria are explained below, followed by the final ranking. The main approach selected is Approach 4, with the use of MKI, two circularity indicators, and the cost dataset filled.

Table 8 Best and Worst Performing Alternatives per Criteria for Approach 1

Criteria	Indicator	Best Performing Alternative	Worst Performing Alternative
Embodied Emissions	MKI/m2	Biobound Betontegel	Traditional Baksteen
Lifetime	Functional Lifetime in years	Traditional Baksteen	Georeton Baksteen and Traditional Red BSS
Distance	Kilometers	Traditional Betontegel	Traditional Baksteen and Georeton Baksteen
Circularity	Number of times it can be reused	Traditional and Georeton Baksteen	Traditional Red BSS
	Emissions from new materials	Georeton Baksteen	Traditional Red BSS
Cost	Price per piece	Traditional Red BSS	Biobound and Geopolymer Betontegel

The final rankings of the alternatives is as follows:

Table 9: Final Rankings of Alternatives for Approach 1

Rank	Material	Overall Preference Score
1	BioBound Betontegel	0.690
2	Geopolymer Betontegel	0.676
3	Traditional Betontegel	0.664
4	Georetron Baksteen	0.651
5	Traditional Red BSS	0.648
6	Traditional Baksteen 2	0.304

Based on the decisions made in this section about the indicators, data, criteria and formulae, Biobound Betontegel performs the best in the analysis and Traditional Baksteen performs the worst. The results are thoroughly analyzed in the Discussions section.

Alternative approaches have also been undertaken to observe the changes in the rankings of materials and analyze the sensitivity of the data to the criteria weights, indicators used and influence levels of the stakeholders. The comparisons are made between MKI versus GWP, two circularity indicators versus 1, using cost data versus no cost data.

1. Approach 1: MKI, two circularity indicators, no cost data
2. Approach 2: GWP, two circularity indicators, no cost data
3. Approach 3: GWP, one circularity indicator, no cost data
4. Approach 4: MKI, two circularity indicators, with cost data
5. Approach 5: GWP, two circularity indicators, with cost data

The rankings of materials in these approaches and the possible explanations for them are explained in the Discussions chapters. Approach 4 and 5 are also analysed from a municipality versus industry experts point of view where all the respondents were given equal influence to the criteria weights, and how the rankings of alternatives may change with the changed criteria weights.

4.4 Creation of the Decision Making Framework

Based on the findings and testing from the above phases of research, the decision-making framework can be created to compile all the activities into a straightforward guideline that can be used by the municipality to make decisions. From this research study, the following process was followed to obtain the decision making framework.

As explained in the research methodology chapter, the decision making process can be divided into:

1. Qualitative data collection
2. Quantitative decision analysis and result

4.4.1 Part 1: Qualitative Data Collection

For qualitative observation and data collection, two main phases need to occur. Information for setting up the MCDA such as MCDA criteria, project objectives, municipality goals for the project and long terms goals, etc. need to be accounted for when making decisions about innovations and how they will be selected. The second phase in data collection is about selecting alternatives for the analysis and obtaining data about this alternatives within each criteria.

The research paper by Marco Cinelli explains the complexities in setting up the MCDA which were then translated into the steps of the MCDA-MSS process:

- (i) The framing of the decision situation to be studied
- (ii) Generation and characterization of alternatives to be considered
- (iii) Development and identification of evaluation criteria
- (iv) Selection of MCDA methods for each case study

The decision situation is later defined in the same research paper as the decision-making problem, or DMP, which was defined through the MCDA-MSS in the MCDA Method Selection phase of this thesis. Consequently, the selection of the MCDA method was also conducted by the researcher, along with the evaluation criteria. Using this information, the MCDA Model in Excel was created for this research study.

It is important, however, for decision makers to define important criteria for the selection of alternatives based on the project goals. The MCDA Model grants decision makers the flexibility to define their own criteria and weights per project, with no interference with the functioning of the model. Thus, the first step in the decision making framework is as follows

Phase 1: “Define the problem characteristics and determine MCDA criteria based on the requirements of the decision recommendation.”

In case of existing projects that the decision maker is seeking to improve, it is also important to analyze the current decision making or testing process in this phase, through a project background study or current state assessment. This phase can be called “Setting up of the DM Model”, and is composed of the three activities:

1. Defining the Decision Making Problem (in this case, the project background)
2. Final Project objectives
3. Selecting the criteria and assigning weights.

The first two activities can be performed in any order as they influence each other, and the last activity is performed after the first two are completed.

Following Phase 1, with the finalization of the criteria, decision makers need to select the alternatives or circular innovations that they want to compare and sort through the MCDA, and then obtain data to measure each alternative’s performance. At least one of the alternatives in the MCDA has to be the reference material. Thus, when considering circular innovations, the reference material can be conventional materials, like the Traditional Betontegel and Traditional Baksteen used in the case study for this thesis. This serves as a benchmark to understand the criteria in which innovations perform better or worse than the traditional materials in use today. Poor performance by innovations in the MCDA for some criteria does not mean an automatic elimination, rather the weights assigned to the criteria allow the decision maker to choose which criteria they think are more important, and poor performance in important criteria along with better performance in others will still result in an overall bad score for the alternative. In the same line of thinking, better performance in one criteria does not mean an automatic selection of the innovation from the MCDA.

The innovations to be selected for the MCDA have to be determined by the decision maker through a preliminary selection process with an initial set of parameters or boundary conditions, that the innovation must fulfil, to qualify for the MCDA. This is also set by the DM, based on the project requirements.

The second phase is thus defined as follows:

Phase 2: “Selection of alternatives and data collection for them based on Phase 1.”

This phase can be called “Data Collection” and can be performed in two activities:

1. Circular Innovation Selection (products or services) through fulfilment of boundary conditions
2. Data that measures performance of the alternatives in each criteria

Phase 1 and Phase 2 thus mark the end of Part 1: Qualitative Data Collection of the decision making framework. The decision makers can now proceed to the set up of the MCDA model with the criteria and data and completing the analysis, as explained in the next section.

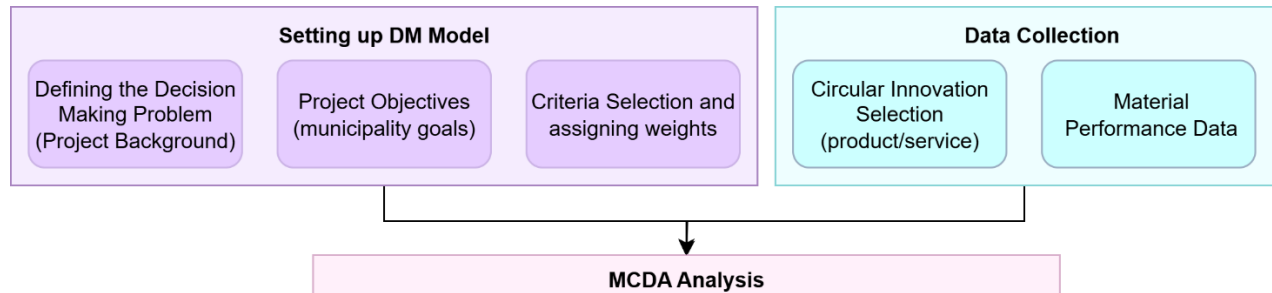


Figure 21 Part 1 of the DMF

4.4.2 Part 2: Quantitative Decision Analysis and Result

Decision makers can now proceed to the quantitative decision analysis and results. This part is composed of performing the MCDA, applying different scenarios and finalizing the results from the MCDA, to determine the best and worst performing alternatives. The transparency of the MCDA model and simple, user-centric build allows decision makers to also retrace the processes in the MCDA that led to certain outcomes, and recalculate the input data if needed.

Part 2 thus starts with the MCDA model, which follows the TOPSIS MCDA method and formulae. The following process forms the manual for using the model and to explain how the flow of information works.

1. **Format:** The model is organized in Excel spreadsheets, with one spreadsheet containing the MCDA Criteria Weight x Stakeholder Influence matrix, and the remaining sheets are each dedicated to one criteria. The final results sheet contains the cumulative scores of alternatives calculated across all the criteria. The formulae for the method are pre-filled in the excel and only material and criteria data has to be input.
2. **Criteria:** The model allows the user to define the criteria and to input weights by each decision maker. The influence of the stakeholder can also be defined by adding a multiplicity factor in the “SH Influence” column. Weights are assigned between 0-1, thus, the total from all the criteria must add up to 1, and this is the verification
3. **Data:** In each criteria sheet, the first step is to ensure the criteria weight is input above the main table. The alternatives are listed on the left column, with information about the material like the supplier and other identifiers following it. The next columns are for the input of the raw data. The Normalization column to the Distance from Anti Ideal solution are pre-programmed with TOPSIS formulae, and will automatically display the data. The ideal and anti-ideal solutions will be min/max functions of the data, where min is the ideal solution and max is the anti ideal solution for cost criteria, and vice versa for benefit criteria. The formulae are easily accessible to the user in the corresponding cells. Following input in all the criteria sheets, the final scores for all the alternatives will be displayed in the “Alternatives Final Scores” sheet. The transparency of the method and digital tool Excel allows the user to follow the flow of information and analyse results conveniently.

The full manual is attached in the supplementary material with screenshots from the tool, and the Excel tool is included in the supplementary material of the thesis report.

This phase is thus defined as follows:

Phase 3: “Conducting multi-criteria decision analysis to evaluate the performance of alternatives from pre determined parameters of phase 1.”

The phase is thus named “MCDA Using the Tool” and the activities of the phase are:

1. Input of MCDA criteria and weights, along with influence level of decision makers if necessary
2. Input of alternatives and data in each criteria sheet
3. Calculation of final rankings of alternatives

Once the MCDA is complete, the results need to be thoroughly analysed by the decision maker to identify strengths and weaknesses of the alternatives and reevaluate weights of the criteria, or the criteria themselves. Different scenarios and project objectives can be modelled in the excel to observe how the performance of alternatives changes. The changing objectives are simply defined into new criteria or different weights for existing criteria to build alternate scenarios. It can be defined as follows:

Phase 4: “Mapping alternate scenarios by modifying the prioritization of criteria through criteria weights and observing the performance of alternatives.”

The phase is thus termed “Multiple Prioritization Scenarios” with the following activities:

1. Analysing the strengths and weaknesses from the full result calculation process in the MCDA
2. Adjusting criteria weights or introducing new criteria and indicators to study different scenarios
3. Defining the most suitable scenario for the project which may be in terms of accuracy, efficiency, data availability, data visualization, etc. from the indicators and criteria.

The final output from Part 2 and the MCDA analysis is the ranking of alternatives, most suitable criteria, best approach for the indicators selected and input data, and most useful comparisons of alternatives. All the phases of Part 2 are represented in Fig 17.

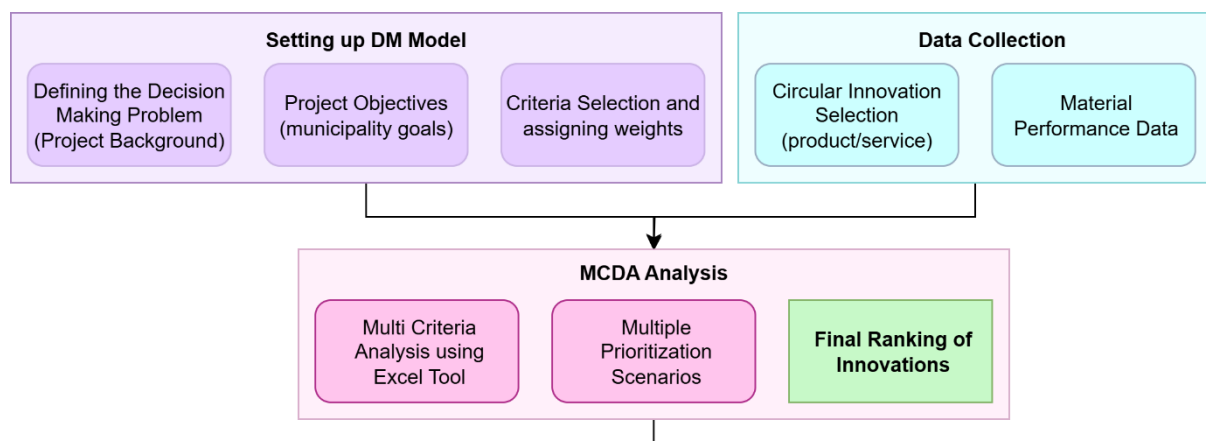


Figure 22 Part 1 and Part 2 of the DMF

After the final ranking of innovations is obtained, an extra step needs to be taken by the decision maker before they can be used in a project or tested in the field labs. The compatibility of the innovation with the current construction process and technology in the project must be checked

(feasibility analysis), and planning for the end-of-life scenarios of the innovation must be executed. This can be done through a material flow analysis to learn about the potential of the material to be reused and what the quality of the material may look like in the future. The innovation may also need specialized skillsets or equipment to be applied in a project, which the decision makers may not be prepared with. Thus, although an innovation performs well in terms of reuse potential, embodied carbon, costs, location and lifetime, the decision maker must ensure they have the resources to accommodate the new technology in their project.

It is ideal that this activity be translated into a criteria for the MCDA model. There are, however, a few challenges associated with this activity. Firstly, it is difficult to numerically measure these aspects as there are currently no numerical indicators or methods to evaluate the performance of innovations in this regard. Secondly, the choice of activity is highly subjective depending on the type of project, project owner and their technical capacity, and in the interest of creating a model that prioritizes its diverse application, it is difficult to find common ground for the exact decision making process that can achieve the results of these activities. Thirdly, all of the activities (MFA, EOL Scenario Building) are long, complex procedures that require extensive data collection and analysis, which is outside the scope of this model, that is focused on the MCDA. Thus, these activities are listed in the decision making framework as accessory analyses, and not part of the MCDA itself. These provide crucial data and have a big influence on the final decision of the innovations, since their lack thereof can lead to subsequent consequences later in the project if this data about the innovation is not included when it is applied in the project.

Thus, full information about the various processes that can be adopted by experts in the industry for this activity is subjective to how the decision maker believes they can best conduct this analysis, and it is out of the scope of this research thesis due to its complexity and incompatibility with MCDA.

If the feasibility analysis goes well and a comprehensive EOL planning is completed, the innovations can be applied in pilot projects (field labs) or directly in a project. Thus, the preliminary decision making process for the circular innovations comes to a close. This framework serves to be a fundamental guideline for project decision makers to set up the MCDA, select innovations, acquire data for them, conduct the analysis and post analysis activities before the innovations can be implemented in the field labs for pilot projects. All the above steps are represented in Fig 18.

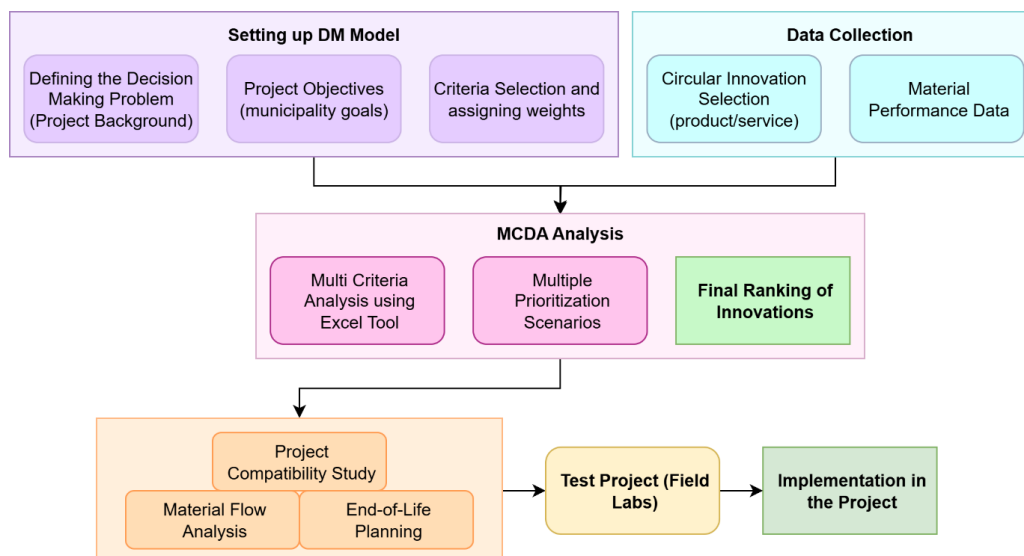


Figure 23 Phases of the Decision Making Framework

4.5 Combining the Decision Making Framework with Construction Phases

Although there is a dire need for circularity in the construction industry, and there is substantial interest to explore possibilities for its implementation in projects and in organizational strategies, its implementation exposes the industry to a new set of challenges that can be extreme enough to disrupt the full project. These challenges were discussed with the stakeholders during the interviews in the data collection phase of this thesis and many of them result from the incorrect application of circularity in construction phases, as various circular strategies must be applied in corresponding construction phases based on the level or risk, uncertainty and change management that is characteristic of those phases, as well as the stakeholders involved. It is thus necessary to map the decision making framework phases to the construction process to understand where and how it is applied to achieve the best implementation of this method.

The research by Gerding et al. (2021b) explains the decision making process in terms of the multi-actor environment of circular strategies and construction phases, to explain the most suitable approach of applying circular strategies with the influence of stakeholders, as summarized in the Scope of Research. One of the important conclusions from the study is that most decisions regarding reduction, reuse and recycling with should be carried out early on in the construction process. The text goes on to say that it is important to have the circularity experts and other conventional actors with acquired expertise in circularity play an influential role in the circular decision making process, and in the pre phase (pre design phase), must aid in deciding between various beginning and EOL scenarios.

A critical point was shared by Respondent 10 in their interview, that to be able to successfully select innovations for the field labs, test their performance and actually implement them in real projects, especially in road infrastructure, decisions about the need for projects should be made at least five years in advance. Five years is roughly the maximum amount of time that is used to test the performance of innovations in the field labs, and when it comes to road infrastructure, the municipality keeps records of when roads need renovations based on the foot traffic and material of a street. Thus, the municipality should recognize the need to implement circularity in the renovation of these roads, select innovations, test them in the field labs, and keep these circular options ready for when the renovations begin and they are needed, to ensure a more continuous circular economy. This is a critical point of future planning that is often overlooked, but is a straightforward measure that can significantly improve the implementation of circular innovations, by projecting their future demand and supply. It is thus necessary to also find a way to join the decision making framework in the end-of-life phase of the construction process.

Thus, the process can be thought to begin with the end-of-life phase, by identifying projects that are soon to release secondary material. Alongside this process, projects in the near future where secondary material can be incorporated must also be identified. The initiation and planning phase is thus scaled up to a larger, strategic level for the incorporation of the circular economy and secondary materials, and more stakeholders will have to be involved. The decision about the need for new projects also occurs by surveying existing roads and areas of use, to check if they need to be renovated or if the full area needs to be redeveloped, and to determine which materials may be released from them and when. If the project owner has this visibility for circularity, they are able to ensure the use of these materials in the design and procurement phase.

The above use of the decision making framework is for the project owner to ensure the supply and demand of circular materials, as an inventory for their future projects. The DM framework can be applied in a second place of the construction process, when the client owner does not have an inventory but is interested in seeking circular materials directly from the industry and circular

suppliers. The client can acquire and network with companies that have a supply of secondary materials through their activity in the circular economy, that is:

1. Obtaining secondary material through circular demolition services and quality assessment of materials from past projects
2. Sourcing secondary material from circular demolition companies
3. Creating new circular materials that incorporate recycled materials
4. Producers of new materials that have greater durability and functional lifetime for more reuse and reduced emissions (not using recycled or other secondary material)

In this model of the project, the Project Initiation, Planning and Design and Procurement phases occur as in most linear economy projects, and the DM framework is used in the Design and Procurement phase to select materials. As seen in the MacLeamy curve from the Introduction chapter of this thesis, the preferred design process should have the maximum effort/effect in the Schematic Design and Design Development phases of the construction cycle (Ilozor & Kelly, 2012b). In the tender specification, circular materials is mandated and can be incentivised to attract more such suppliers, and a greater competition allows more innovation with lower prices. Examples of tendering procedures that fuel the circular economy are:

1. Design and Innovation teams
2. Sustainability public procurement (United Nations Environment Program, 2021)
3. Product Service Systems (Tukker, 2013)

In the DM framework, it is also specified that a feasibility analysis of the materials should be conducted, which usually occurs in the design and procurement phase, which further requires the framework to be used here. The main circular strategies to be applied in the various construction phases has been explained by Gerding et al. (2021b) with the multi actor environment and circular strategies (CSs) as seen in Fig 19, which is also included in the diagram.

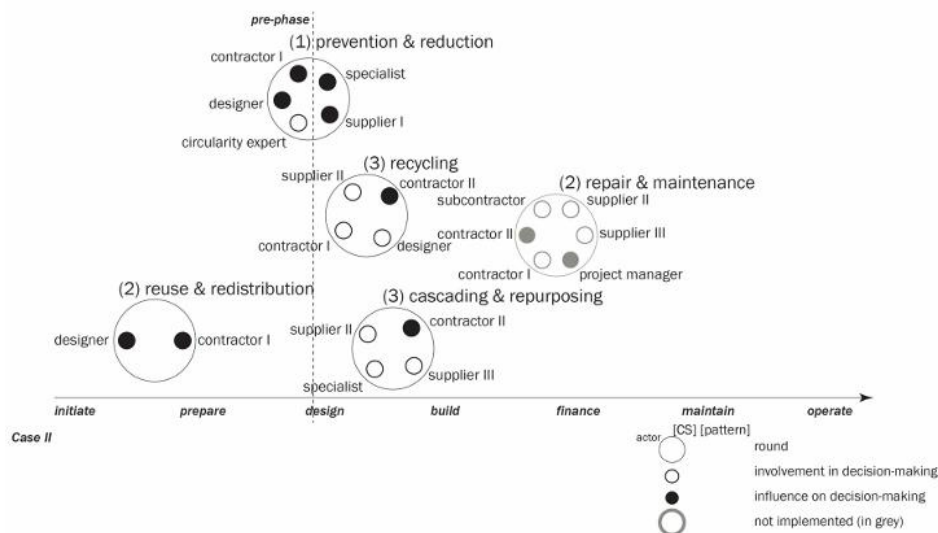


Figure 24 Decision-making process including involved actors (CSs and accompanying pattern) Gerding et al. (2021b)

Fig 20 by the shows the UNEP Circularity Approach by the United Nations Environmental Programme (2025), which is a material flow diagram and the R Ladder strategies connecting to the material flow. The R ladder strategies and their connections to the construction activities are detailed in this diagram, and this loop is used to create the circular material flow (in yellow) in the main diagram.

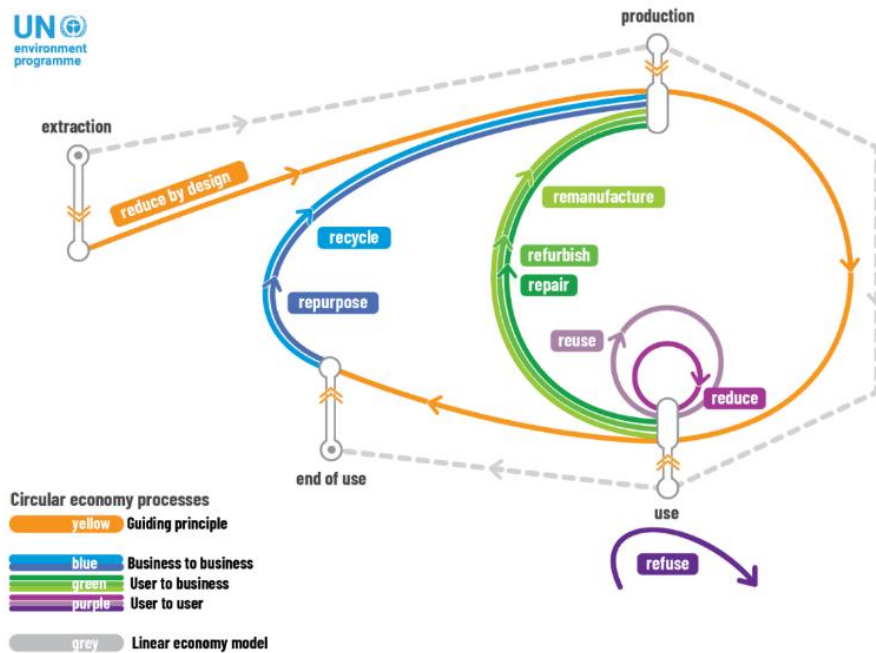


Figure 25 UNEP Circularity Approach (United Nations Environmental Programme, 2025)

The decision making framework is combined with the construction phases and the circular economy as seen in Fig 21.

The DM Framework has the best applicability in the pre phase (Project Initiation) and the Design and Procurement phase, but it receives majority of its input in the Operation and Use phase and the End of Life phase. The circular material flow creates a closed material loop to reduce the manufacture of new materials and thus reducing emissions. The construction phases of the linear economy can be followed, but it is important to always carry out these activities with the circular strategies in mind, and that can be done through the activities for enhancing circularity that have been mentioned in the blue boxes. The field labs and testing materials is a crucial step in the circular economy as its results have multiple applications in the closed material loop. This diagram represents all the components and research that were acquired to build the decision making framework, in this section.

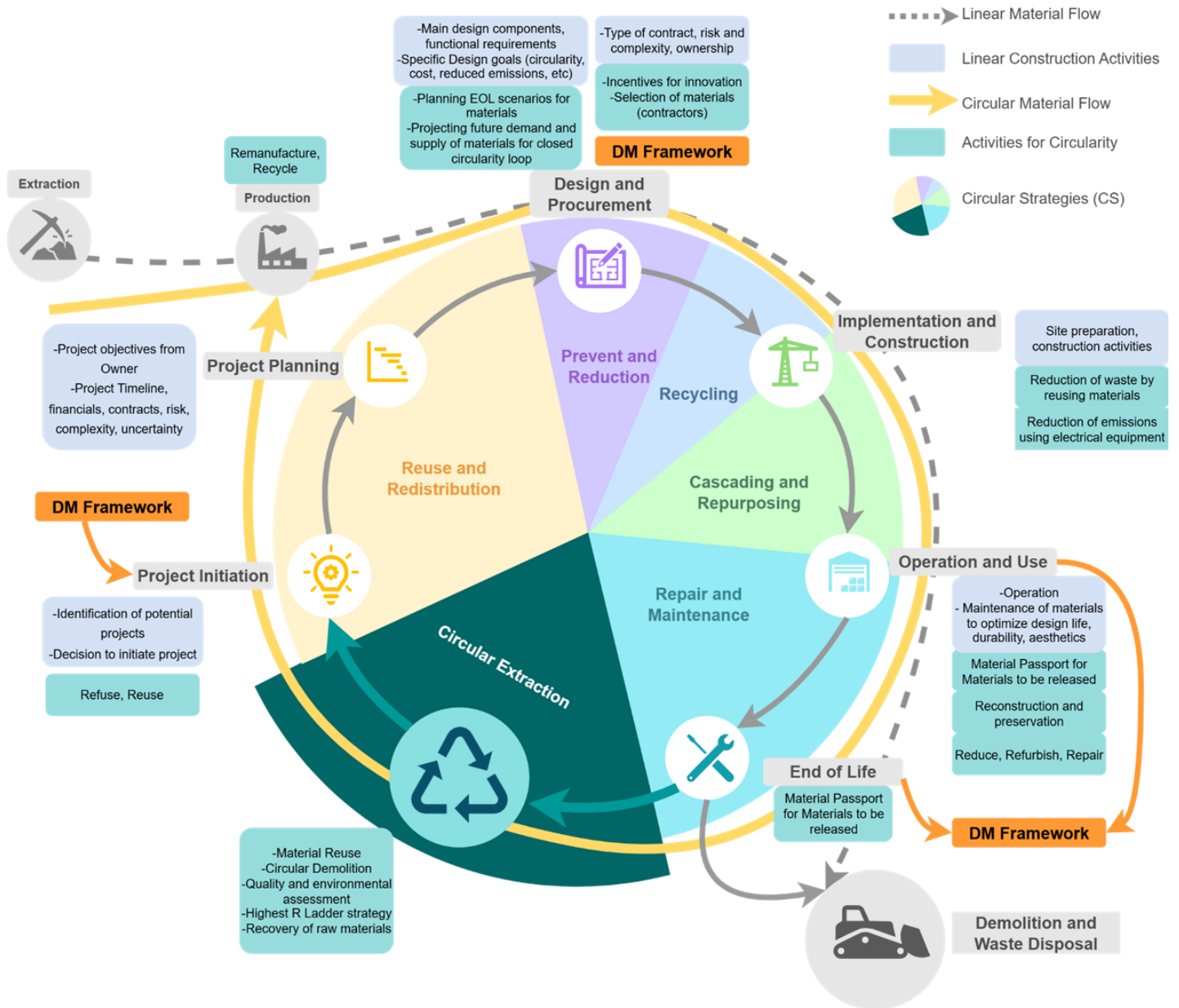


Figure 26 Circularity in Construction Phases and DM Framework

4.6 Stakeholders Involved in Phases of the Decision Making Framework

The required and recommended stakeholders for the different construction phases from the above diagram are as follows:

Operation and Use

Required: Client, Maintenance Contractors

Highly Recommended: Surveys from Residents, Designers

End of Life Phase

Required: Client, Circularity Experts (Consultants), Circular Demolishers (Contractors), Circular Quality Surveyors

Highly Recommended: Clients from other projects

Project Initiation and Planning

Required: Client, Circularity Experts, Designers

Highly Recommended: Innovation Team, Project sponsors

Design and Procurement Phase

Required: Client, Circularity Experts, Designers, Contract Managers, Suppliers with Circular Materials and Innovations

Highly Recommended: Process Managers, Building contractors

Components of Prototype 2

The following are the main components of Prototype 2:

- Final MCDA Tool and Decision-Making Framework including stakeholder involvement through Behaviour Decision Theory, Applying Systems Thinking/Dynamics for the application of the DMF in construction phases
- Final MCDA results from evaluating the performance of materials, to be compared with the actual results of the field labs (Discussion chapter).

4.7 Phase 3: Final Results and Discussion

Results from Testing the Framework

The decision makers who were interviewed as well as two circularity experts were sent the decision making framework and MCDA tool to request feedback about the ease of use, completeness and other feedback. Two circularity experts and one decision maker have provided their feedback for the Excel tool, the DMF text, and the DMF Diagram with the circularity activities.

Changes in the Excel:

The following are the changes recommended by the respondents in the Excel:

1. Adding list of criteria that could be used by DMs directly in the Excel, along with sources for the indicators.

For this, a new sheet was added in the beginning of the Excel with the guidelines from Platform CB'23, NPDW, and HNN, as well as more instructions on how to use the Excel tool.

2. More user friendly.

One of the respondents stressed the importance of adding key information from the DMF file to the Excel, since It may be unlikely that the Excel tool is always accompanied by the DMF. This has been added in the first sheet as well.

Changes in the DMF Text

The following changes were recommended for the main text in the DMF:

1. Section 1.2.1 can be amended to better explain the process of choosing criteria and linked to the first page of the Excel tool.
2. Specify whether the Excel tool is only meant for materials or if it can be used for processes as well. If so, how can it be used for processes?
3. Explain how DMs can include composite elements that contain more than one type of material.
4. In part 1, include information about the roles of stakeholders and their activities.
5. Include R Ladder in the Appendix with explanation for each step and that the goal is to get the maximum R ladder step for the materials in the activity

Changes in the DMF diagram

The following changes were mentioned for the circularity activities in the DMF diagram:

1. Different places to put the material passport. It is made in the execution phase, when materials are sourced. It is used in the operational phase.
2. At EOL, either materials get inventoried when they get a second life or some go to waste
3. Construction phases for a traditional project are actually Project Initiation, procurement for the design team, design, second procurement for contractors. Materials are selected by the design team usually, and the contractors just use it. Project* is using secondary materials so it is a different type of project (maybe the yellow line is defined as a circular project)
4. Remove recycling from production and put it near the end of life phase near waste disposal
5. Add grey tabs in the legend, remove electrical equipment (or say equipment that uses renewable or circular energy), change reconstruction to renovation

The DMF diagram with the changes highlighted in pink, is shown in Fig 22.

Overall Feedback for DMF

The decision makers evaluated the DMF from an organizational and implementation perspective. A common feedback provided was to make the Excel and DMF more usable. With further feedback, it was possible that lower customization and greater back-end programming would be more useful on the project level, due to the limited time granted to practitioners, whereas the current framework is useful from the strategic level of the municipality. The decision makers suggested that the framework can be used by higher level departments in the municipality to customize the tool for direct use by the field labs and other similar projects, who have the resources to carry out the research and collaboration required for the setup of the MCDA.

Components of the Final DMF and Excel Tool:

Thus, the components for the last prototype of the DMF for this study are:

- Improved DMF based on feedback from decision makers and industry experts
- Validation of results from Prototype 2 with the results from the field labs

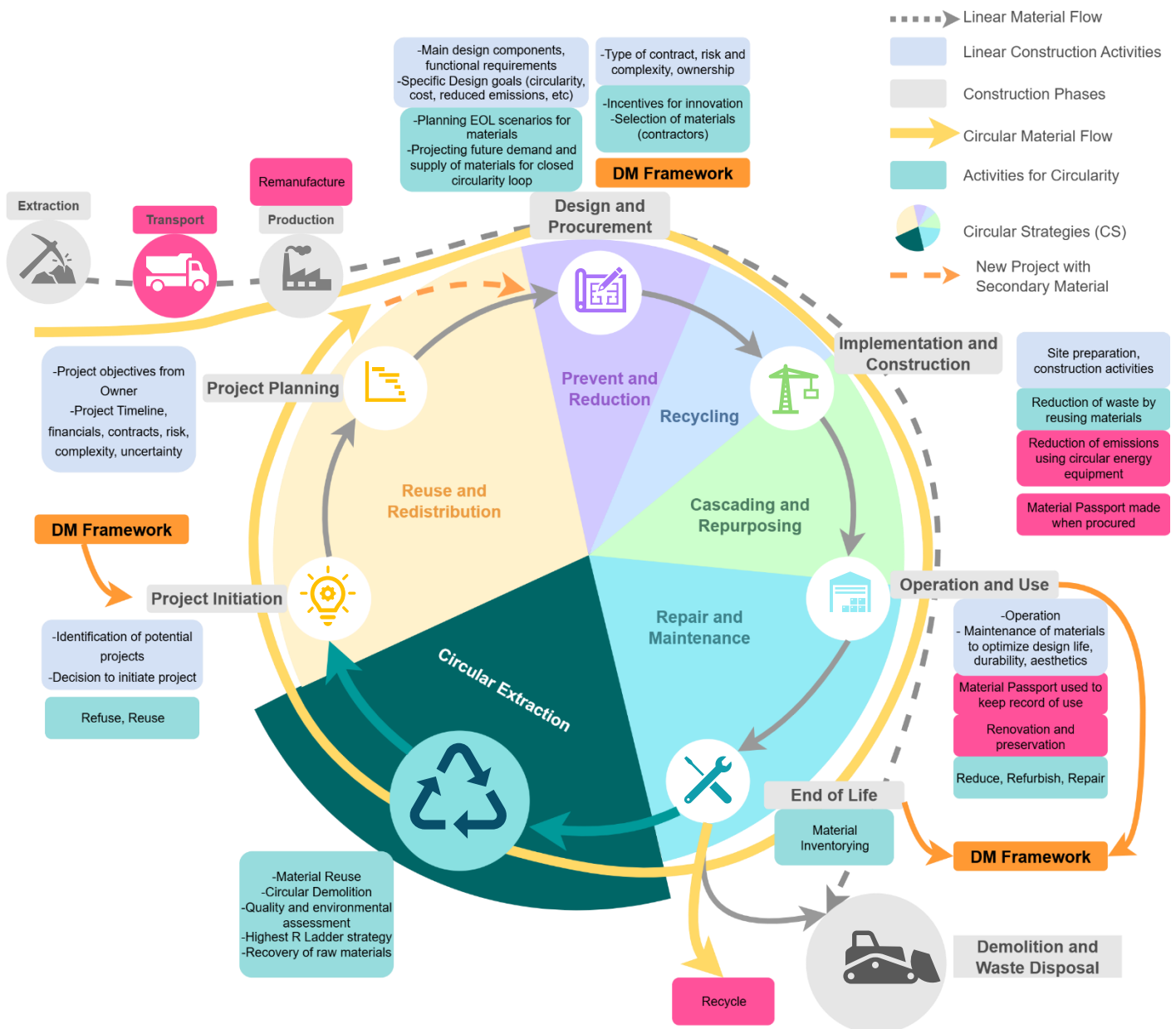


Figure 27 Circularity in Construction Phases and DM Framework with Respondents' Feedback (changes highlighted in pink)

4.8 Reflection from Phase 2

Some research output from Phase 2 have been explained in the Discussions chapter.

Key Moments of Adaptation:

- Creation of Prototype 1- Stakeholder grouping, criteria weights, final criteria, stakeholder perceptions for qualitative part of the DMF
- Creation of Prototype 2- Selection of alternatives, getting data for the alternatives, final indicators, results from the MCDA, final DMF and MCDA

Challenges:

- Many decision theories were adopted in the beginning of the study, and it was challenging to balance theory with practical requirements of the DMF.

- Scheduling and conducting interviews is a challenging process and with the limited scope of the thesis, thematic analysis to extract statements for the DMF was not conducted, rather the criteria weighting was used to map constraints and tendencies.
- It would have been preferable to conduct a second round of interviews for the feedback of the DMF, but this was again not possible within the time and communication constraints of the thesis, and an online questionnaire was used to gather information.
- It was challenging to find data for the criteria and indicators that were selected from literature, especially for circularity and cost. The materials in the field labs were not evaluated on the basis of those criteria, although these criteria are very important to measure performance, especially sustainability, mechanical properties and circularity.
- In pursuit of simplicity and flexibility, the TOPSIS method was selected and the method was very useful in the MCDA. It was discovered to be highly sensitive to criteria weights, however.

Adjustments:

- Thematic analysis would have been useful, but was replaced by criteria weighting to map trade-offs and challenges, which were then incorporate in the DMF.
- Online questionnaire was used in place of a second round of interviews
- Due to the challenges in data collection, there was a lot of uncertainty about which criteria could be used. One of the main challenges was cost. This limitation was documented in the thesis, and scenarios including and excluding cost data were included in the sensitivity analysis, which further explains the impact of cost as a highly prevalent constraint in circularity adoption.
- The limitations of the TOPSIS method were explained in the research, including the limited application due to the ideal and anti-ideal solutions. Additional steps for careful selection of alternatives (sample design) were included in the DMF for stakeholders, and it is important to include a larger number of alternatives to create a better represented sample set for the MCDA.

5. Discussion

Through the interviews, literature review and MCDA analysis, a decision-making framework was created in the previous section, and two diagrams were created: one with the phases of the framework itself, and one to represent the full decision-making process combining all the knowledge gathered in this study to enable the circular economy, including the specific activities that must be performed in construction phases, where the decision-making framework needs to be applied to actually influence the circular material flow and enable the closing of the material loop, and the stakeholders to be involved. The research process yielded interesting findings at every step, and highlighted the many limitations of the current decision-making infrastructure as well as the process used to create this framework, which will be explored in this section. This section also explores the assumptions and models explored for the MCDA tool and how the ranking of materials changed depending on those decisions, to learn how the model could be optimised.

5.1 Interview Results

5.1.1 Criteria Weights

The results of the criteria weights have been included in Appendix 1. They were obtained from the interviews, and the decision makers from the field labs were given the double the weights to represent their increased influence for the MCDA of this project, through a weighted average calculation. The contributions of each respondent to the final score of a criteria is also given in Appendix 1. After obtaining the average weight for each criteria, it is seen that Embodied Emissions has the highest weight at 0.26, followed by Lifetime at 0.23. Circularity (reusability) and Cost have the same weight at 0.20, and the Distance has the lowest weight at 0.12. Table 5 summarises the main points of discussion.

Table 10: Stakeholder Categories and Contributions to Criteria Weights

Criteria with Weight	Decision Makers Contribution	Range of Values	Municipality Contribution	Range of Values	Industry Experts Contribution	Range of Values
Embodied Emissions (0.26)	49%	0.25-0.34	57.5%	0.25-0.4	42.5%	0.05-0.6
Lifetime (0.23)	44%	0.20-0.25	49.8%	0.20-0.25	50.1%	0.1-0.35
Circularity (0.20)	52.9%	0.20-0.25	59.8%	0.20-0.25	40.23%	7 → 0.05-0.2 2 → 0.26,0.3
Cost (0.20)	34%	0.1,0.13,0.13,0.25	34.3%	0.01-0.25	65.6%	3 → 0.05-0.1 6 → 0.23-0.6
Distance (0.12)	39.25%	0.05-0.2	43.9%	0.05-0.2	56.07%	0.05-0.3

The following are the main takeaways from the results:

1. Although **Embodied Emissions** had wide range, from 0.05 to 0.6, all four decision makers who were interviewed assigned a weightage higher than 0.25, and with double the influence, significantly contributed to the high weight of the criteria. The combined contribution of the decision makers was 49%, despite being only 29% of the respondents. The outlier result was from a process manager from the industry who assigned a weight of 0.6 to this criteria. The lowest scores for this criteria were given by experts from the industry like process managers, circularity experts and circular innovators. Thus, the lifecycle emissions of these materials is still a priority for the municipality, although many experts feel it is not given the same importance during project implementation.
2. **Lifetime** comes in second place, with a range of values from 0.1 to 0.35. The four decision makers assigned a value of 0.20-0.25 for this criteria even before their influence was factored in, with a 44% contribution. 7 of the other respondents (from the industry) assigned scores similar to theirs or more, with a range from 0.2-0.35, with only 4 others giving low scores (0.1-0.2) to the criteria. Lifetime as a criteria thus important for the municipality in the initial decision making and carries its importance during project implementation.
3. **Circularity** or reusability has scored third place, with a range of 0.05-0.3. This is a surprising result given the high interest of the field labs decision makers for the criteria and their high influence, with a combined contribution of 52.7% to the score of this criteria, which is higher than the previous two criteria, and all assigning a score of 0.2-0.25. Majority of the other respondents (5 people), however, have assigned a score of lower than 0.16 to this criteria, and a total of 7 experts have assigned a score of 0.2 or lower. This includes process managers, circularity experts and circular innovators. This highlights the contrast between the necessity of circularity perceived by the municipality and the challenges with its implementation in projects.
4. **Cost** is tied at third place with the same score as circularity, with a range of 0.01 to 0.6, which is the largest range from all the criteria. It is important to note that decision makers have a 34% contribution to its score only, assigning it values from 0.1 to 0.25, while other respondents have highly varying scores depending on their role in the construction process. The highest score is 0.6 granted by a circular innovator in the industry, and the lowest score for circularity was 0.01, assigned by a member of the Municipality of Amsterdam Innovation Team. It is also very important that cost and circularity have the same score ultimately, and this is discussed further in the next paragraph.
5. **Distance** from the supplier to the project site has the lowest score of all the criteria (0.12), with a range of 0.05 to 0.3. From a municipal point of view, it is not a big part of the decision making in the field labs since only a small quantity of materials is ordered for it and at lower costs and volume, distance does not have a big influence on the availability of the material, cost or emissions, which would be greatly affected at higher volumes. The contribution from the decision makers is 39.25%, with the highest contribution of all the stakeholders to be from Respondent 13, who is from the municipality. The total contribution is still higher than that of costs. Industry experts have also assigned an overall low score to distance mostly within the range of 0.05-0.13 except a process manager from the industry who assigned a weight of 0.28 to the criteria, with the second-highest contribution. Although distance affects many other criteria, when it comes to difficult trade-offs, stakeholders give more importance and have observed greater effects from the other criteria on the implementation of circular innovations than distance.

Numerous respondents expressed that all five criteria are extremely important and found it challenging to make trade-offs when assigning criteria. A few expressed the importance of selecting

boundary conditions and chance criteria rather than distributing weights to them, since many criteria are necessities. There were also respondents on the other extreme, who wanted to assign the same weight to all five criteria, since it was difficult to differentiate their importance. The respondents were informed about the inevitability of trade-offs in decision-making, and they were encouraged to differentiate between criteria wherever possible. The respondents were also asked if there were other criteria that should be included in the MCDA, and those results have been discussed later in this chapter. The apparent trade-offs made by stakeholders above have been explained in the next section, with reference to the expected trade-offs from the Results chapter.

5.1.2 Trade-offs in Criteria Weights

From the results of the criteria weights, an interesting model of the current industry and circular economy takes place. The difference between the need for circularity versus the challenges in its actual implementation, the requirements from the client versus the constraints of contractors, the expectations of the municipality versus the results from the project, the assessment of the field labs versus the compatibility of the innovation with the project site, etc. are some of the dynamics that were highlighted during the interviews and the from the criteria weights. The following section explore some of these trade-offs.

Circularity vs Cost

One of the most significant results from the criteria weights is the tied scores of Criteria and Cost. The following table compares their results.

Table 11: Criteria Comparison of Circularity and Cost

	Circularity	Cost
Contribution from DMs	52.7%	34%
Contribution from the Municipality	60%	34.3%
Interest of DMs	Highest among all criteria	Lowest among all criteria
Range of scores of DMs	0.2-0.25 (before double influence)	0.1-0.25 (before double influence)
Range of Scores from Industry	0.05 to 0.16 --- 5 experts 0.2 to 0.3 --- 4 experts	0.01 to 0.1 --- 4 experts 0.23 to 0.6 --- 6 experts
Total Range	0.05 – 0.3	0.01 – 0.6
Final Score	0.2	0.2

Even with the large difference in the criteria weights for circularity and costs, due to the municipality considering circularity to be the most important and cost to be the least important factor in decision-making, the two criteria have the same final weights. This and the huge range in the scores for cost, highlight the opposite perspective that is seen by the industry. Majority of process managers, circularity experts, even circular innovators, expressed cost being a large constraint to the implementation of circularity in projects, while researchers still found. The results of the criteria weights represent the prevalent conflict between the goals and ambitions of the industry for circularity which is prevalent until the design and procurement stage, and the constraints of cost during the implementation and construction stages.

Respondent 5 and Respondent 1, who are process managers in circular projects, explained in their interviews that although circularity is a primary objective during project initiation, there are often no reporting obligations or parameters to measure the level of circularity that has been implemented, whereas regular cost and time reporting was mandated. When costs had to be reduced in a project or there were delays, the first substitution occurred in replacing circular products and services with

traditional ones, without any objection from the client. (Respondent 12), a circularity expert and innovator, explained that project sponsors and insurers were not included often in discussions about the necessity of circularity in a project, but were only brought in during discussions about finances. Often, their only interest was the return on investment, and without participating in more meetings for circularity planning, it was difficult to justify the higher upfront costs for circular projects to them, even if the result was lower costs in the future due to reuse and low maintenance. This respondent also explained that the market has numerous circular projects and materials that match the cost or are even cheaper than conventional projects and materials, but there is a presumed notion of higher costs for circularity which results from a low awareness of these project. When making a trade-off, the municipality thus chooses greater circularity and higher upfront costs while the industry still chooses lower upfront costs and lower circularity.

Table 7 (a and b): Score Comparison for Circularity and Costs

Interview Respondent	Circularity	Cost
ProcMI 1	0.1	0.3
RTU	0.3	0.08
CExl 1	0.26	0.24
ProcMI 2	0.16	0.23
CExl 2	0.05	0.3
CExl 3	0.05	0.45
InCI	0.1	0.6
ProcMI 3	0.2	0.05
CExl 4, InCI	0.2	0.1

(a)

Interview Respondent	Circularity	Cost
InTM (Municipality)	0.25	0.01
AMS (Decision Maker) 1	0.23	0.13
InCM (Decision Maker)	0.25	0.13
AMS (Decision Maker) 2	0.25	0.25
ProcMM (Decision Maker 3)	0.2	0.1

(b)

This also highlights the importance of considering cost during the initial decision making process by the client (in this case, the municipality) and including industry players in the setup of the process, to circumvent the challenges of implementation later in the project.

This aligns with the expected trade-offs mentioned in the Results section:

3. Decision between a Higher Upfront Cost (Circularity) for Greater Circularity and Reuse (that is, lower emissions and lower costs in the future) versus Lower Upfront Costs and Lower Reuse (traditional material, higher maintenance and new material costs)

Embodied Emissions vs Cost

The second trade-off relation to be analyzed further is between embodied emissions and cost. The below table compares their scores in summary.

Table 12: Criteria Comparison of Embodied Emissions and Cost

	Embodied Emissions	Cost
Contribution from DMs	49%	34%
Contribution from the Municipality	59%	34.3%
Interest of DMs	Second Highest	Lowest among all criteria
Range of scores of DMs	0.25-0.24 (before double influence)	0.1-0.25 (before double influence)
Range of Scores from Industry	0.05 to 0.2 --- 5 experts 0.22 to 0.6 --- 4 experts	0.01 to 0.1 --- 4 experts 0.23 to 0.6 --- 6 experts
Total Range	0.05 – 0.6	0.01 – 0.6
Final Score	0.26	0.2

With the highest overall score, embodied emissions are the priority for the decision makers, while scoring low among industry experts. An important comparison here is to observe that out of the six highest scores for cost among the industry, ranging from 0.23 to 0.6, four of them have assigned low scores to embodied emissions, ranging from 0.5 to 0.14, and the other two with scores 0.2 and 0.22. The remaining three industry experts gave low scores to cost and higher scores to embodied emissions.

Table 13: Industry Experts and Cost Trade-offs

Interview Respondent	Embodied Emissions	Cost
ProcMI 1	0.2	0.3
RTU	0.3	0.08
CExI 1	0.22	0.24
ProcMI 2	0.07	0.23
CExI 2	0.05	0.3
CExI 3	0.14	0.45
InCI	0.1	0.6
ProcMI 3	0.6	0.05
CExI 4, InCI	0.3	0.1

All the respondents from the municipality assigned higher scores for embodied emissions (0.25 – 0.4) but three out of the 4 decision makers assigned low scores to cost. Only one of them assigned the same score to embodied emissions and cost.

Table 14: Municipality and Trade-offs between Embodied Emissions and Cost

Interview Respondent	Embodied Emissions	Cost
InTM (Municipality)	0.4	0.01
AMS (Decision Maker) 1	0.34	0.13
InCM (Decision Maker) 4	0.25	0.13
AMS (Decision Maker) 2	0.25	0.25
Gemeente Amsterdam (Decision Maker) 3	0.3	0.1

It is thus evident that majority of the industry experts have observed cost being prioritized over lower embodied emissions in projects, or at least treated as a constraint. At the municipal level of planning, however, embodied emissions are prioritized over costs. This again highlights the disconnect in the process of circularity and sustainability implementation in the construction industry, and embodied emissions has a higher score than cost, even though the industry still grants it low scores.

This is in line with the expected trade-offs from the Results section:

1. Obtaining the highest reductions in emissions, for the lowest product cost

Lifetime vs Circularity

Lifetime has scored slightly higher than circularity. In this study, lifetime has been described through functional lifetime as a measure of the durability and thus the residual quality of a material at the end of life, thus influencing the circularity of a material as well. It is commonly understood that activities and materials that prolong lifetime ultimately also increase the circularity of those materials and projects by reducing the need for new materials and increasing the quality of secondary materials. But the scores assigned to lifetime show that this correlation and causation is not well understood among stakeholders. All the decision makers and members of the municipality assigned very similar scores to both lifetime and circularity, but 7 out of 9 industry experts assigned scores with a difference of 10% or more to both criteria. The 2 experts who assigned similar scores were a researcher and a circular innovator, both with exclusive focus on circularity in their professional backgrounds.

Table 15 (a and b): Score Comparison for Lifetime and Circularity

Interview Respondent	Lifetime	Circularity
InTM (Municipality)	0.24	0.25
AMS (Decision Maker) 1	0.25	0.23
InCM (Decision Maker)	0.25	0.25
AMS (Decision Maker) 2	0.2	0.25
Gemente Amsterdam (Decision Maker) 3	0.2	0.2

(a)

Interview Respondent	Lifetime	Circularity
ProcMI 1	0.35	0.1
RTU	0.24	0.3
CExI 1	0.15	0.26
ProcMI 2	0.26	0.16
CexI 2	0.3	0.05
CexI 3	0.2	0.05
InCI	0.1	0.1
ProcMI 3	0.1	0.2
CexI 4, InCI	0.35	0.2

(b)

One possible explanation for this difference is the definition of circularity. Many respondents expressed the non-uniform definition of the term, and the assumptions of higher costs or challenges with specialized materials, that were attached to it. While a longer lifespan is a desired quality in most materials and services, most of the industry considers traditional materials and services when they hear the term, with a longer operation and use phase, rather than considering the greater reuse and residual quality at the end of life, which enables circularity. The notion of innovation that is attached with the term circularity invokes feelings of uncertainty, risk and expenses for many. This is unfortunately a barrier that is prevalent in the construction industry and must be improved through more collaborations and knowledge sharing.

Another possible explanation for these scores is that circularity in a project can often also mean the use of secondary materials, which are still considered less aesthetic and less durable, whereas a longer lifetime can be applied to both new materials which are considered more aesthetic and durable, as well as secondary materials. With many stakeholders still preferring new materials, they are biased to the term lifetime. This offers an explanation for the expected tradeoff from the Results section:

5. Less aesthetic and less durable bricks (reused bricks that have lower emissions, no construction waste) vs more aesthetic and more durable bricks (new bricks that have higher emissions, higher construction waste)

In many projects, circularity is realized through the use of secondary materials. One of the biggest decisions that is made in the beginning is the choice between new materials and secondary materials. Many respondents have also described the importance of aesthetics when it comes to choosing circularity. This can be visualized in terms of choosing new materials which are more aesthetic and have more durability (better durability at the start of life) versus secondary material that may have rough edges and lower durability. Using new materials brings in much higher emissions in the project while the emissions from using secondary materials is almost nil. This is thus a trade-off between embodied emissions, lifetime and circularity. For this case study, new conventional materials were not used, and thus, and it is not possible to quantify this trade-off with the current data. It is crucial to understand that this is the trade-off that is often made when decision makers choose between new and secondary materials for a project, and awareness of this bias allows more stakeholders to understand the necessity of circularity.

Distance versus Embodied Emissions

For the trade-offs related to distance:

2. Obtaining the highest reductions in emissions for the shortest distance between the supplier and the project site
4. Greater distance for circular materials (higher transport emissions, lower manufacturing emissions due to reuse) vs Shorter distance for traditional materials (lower transport emissions, higher manufacturing emissions)

Most stakeholders have assigned a lower score to distance, possibly since it is believed that other criteria represent the undesirable effects of distance to a good extent already, and have a larger influence on the selection of the product. They would also choose a circular product that is located slightly farther away. Thus, decision makers, industry experts and the municipality as a whole, prioritize reduction in embodied emissions and greater circularity from the product, with a possible greater distance, rather than a shorter distance for less circular or sustainable product.

5.1.3 Important Criteria Excluded from MCDA

During the interviews, respondents were asked if they would include any more criteria in the MCDA. There were also criteria from literature that were considered for research, but were not selected. The following selection explains these decisions.

Scalability and Availability

Availability as a criteria was considered earlier during the research study as a way to measure the accessibility of a material. It was proposed to be measured by the number of suppliers who could provide the material, their distances from the project site, and how much of the material was available at present and in the near future. The last component took further shape as Scalability, which could be measured as the percentage of the projected demand that could be fulfilled by suppliers for a material. Numerous respondents also expressed its importance during interviews, including decision makers. With further research, it was discovered that the data required to measure these characteristics, although simple in theory, were not collected by the decision makers for the field labs. The only data available was the distance of the supplier from the project site, and each material was brought to the field labs by one supplier only, since the process of the field labs was initiated when they were approached by a supplier to test their own product. This created a monopoly for the supplier by the municipality, which also increased prices with no guarantee of supply.

It is crucial for decision makers include this criteria for the selection of materials or products, to ensure that the application of these materials is actually feasible for numerous projects at present and in the future. As explained before, the process should be initiated by governments and public clients, who specify the base requirements of the products and services and push market players to fulfil those, either through public tenders for innovation or through policies and mandates. In the short term, the municipality must put out public tenders and connect them with the field labs, with this criteria as part of the decision making, resulting in competitive prices, greater supply and more innovation for circularity.

Time

Numerous process managers and circularity experts expressed the effects of circular materials on the time aspect and project schedule, during their interviews. Circular materials are currently more scarce than traditional materials, which increases the time for procurement, and when designers incorporate circular materials in their project design, there are usually no existing templates for the designs, and which increases the time taken at this stage as well. During construction, circular products may need specialized equipment and specially skilled labour, which adds to the time taken for training and procurement of these services. Time is money, ultimately, thus it is important to gather data about this factor when assessing circular materials.

The time taken for implementation of a circular material was not measured during the field labs. As important as it is, due to the unavailability of data, it was excluded from the MCDA of this study. There are also no straightforward indicators that can be used to measure the extent of specialized skills or equipment that is required for a material. This is an aspect that needs further research and development to be implemented in decision making in the future.

Aesthetics

Majority of the decision makers expressed aesthetics as being a deciding factor in selecting materials in the field labs. How a secondary material affects the overall look of the neighbourhood was measured through surveys with residents and their own visual inspection. Aesthetics carries a lot of similarity to the quality of the material and the durability, which was assigned through quality inspections of the secondary materials by the circularity consultants of the field labs. Through further discussions with the decision makers it was concluded that aesthetics and quality inspection is similar to durability and is affected greatly by the functional lifetime of the product. It is also a data point that is obtained by the municipality and field labs, and not by the suppliers of the material itself, and this may happen before or after the pilot project is complete.

This process of measuring the aesthetics of a material must be streamlined by the decision makers, to be used in the MCDA. This criteria will thus have to be included in future versions of this decision making framework.

Designing for Circularity

Industry experts expressed the need to measure the extent to which a material is designed to be circular at the end of its life, and the R Ladder strategy that is followed by the project itself, as a way to measure its circularity. It was discovered that multiple circular innovators, designer and consultants, focus their circularity strategy for a project around achieving the highest possible strategy on the R Ladder, to the maximum extent, before moving to the next, lower strategy. When taking on a project, these designers first evaluate if the requirements of the client in terms of capacity, project size in terms of area of land, amount of resources, etc is necessary, or if the client's requirements can be realized using less resources, which is the Refuse strategy. Similarly the next step is to evaluate to

what extent the material requirements can be fulfilled using secondary or biobased materials, which pertains to the Reduce and Reuse strategies, and so on.

In terms of designing products for more circularity, modularity is an effective solution. Products can also be designed for longer functional lifetimes, better quality, similar to how Biobased Betontegels are designed with both sides being usable, which allows one side to retain 100% quality at the end of the first use. It is important to have a way to measure the extent of circularity in the design of a material, but current data in the field labs could not be used other than in the Lifetime criteria. There are indicators that can be used to measure this, and this capability should be developed for decision making frameworks.

An alternative scenario was considered to observe the trade-offs and criteria weights if the decision makers were given the same influence of the industry experts. Table 12 gives the results.

Table 16: Criteria Weights when all respondents have same influence

Sl No	Interview Respondent	Interview Respondent	Weights	Embodied Emissions	Lifetime	Circularity	Distance	Cost	Total
1	Respondent 1	ProcMI 1	1	0.2	0.35	0.1	0.05	0.3	1
2	Respondent 2	RTU	1	0.3	0.24	0.3	0.08	0.08	1
4	Respondent 3	InTM (Municipality)	1	0.4	0.24	0.25	0.1	0.01	1
5	Respondent 4	CExI 1	1	0.22	0.15	0.26	0.13	0.24	1
3	Respondent 5	ProcMI 2	1	0.07	0.26	0.16	0.28	0.23	1
7	Respondent 6	AMS (Decision Maker) 1	1	0.34	0.25	0.23	0.05	0.13	1
6	Respondent 7	CExI 2	1	0.05	0.3	0.05	0.3	0.3	1
8	Respondent 8	CExI 3	1	0.14	0.2	0.05	0.16	0.45	1
9	Respondent 9	InCM (Decision Maker)	1	0.25	0.25	0.25	0.12	0.13	1
10	Respondent 10	AMS (Decision Maker) 2	1	0.25	0.2	0.25	0.05	0.25	1
11	Respondent 11	InCI	1	0.1	0.1	0.1	0.1	0.6	1
12	Respondent 12	ProcMI 3	1	0.6	0.1	0.2	0.05	0.05	1
13	Respondent 13	ProcMM (Decision Maker 3)	1	0.3	0.2	0.2	0.2	0.1	1
14	Respondent 14	CExI 4, InCI	1	0.3	0.35	0.2	0.05	0.1	1
	Average Weights	Average Weight		0.25	0.23	0.19	0.12	0.21	1.00

Embodied Emissions and Lifetime remain the highest ranking criteria, and Distance gets the same weight, but Cost gets the third highest weight, followed by circularity. This exercise displays the extent to which cost is still prioritized by much of the construction industry, and the importance of assigning weights to the respondents as well, when setting up the MCDA for analysis. The contributions are in Appendix 1d. This scenario was used to in the MCDA approach as well, to observe if the rankings of alternatives change and how.

5.2 MCDA- Results, Criteria and Modes

The MCDA has been studied through 5 approaches to check the sensitivity of the results. Although the only material that was successful in the field labs is the Geopolymer Betontegel, it has not been the best performing material in any approach, rather performing second-best after Biobound Betontegel for its best results.

Approach 1: MKI, Two Circularity Indicators, Null Dataset For Cost

This is the first approach of the MCDA taken for this research study. The following are the considerations for this approach:

Table 17: Considerations of Approach 1

Sl No	Criteria	Weight	Important Points
1	Embodied Emissions	0.26	MKI used as indicator
2	Lifetime	0.23	Functional Lifetime considered
3	Distance	0.12	Distance between supplier and project site
4	Circularity	0.2	Two indicators combined- reusability and emissions per 100 years
5	Cost	0.2	Null dataset

The MCDA resulted in Biobound Betontegel performing the best and the Traditional Baksteen performing the worst. The table from the Results chapter has been copied below.

Table 18: Result for Approach 1

Final Rank	Alternatives	Overall Preference Score
3	Traditional Betontegel	0.698
1	BioBound Betontegel	0.749
2	Geopolymer Betontegel	0.733
6	Traditional Baksteen 2	0.285
4	Georetron Baksteen	0.686
5	Traditional Red BSS	0.635

During the first approach, the cost criteria is given a null dataset, since the costs of the materials from their suppliers was not available. For circularity, two indicators (one cost indicator and one benefit indicator) were used to assess the performance of the material, and the average distance to the ideal and anti-ideal solutions for each alternative was taken and squared for the final score. For Embodied emissions, MKI was first used as an indicator since the field labs have used MKI before for their selection process.

Biobound Betontegel has performed as the highest ranking alternative in this approach. Considering the weights of the criteria, it had the best performance in Embodied Emissions (and was the ideal solution), and second best in all the other criteria (except cost). A functional lifetime of 50 years is only half that of Traditional Baksteen, but the huge difference in emissions sets Biobound Betontegel ahead of all other materials.

Traditional Baksteen has the lowest rank and performance of all the material. Considering a functional lifetime of 100 years, which is the highest in the criteria, this is a surprising result since circularity also considers this figure for the score. It has performed the worst in Embodied Emissions and Distance, and even though it has performed the best in Lifetime and Circularity, the large difference between Traditional Baksteen and the other materials has significantly impacted its score.

Overall, the Betontegel variants have performed better than the Baksteen and BSS materials. This may be due to better emissions, and better overall performance in all criteria. The Distances from Ideal and Anti-ideal solutions for all the materials in this approach have been attached in Appendix 2.

Approach 2: GWP, Two Circularity Indicators, Null Dataset For Cost

The only change done for Approach 2 is using the GWP (Global Warming Potential) as an indicator for Embodied Emissions instead of MKI. GWP is originally measured in kg CO₂-eq units, from the manufacturing. When multiplied by the thickness of the material, we get the GWP per m², which is used for the analysis since the performance of the materials in the field labs is measured in m². The following are the results.

Table 19: Results of Approach 2

Final Rank	Alternatives	Overall Preference Score
4	Traditional Betontegel	0.468
1	BioBound Betontegel	0.648
2	Geopolymer Betontegel	0.623
5	Traditional Baksteen 2	0.424
3	Georetron Baksteen	0.566
6	Traditional Red BSS	0.275

There are big changes to the ranking here. Biobound Betontegel still performs as the best overall, but has smaller differences to the other materials. Georetron now takes 3rd place, compared to the previous approach where it took 4th place. Traditional Betontegel has now taken 4th place compared to 3rd place from earlier. Traditional Baksteen now takes 5th place compared to last place previously, and Traditional Red BSS is the worst performer.

The influence of embodied emissions in the MCDA is evident, due to its high criteria weight, and large differences in the scores of the materials in it. Just by changing the indicator from MKI to GWP, 4 out of 6 materials have changed rank. This stark contrast is the reason there is constant conflict between stakeholders in the use of MKI versus GWP to represent LCA and emissions. (Respondent 12) elaborated on this subject, explaining that GWP as an indicator of the exact CO₂ emissions of a material was a better indicator of its sustainability, whereas the diversity of emissions data in MKI and the weights assigned to them allowed suppliers to manipulate the performance of materials to show more optimistic results, and converting them from their units to euros induced the risk of data lost to complex calculations. They explained that GWP and CO₂ equivalent emissions was sufficient to judge materials and processes in the construction industry since most of its negative impact to the environment was from CO₂, due to the manufacturing and construction practices. (Tanya) also explained that it is disadvantageous to have the policy making and governance controls within the same organization, which is the case in the Netherlands as the NMD and the MKI. By doing so, there is no authority to check the legitimacy of the policy, especially when it has been mandated by most municipalities to be used by companies. This debate between the MKI and the GWP is an example of this phenomenon. With such varying results, it is difficult to determine which approach is more suitable, since the MKI reporting has been mandated by the NMD, but the GWP may be a more accurate indicator. The distances from the ideal and anti-ideal solutions for this approach have been provided in Appendix 3.

Approach 3: GWP, One Circularity Indicator (Reusability), Null Dataset For Cost

For this approach, circularity is measured only by the reusability indicator. The results are as follows:

Table 20: Results of Approach 3

Final Rank	Alternatives	Overall Preference Score
5	Traditional Betontegel	0.394
3	BioBound Betontegel	0.443
4	Geopolymer Betontegel	0.436
2	Traditional Baksteen 2	0.677
1	Georetron Baksteen	0.720
6	Traditional Red BSS	0.180

There are numerous indicators that have been recommended by circular centric organizations in the Netherlands as detailed in the Research Context section. At the field labs, however, circularity was determined through EPD data and quality inspections, which were mostly visual in nature. Due to a lack of data that matched the recommended indicators, circularity for this MCDA was measured using two indicators- number of times it can be reused in 100 years, and the emissions for 100 years.

The results of using only one criteria (number of times a material can be reused assuming 100% quality for new material and 0 at the end of functional lifetime, with reuse allowed for all levels of quality in between) is compared with the results of using both indicators, to assess how the rankings may change. As shown in Table 15, the rankings for all materials has changed except Traditional Red BSS, as compared to the results from Approach 2. Georetron Baksteen is now the highest ranking material, with Traditional Baksteen in 2nd place compared to 5th place in the previous approach, Biobound at 3rd compared to 1st in all other approaches, Geopolymer and Traditional Betontegel following it in 4th and 5th place.

The biggest change is for Traditional Baksteen in 2nd place. This is likely due to the amplification of its high performance from the functional lifetime, which is used to calculate the number of times a material can be reused. When the road replacement values are similar among all the materials, this indicator's performance relies on the functional lifetime, and when it is left unbalanced, it disproportionately boosts the performance of the material. The high emissions from Traditional Baksteen are compensated by its performance in circularity. This is of course, not an ideal outcome, and a similar phenomenon would occur if only Emissions in 100 Years would be used for circularity. Thus, in this MCDA, circularity needs representation by both indicators to paint an accurate picture of these materials. The distances from the ideal and anti-ideal solutions for this approach have been provided in Appendix 4 .

Approach 4: MKI, Two Circularity Indicators, Cost Data Included

Approach 4 considers the inclusion of cost data in the same analysis done as Approach 1, with MKI used as the indicator for emissions. As seen in Table 16, the rankings of the alternatives remain the same as the first approach. The three innovative materials, i.e. Biobound Betontegel, Geopolymer Betontegel and Georetron Baksteen are 0.95, 0.95 and 0.92 respectively, and the costs of Traditional Betontegel, Traditional Baksteen and Traditional Red BSS are 0.88, 0.65 and 0.36 respectively, the other scores in criteria like emissions and lifetime have a greater influence on the score. Traditional Red BSS has the worst score in 3 out of 5 criteria but has a significantly lower cost. Traditional Baksteen has the second lowest cost, but performs as the worst alternative in 2 out of 5 criteria. Although Cost has a weight of 0.20, traditional materials are performing poorly in sustainability and circularity criteria, leading to the same result with or without cost. Table 16 shows the ranking of alternatives for this approach.

Table 21: Results of Approach 4

Final Rank	Alternatives	Overall Preference Score
3	Traditional Betontegel	0.664
1	BioBound Betontegel	0.690
2	Geopolymer Betontegel	0.676
6	Traditional Baksteen 2	0.304
4	Georetron Baksteen	0.651
5	Traditional Red BSS	0.648

Since cost is one of the main points of conflict in the construction industry, the situation when all stakeholders are given the same weights is considered, to compare the influence of the municipality and the industry experts. This is shown in Table 17.

Table 22: Results of Approach 4 if Municipality and Industry Experts had same influence

Sl No.	Final Ranking of Alternatives	
3	Traditional Betontegel	0.698
1	BioBound Betontegel	0.747
2	Geopolymer Betontegel	0.731
6	Traditional Baksteen 2	0.279
5	Georeton Baksteen	0.675
4	Traditional Red BSS	0.635

In this case, where cost has a weight of 0.21 and circularity has a weight of 0.19, Traditional Red BSS comes to 4th place instead of 5th from the previous table, and Georetron comes to 5th instead of 4th. With a small change, the traditional material gets a better rank than an innovative material. This is observed frequently in projects for circularity during implementation phases.

Approach 5: GWP, Two Circularity Indicators, Cost Data Included

Approach 5 is an alternative to Approach 2, and uses cost data in the analysis with GWP as the indicator for emissions. The results are shown in Table 18.

Table 23: Results of Approach 5

Sl No.	Final Ranking of Alternatives	
5,4	Traditional Betontegel	0.439
1	BioBound Betontegel	0.580
2	Geopolymer Betontegel	0.558
4,5	Traditional Baksteen	0.442
3	Georetron Baksteen	0.527
6	Traditional Red BSS	0.359

The red text denotes the score without cost data. The traditional materials have different rankings. Traditional Betontegel has moved to the 5th place from the 4th, and traditional Baksteen has moved to the 4th place to the 5th. In spite of the high costs, the innovative materials have the same rankings, showing their impactful performance in embodied emissions, circularity and lifetime.

The same as the previous approach, the stakeholders are given equal weights to observe if the results change, which is shown in Table 19.

Table 24: Results of Approach 5 if Municipality and Industry Experts had same influence

Sl No.	Final Ranking of Alternatives	
5	Traditional Betontegel	0.440
1	BioBound Betontegel	0.567
2	Geopolymer Betontegel	0.548
4	Traditional Baksteen 2	0.446
3	Georetron Baksteen	0.512
6	Traditional Red BSS	0.376

The results have stayed the same. Thus, with MKI, the results change when all the stakeholders are given the same weight, but with GWP, the results stay the same. This is an interesting phenomenon, indicating that MKI is sensitive to changes in the cost, whereas GWP is not affected by the cost. Ideally, the environmental performances of materials should be free from the cost of the material, since they are separate criteria and perform as one of the most frequent trade-offs DMs make in projects. This is an important argument that stresses the need to use GWP in making decisions for circularity.

5.3 Discussion of Results from the Decision Making Framework

The Decision-making framework was created in two parts, and combined with a circular support system of activities in the construction phases to enable the circular economy. The discussion here is about the process of creating the framework and the limitations of the framework itself.

5.3.1 Process of Creating the Framework

The research process consists of data collection through a literature review and interviews, followed by the creation of the MCDA Excel tool, and the final framework.

1. **Data Collection:** The MCDA method, criteria and indicators were determined through the literature review, along with information about the activities needed to build a circular support system for the application of the decision-making framework. The criteria were then verified through interviews with decision makers from the field labs and experts from the industry. Although the information collected was analysed and verified, interviews as a method introduce a level of subjectivity in the research process that can be minimized, but not fully eliminated. To work around this limitation, respondents were asked to rank and assign weights to criteria, making the process as numerical as possible, which were used directly in the MCDA. The data was still based on human perspective, which is prone to bias and subjectivity. While designing a research study that aims to create an accessible, user-friendly tool, it is important to include the users in the creation and testing process, and subjectivity has been minimized through purposive sampling.
2. **Creation of the MCDA:** While setting up the tool in Excel, although Excel was selected due to its simplicity and wide applicability, there were numerous assumptions that had to be made, and this was only possible from the academic research point of view. In practice, navigating the requirements for the MCDA criteria and indicators, and ensuring the data is available will require additional resources from the decision makers. This research study provides a guideline for these steps, and has worked towards simplifying the process with the inclusion of all important aspects, but this remains a limitation.
3. **Creation of the Final Framework:** Decision-making frameworks are widely used as topics in scientific research, and are one of the best methodologies to represent academic findings in practical formats to be used in the industry. The flexibility for creating frameworks however, is an advantage as well as a liability. The lack of a fixed format for this research method allows

researchers to choose any structure for the research design and final product, but this abundance of choice makes it difficult to determine which methods are best suited for the research objectives, and which methods are most applicable in the given context. If not edited properly, frameworks can also be too complex for practical use or too simple for scientific research, and there are no standards to determine this at the beginning of research.

5.3.2 Strengths and Limitations of the Framework

The Decision making framework of this study consists of the Data Collection Process, the MCDA setup and Results, and the Circular Support system to enable its best use. The success criteria of the final framework were detailed in the Research Methodology section:

1. Inclusion of all important properties to test circular innovations

The MCDA excel tool in the framework includes many of the important criteria for the selection of circular materials, and the tool was created so that decision makers can add any number of criteria that they want. However, due to the unavailability of data, all the important criteria were not included in the MCDA.

2. Accurately capturing stakeholder opinions through interviews and analysis, well represented in the final framework

The perspectives of stakeholders were captured in the form of criteria weights in the interviews, which were used directly in the MCDA excel and decision makers were given greater influence. The challenges expressed by the stakeholders, and their ideas for solutions, were used to build the circular support system for the framework and create a full guide for its application. Thus, their opinions were captured and well represented in the final framework.

3. Ease of use by many, by creating it on widely accessible software and with simple, clear process to get the results

During the feedback process, the decision makers and two industry experts were asked about the utility of the tool, and ease of access. As a combined result, the respondents appreciated the necessity of such a tool and found it easy to navigate the Excel. However, a few of them found the criteria setups conflicting, and shared concerns about the repetition of the indicators. The TOPSIS method is sensitive to criteria weights and if there is repetition, it will affect the final results of the alternatives. Thus, in pursuit of simplicity in the method, the pre-MCDA steps and data collection have to be carefully executed with minimal repetition in the criteria, and this requires a lot of resources, as explained in the previous section.

The framework allows decision makers the flexibility and accessibility, but given the resources, the tool created to assess the materials from the field labs is lacking data. With the details of the data that is still required, the framework can be improved further to include more important criteria, and improve the accuracy of the results.

6. Conclusion and Recommendations

6.1 Reflection-on-Action: Learning from the Research Process and Theoretical Application

The research approach of RtD+Action research through cycles of planning, acting, observing and reflecting made it evident that the creation of a decision-making framework is not a linear process, and is rather adaptive and context dependent. New challenges emerged in each cycle of prototyping, for which solutions were found from similar other research studies, or conceptually created, to be tested later in the research process or documented as learnings for future research. Through this study, a deeper understanding of how knowledge is created through interactions and iterations was gained, which was documented after every prototype.

It was also discovered that there is still a great disconnect between theory and practice. Criteria and researched based expectations were not always applicable in the practical context due to lack of knowledge, resources and more. The TOPSIS method, while theoretically suitable for the case, faced significant limitations during applications. Solutions were formulated to combat these limitations and both were documented in the study. Data that was necessary to create a robust decision-making process was not available from the project case study, which further highlighted the limitations in the current process, for which solutions were created.

The MCDA method performed well in the research and practical context. The method performed as an effective bridge between the theories and the practical decision context, as it provided a structured evaluation of alternatives while remaining flexible to stakeholder values and circularity objectives.

This reflection highlights how theoretical insights evolved through action. Concepts that initially appeared abstract, such as stakeholder value alignment or innovation diffusion, became tangible when tested through prototyping and dialogue. Conversely, practical challenges (e.g., conflicting priorities, data gaps) exposed the limits of theoretical models, prompting contextual adaptations.

Ultimately, reflecting on the process clarified that decision-making frameworks for circular innovation must be iterative, transparent, and participatory. The research journey itself mirrored this principle: each cycle of design and reflection deepened theoretical understanding while improving the framework's real-world relevance, demonstrating the recursive nature of learning that defines both RtD and Action Research.

6.2 Conclusions from the sub-research questions

Phase 1 of research aimed to answer SRQ1 and SRQ2 of the research questions.

SRQ1: "What are the components of innovation decision making frameworks, and what is the industry standard for testing circular innovations in terms of the process and the trade-offs preferred by stakeholder categories?"

The data collection through the theoretical background revealed that decision making frameworks required two main components, the qualitative and quantitative component. For the qualitative component, the literature reviews and interviews were used to learn about circular decision making frameworks and organizations with resources for circularity in the Netherlands, some of the most important being Platform CB'23's guidelines and indicators, Het Nieuwe Normaal and the NPDW. Through the interviews the current testing process of the field labs in Amsterdam was also understood, which revealed some of the limitations of the process based on the challenges faced by the decision makers and components from the frameworks found in literature that were missing in the field labs. During the interviews, stakeholders also revealed what they prioritise when it comes to selecting a material.

SRQ2: “What are the steps required to create a decision-making tool that captures criteria trade-offs and scores innovations with a prioritization of diverse stakeholder perspectives?”

From the literature review the main components of the decision making framework to be created were revealed, and the multi-criteria decision analysis was chosen as the quantitative tool for the framework. During the interviews, decision makers as well as industry experts were asked to rank and assign weights to five criteria pre selected from literature, that is: lifecycle emissions, mechanical properties or design life, cost, circularity and availability. Through this, the trade-offs that were made by diverse stakeholders in the industry was understood, which also revealed a great diversity in the understanding of circularity and the challenges with its implementation that were different based on the role performed by the stakeholder in the construction process. The municipality and decision makers of circularity projects gave high rankings to emissions and circularity with low rankings to costs, but industry experts like process managers gave higher scores for cost as they experienced cost to be a large constraint even in projects that prioritized circularity. Circularity consultants gave equal scores to circularity or emissions and cost as they were more aware of innovations that matched the costs of traditional materials, which further shows that many industry experts need more awareness of circularity options that perform better than traditional materials in terms of traditional constraints like costs and time. With increased awareness, they are more likely to select and implement circularity in their projects and inspire more stakeholders.

Phase 2 was focussed around answering SRQ3 and SRQ4. The following can be concluded for these questions.

SRQ3: “How can the decision making tool and framework be validated using innovations from the project case study and feedback from the decision makers about its ability to improve the current decision-making process at the project?”

After the data collection from Phase 1, the MCDA structure was created with the circularity and indicators. Circular innovations were then selected for the MCDA from the materials that have been tested at the field labs of Amsterdam, which was selected as the project case study. While gathering material data, it became evident that not all circularity indicators and criteria could be used for the MCDA, due to the lack of data. The criteria were then modified to be embodied emissions, functional lifetime, cost, circularity and distance. The results from the MCDA revealed that there are numerous approaches to extract the results, and the preferences of the decision makers can determine which innovations perform well. Thus, the planning for the set up of the MCDA is a critical step to the decision making process. Feedback from the stakeholders was requested for the decision making framework that was created as well.

SRQ4: “How can the decision making framework be applied across construction phases, and what are the supporting circular activities that must be applied for the best use of this framework?”

It was important to also include the activities that had to be performed for the most utility of the decision making framework and its proper application. The construction phases were selected to represent these activities and the stakeholders that had to be involved at every stage, and the activities for circularity that should be performed in each construction phase were also mentioned. Thus the comparison between the linear and circular economy was demonstrated in the diagram, along with the points at which the decision making framework could be applied. Through data from Phase 1 and Phase 2, it was concluded that the DMF had to include inputs from the operation and use phase as well as the end of life phase, to learn about secondary materials that were to be released and their expected quality based on their use period and construction methods. At this stage, future potential projects also have to be identified, like roads that had to be renovated or replaced in the near future. The pilot projects in the field labs testing process took approximately 4-5 years for completion, and it was important that these innovative materials were ready for application at the start of new projects. Thus, the DMF had its application from the planning and initiation phase. The second application of

the DMF is separate from the above process. It can be used in the design and procurement stage for tendering and selecting suppliers who could provide secondary material for new projects, in cases when the client did not have a repository of secondary material from past projects.

7.2 Conclusions from the main research question

The main research question proposed for this study is as follows.

MRQ: “How can a decision making framework be developed based on the Amsterdam case study that balances trade-offs in circularity and is evaluated by stakeholder perspectives to rank circular innovations?”

Through the research study, the decision making framework was created by analysing existing literature and industry testing processes to identify limitations, including stakeholder perspectives and trade-offs in a quantitative tool, validating the tool using material data from project case study, and mapping the application of the decision making framework in the current construction process. Due to the data constraints, it was not possible to include all the important criteria in the tool. This one of the most important directions of improvement for the decision making process, and the activities that are required to realise this were also explained in the DMF construction process.

6.3 Recommendations for Future Research

At the current state of data collection and testing of innovations in the industry, the MCDA TOPSIS method had the most applicability compared to other methods, when creating a DMF that was focussed on ease of use, flexibility and scalability. Future research is required to create more structure in the process of creating a decision making framework. The DMF can be developed further for better application in future projects, and its utility can be strengthened through trial and error in more projects. It is also evident that the decision making process in the industry must be connected more closely with the available scientific methods for data collection and testing of materials to enable the circular economy. Most importantly, collaboration between diverse stakeholders is the key to unlocking the full potential of the circular economy.

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Appendix 1

Appendix 1a: Final Criteria Weights

Sl No	Interview Respondent	Weights	Embodied Emissions	Lifetime	Circularity	Distance	Cost	Total
1	Respondent 1	1	0.2	0.35	0.1	0.05	0.3	1
2	Respondent 2	1	0.3	0.24	0.3	0.08	0.08	1
4	Respondent 3	1	0.4	0.24	0.25	0.1	0.01	1
5	Respondent 4	1	0.22	0.15	0.26	0.13	0.24	1
3	Respondent 5	1	0.07	0.26	0.16	0.28	0.23	1
7	Respondent 6	2	0.34	0.25	0.23	0.05	0.13	1
6	Respondent 7	1	0.05	0.3	0.05	0.3	0.3	1
8	Respondent 8	1	0.14	0.2	0.05	0.16	0.45	1
9	Respondent 9	2	0.25	0.25	0.25	0.12	0.13	1
10	Respondent 10	2	0.25	0.2	0.25	0.05	0.25	1
11	Respondent 11	1	0.1	0.1	0.1	0.1	0.6	1
12	Respondent 12	1	0.6	0.1	0.2	0.05	0.05	1
14	Respondent 13	2	0.3	0.2	0.2	0.2	0.1	1
13	Respondent 14	1	0.3	0.35	0.2	0.05	0.1	1
	Average Weights		0.26	0.23	0.20	0.12	0.20	1.00

Appendix 1b: Contributions of Respondents to Final Criteria Weights

Sl	Name	Background	Embodied Emissions	Lifetime	Circularity	Distance	Cost
1	Respondent 1	ProcMI 1	4.29	8.56	2.83	2.34	8.38
2	Respondent 2	RTU	6.44	5.87	8.50	3.74	2.23
4	Respondent 3	InTM	8.58	5.87	7.08	4.67	0.28
5	Respondent 4	CExI 1	4.72	3.67	7.37	6.07	6.70
3	Respondent 5	ProcMI 2	1.50	6.36	4.53	13.08	6.42
7	Respondent 6	AMS (Decision Maker) 1	14.59	12.22	13.03	4.67	7.26
6	Respondent 7	CExI 2	1.07	7.33	1.42	14.02	8.38
8	Respondent 8	CExI 3	3.00	4.89	1.42	7.48	12.57
9	Respondent 9	InCM (Decision Maker)	10.73	12.22	14.16	11.21	7.26
10	Respondent 10	AMS (Decision Maker) 2	10.73	9.78	14.16	4.67	13.97
11	Respondent 11	InCI	2.15	2.44	2.83	4.67	16.76
12	Respondent 12	ProcMI 3	12.88	2.44	5.67	2.34	1.40
13	Respondent 13	Gemente Amsterdam	12.88	9.78	11.33	18.69	5.59

		(Decision Maker) 3					
14	Respondent 14	CExI 4, InCI	6.44	8.56	5.67	2.34	2.79
			100.00	100.00	100.00	100.00	100.00

Appendix 1c: Final Criteria Weights when Stakeholders are given same weights

Sl No	Interview Respondent	Interview Respondent	Weights	Embodied Emissions	Lifetime	Circularity	Distance	Cost	Total
1	Respondent 1	ProcMI 1	1	0.2	0.35	0.1	0.05	0.3	1
2	Respondent 2	RTU	1	0.3	0.24	0.3	0.08	0.08	1
4	Respondent 3	InTM (Municipality)	1	0.4	0.24	0.25	0.1	0.01	1
5	Respondent 4	CExI 1	1	0.22	0.15	0.26	0.13	0.24	1
3	Respondent 5	ProcMI 2	1	0.07	0.26	0.16	0.28	0.23	1
7	Respondent 6	AMS (Decision Maker) 1	1	0.34	0.25	0.23	0.05	0.13	1
6	Respondent 7	CExI 2	1	0.05	0.3	0.05	0.3	0.3	1
8	Respondent 8	CExI 3	1	0.14	0.2	0.05	0.16	0.45	1
9	Respondent 9	InCM (Decision Maker)	1	0.25	0.25	0.25	0.12	0.13	1
10	Respondent 10	AMS (Decision Maker) 2	1	0.25	0.2	0.25	0.05	0.25	1
11	Respondent 11	InCI	1	0.1	0.1	0.1	0.1	0.6	1
12	Respondent 12	ProcMI 3	1	0.6	0.1	0.2	0.05	0.05	1
13	Respondent 13	ProcMM (Decision Maker 3)	1	0.3	0.2	0.2	0.2	0.1	1
14	Respondent 14	CExI 4, InCI	1	0.3	0.35	0.2	0.05	0.1	1
	Average Weights	Average Weight		0.25	0.23	0.19	0.12	0.21	1.00

Appendix 1d: Contributions of Respondents to Final Criteria Weights with equal influence

Sl	Name	Background	Embodied Emissions	Lifetime	Circularity	Distance	Cost
1	Respondent 1	ProcMI 1	5.68	10.97	3.85	2.91	10.10
2	Respondent 2	RTU	8.52	7.52	11.54	4.65	2.69
4	Respondent 3	InTM	11.36	7.52	9.62	5.81	0.34
5	Respondent 4	CExI 1	6.25	4.70	10.00	7.56	8.08
3	Respondent 5	ProcMI 2	1.99	8.15	6.15	16.28	7.74
7	Respondent 6	AMS (Decision Maker) 1	9.66	7.84	8.85	2.91	4.38
6	Respondent 7	CExI 2	1.42	9.40	1.92	17.44	10.10
8	Respondent 8	CExI 3	3.98	6.27	1.92	9.30	15.15

9	Respondent 9	InCM (Decision Maker)	7.10	7.84	9.62	6.98	4.38
10	Respondent 10	AMS (Decision Maker) 2	7.10	6.27	9.62	2.91	8.42
11	Respondent 11	InCI	2.84	3.13	3.85	5.81	20.20
12	Respondent 12	ProcMI 3	17.05	3.13	7.69	2.91	1.68
13	Respondent 13	ProcMM (Decision Maker 3)	8.52	6.27	7.69	11.63	3.37
14	Respondent 14	CExI 4, InCI	8.52	10.97	7.69	2.91	3.37
			100.00	100.00	100.00	100.00	100.00

Appendix 2

Appendix 2a: Approach 1- MKI, Two Circularity Indicators, Null Dataset For Cost

Results- Ideal Distances

Sl No	Name of Material	Embodied Emissions	Lifetime	Distance from Amsterdam	Cost	Circularity	Sum	Separation Value
1	Traditional Betontegel	0.000197	0.006235	0	0	0.004713 268	0.01 1146 151	0.1055753 34
2	BioBound Betontegel	0.000000 000	0.006235	0.000153107	0	0.001111 659	0.00 7500 265	0.0866040 73
3	Geopolyme r Betontegel	0.000166	0.006235	0	0	0.001778 264	0.00 8180 116	0.0904439 91
4	Traditional Baksteen 2	0.060902	0	0.00503518	0	0.001407 651	0.06 7345 24	0.2595096 15
5	Georetron Baksteen	0.000001	0.008979	0.00503518	0	0	0.01 4015 626	0.1183876 1
6	Traditional Red BSS	0.001194	0.008979	0	0	0.006326 374	0.01 6499 021	0.1284485 16

Approach 1 Results- Anti-Ideal Distances

Sl No	Name of Material	Embodied Emissions	Lifetime	Distance from Amsterdam	Cost	Circularity	Sum	Separation Value
1	Traditional Betontegel	0.054165	0.000249	0.00503518	0	0.000118	0.059568589	0.244066771
2	BioBound Betontegel	0.060902	0.000249	0.003432246	0	0.002134	0.066718233	0.258298728
3	Geopolymer Betontegel	0.054703	0.000249	0.00503518	0	0.001396	0.061383897	0.247757739
4	Traditional Baksteen 2	0.000000	0.008979	0	0	0.001766	0.010744785	0.103657056
5	Georetron Baksteen	0.060335	0	0	0	0.006326	0.066661724	0.258189317
6	Traditional Red BSS	0.045044	0	0.00503518	0	0.000000	0.050079579	0.223784671

Appendix 3

Appendix 3a: Approach 2- GWP, Two Circularity Indicators, Null Dataset For Cost

Results- Ideal Solution Distances

Sl No	Name of Material	Embodied Emissions	Lifetime	Distance from Amsterdam	Cost	Circularity	Sum	Separation Value
1	Traditional Betontegel	0.003894	0.006235	0	0	0.004713268	0.014842654	0.121830432
2	BioBound Betontegel	0.00000000	0.006235	0.000153107	0	0.001111659	0.007500265	0.086604073
3	Geopolymer Betontegel	0.000209	0.006235	0	0	0.001778264	0.00822282	0.090679768
4	Traditional Baksteen 2	0.014184	0	0.00503518	0	0.001407651	0.020626358	0.143618795
5	Georetron Baksteen	0.000064	0.008979	0.00503518	0	0	0.014078146	0.118651364
6	Traditional Red BSS	0.019713	0.008979	0	0	0.006326374	0.035018292	0.18713175

3b: Anti Ideal Solution Distances

Sl No	Name of Material	Embodied Emissions	Lifetime	Distance from Amsterdam	Cost	Circularity	Sum	Separation Value
1	Traditional Betontegel	0.006084	0.000249	0.00503518	0	0.000118	0.011487286	0.107178758
2	BioBound Betontegel	0.019713	0.000249	0.003432246	0	0.002134	0.025528623	0.159776791
3	Geopolymer Betontegel	0.015862	0.000249	0.00503518	0	0.001396	0.022542811	0.150142635
4	Traditional Baksteen 2	0.000454	0.008979	0	0	0.001766	0.011198802	0.105824391
5	Georetron Baksteen	0.017533	0	0	0	0.006326	0.023859285	0.15446451
6	Traditional Red BSS	0.000000	0	0.00503518	0	0.000000	0.00503518	0.070959005

Appendix 4

Appendix 4a: Approach 3: GWP, One Circularity Indicator (Reusability), Null Dataset For Cost

Ideal Solution Distances

Sl No	Name of Material	Embodied Emissions	Lifetime	Distance from Amsterdam	Cost	Circularity	Sum	Separation Value
1	Traditional Betontegel	0.003894	0.006235	0	0	0.057855172	0.067984557	0.260738485
2	BioBound Betontegel	0.000000000	0.006235	0.000153107	0	0.057855172	0.064243778	0.253463564
3	Geopolymer Betontegel	0.000209	0.006235	0	0	0.057855172	0.064299727	0.253573909
4	Traditional Baksteen 2	0.014184	0	0.00503518	0	0	0.019218707	0.138631551
5	Georetron Baksteen	0.000064	0.008979	0.00503518	0	0	0.014078146	0.118651364
6	Traditional Red BSS	0.019713	0.008979	0	0	0.075211723	0.103903641	0.322340877

4b: Anti Ideal Solution Distances

Sl No	Name of Material	Embodied Emissions	Lifetime	Distance from Amsterdam	Cost	Circularity	Sum	Separation Value
1	Traditional Betontegel	0.006084	0.000249	0.00503518	0	0.017357	0.028725349	0.169485542
2	BioBound Betontegel	0.019713	0.000249	0.003432246	0	0.017357	0.040751016	0.201868808
3	Geopolymer Betontegel	0.015862	0.000249	0.00503518	0	0.017357	0.038502918	0.196221604
4	Traditional Baksteen 2	0.000454	0.008979	0	0	0.075212	0.084644859	0.290937896
5	Georetron Baksteen	0.017533	0	0	0	0.075212	0.092744634	0.304540037
6	Traditional Red BSS	0.000000	0	0.00503518	0	0.000000	0.00503518	0.070959005

Appendix 5

Criteria Weights and Additional Criteria from Interviews

Respondents 1 and 2 expressed their rankings verbally, which is found in the transcripts.

Respondent 3

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Solution: policies and continuity in knowledge

Lifecycle Emissions/Impact (sustainability)	40%
Reusability Potential (circularity)	25%
Mechanical Properties (function)	24%
Availability	10%
Cost	1%
Political influence (different goals)	

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27-6-2025 5

Respondent 4

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Availability	13%
Cost	24%
Lifecycle Emissions/Impact (sustainability)	22%
Mechanical Properties (function)	15%
Circularity properties	26%

TU Delft

7-7-2025 5

Respondent 5

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Time- Does not take too much time to implement (compatibility)	30%
Availability	22%
Mechanical Properties (function)	20%
Cost	17%
Circularity properties	10%
Lifecycle Emissions/Impact (sustainability)	1%

TU Delft

10-7-2025 5

Respondent 6

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Comparison with the old way
Environmental Costs in the form of money

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Lifecycle Emissions/Impact (EPDs, maintainability)	30%
Mechanical Properties (durability or lifespan)	21%
Circularity properties	19%
Storage (opslag ruimte)	18%
Cost (procurement and maintenance)	10%
Availability / Logistics (transport)	2%

19-7-2025 5

Respondent 7

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

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Chance criteria

Boundary Conditions	
Mechanical Properties (durability or lifespan)	0%
Availability / Logistics (transport)	0%
Cost (procurement and maintenance)	0%
Aesthetics	0%
Circularity properties	5%
Lifecycle Emissions/Impact (EPDs, maintainability)	5%

21-7-2025 5

Respondent 8

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

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Cost (procurement and maintenance)	45%
Mechanical Properties (durability or lifespan)	20%
Availability / Logistics (transport)	16%
Lifecycle Emissions/Impact (EPDs, maintainability)	14%
Circularity properties	5%

21-8-2025 5

Respondent 9

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Circularity (amount of material suitable for Reuse/Recycle)	25%
Lifecycle Impact (EPDs, GWP)	25%
Mechanical Properties (lifespan, frequency of maintenance)	25%
Cost (cost of the material, cost of transportation)	13%
Availability (number of sellers/ distance from project)	12%

Respondent 10

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Cost (cost of the material, cost of transportation)	25%
Circularity (amount of material suitable for Reuse/Recycle)	25%
Lifecycle Impact (EPDs, GWP)	25%
Lifetime/ Mechanical properties	20%
Availability (number of sellers/ distance from project)	5%

Respondent 11

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Cost (procurement and maintenance)	60%
Mechanical Properties (durability or lifespan)	10%
Availability / Logistics (transport)	10%
Lifecycle Emissions/Impact (EPDs, maintainability)	10%
Circularity properties	10%

Respondent 12

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Lifecycle Emissions/Impact (EPDs, maintainability)	60%
Circularity properties	20%
Mechanical Properties (durability or lifespan)	10%
Availability / Logistics (transport)	5%
Cost (procurement and maintenance)	5%

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Lifecycle Emissions/Impact (EPDs, maintainability)	50%
Circularity properties	15%
Availability / Scalability	15%
Mechanical Properties (durability or lifespan)	10%
Availability / Logistics (transport)	5%
Cost (procurement and maintenance)	5%

Respondent 13

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- MKI vs GWP, Cost Data, Scalability, Reuse (Circularity)
- Functional lifetime of these materials

Lifecycle Impact (EPDs, MKI/GWP)	30%
Design Life/Functional Lifetime	20%
Availability (distance from project/scalability for the future)	20%
Circularity (Number of times it can be Reused in 100 years)	20%
Cost (cost of the material, quote from supplier)	10%

Aesthetics

Measured by Residents surveys

Section 2 (Ranking Criteria) (25 min)

- The criteria used for the MCDA is given on the right, determined by the researcher based on literature and preliminary study of the project. Would you add any more criteria to this list?
- Ranking: Please arrange the given properties (criteria) from most important to least important, the top criteria being the most important:
- Weightage: What percentage will you give the criteria for its importance?
- What is the reason behind this ranking and weightage?

Mechanical Properties (durability or lifespan, quality)	35%
Lifecycle Emissions/Impact (EPDs, maintainability)	30%
Circularity properties	20%
Cost (procurement and maintenance)	10%
Availability / Logistics (transport)	5%



Availability (separate)

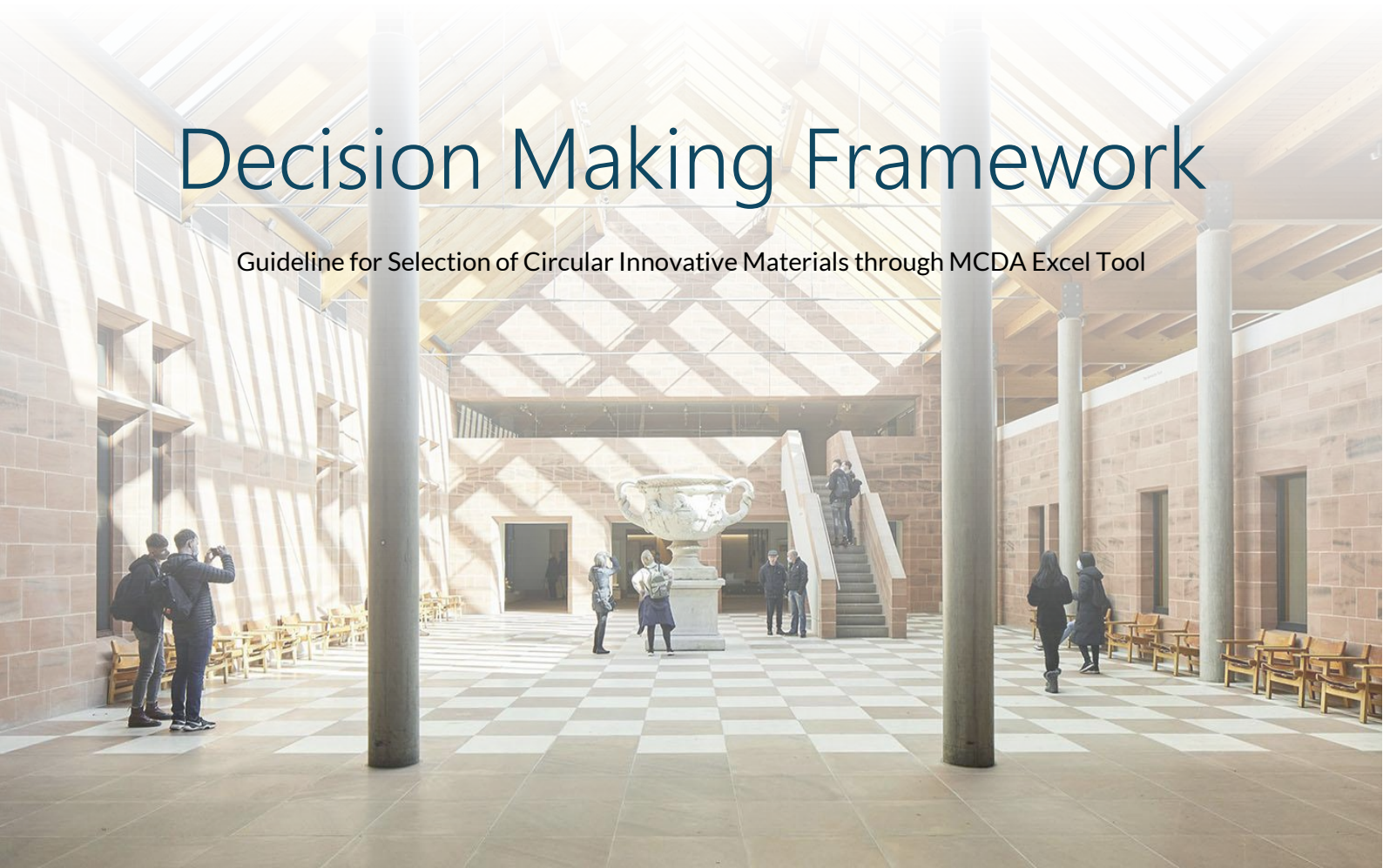
15-9-2025 5

Appendix 6- Decision-Making Framework and Excel Tool (next page)



Decision Making Framework

Guideline for Selection of Circular Innovative Materials through MCDA Excel Tool



From the Master Thesis study by

Nivedita Gnanavelan

Delft University of Technology

MSc in Construction Management and Engineering

This framework has been created in consultation with the Master Thesis committee from TU Delft, the AMS Institute, The Municipality of Amsterdam and circularity experts in the construction industry of the Netherlands. It is publicly accessible through the TU Delft Repository. Created in September 2025.

Abstract

This decision making framework was created to enable the selection of circular innovative materials for projects with the flexibility and inclusion of important selection parameters including reusability, availability, cost, emissions and more. It has been created as part of the Master Thesis research study by the author, pursuing an MSc Construction Management and Engineering. The aim of the framework is to enable decisions for circularity that are combined with the infrastructure they need for their actual implementation in projects. It has two parts- the first part explains the full decision-making process and activities that need to be performed by stakeholders to ensure optimal use of this resource, and the second part contains a manual for the MCDA Excel tool which has been automated to provide results based on the inputs provided by the decision-maker. The Excel format allows decision-makers to transparently follow the flow of information, formulae used, and determine how the results were generated, to identify the limitations of materials and rework inputs like criteria and criteria weights. The Excel file has been included as supplementary material.

The data collection for this framework was conducted through interviews and a literature review, to study stakeholder perspectives about the challenges of current decision-making processes and optimise the utility of the tool. The test data for this tool was gathered from decision makers at the field labs in Amsterdam where circular innovations and road materials were tested in an accelerated timeframe to select the best performing materials, and prepare the for implementation in future projects. This framework functions to improve the barriers of risk and uncertainty in the performance of circular innovations, and provide a streamlined process for decision-making that will encourage the use of circular innovations in future projects, to enable a more integrated circular economy.

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Part 1- Decision-Making Framework

1.1 Theoretical Background and Nomenclature

This framework has been built using research decision-making and innovation methodologies from literature as well as by analysing current decision-making processes in the construction industry of the Netherlands. The following concepts and nomenclature are used throughout the framework and will help the decision-maker navigate the document.

1.1.1 Concepts and Nomenclature

Multi Criteria Decision Analysis

One of the primary tools employed for building the decision making framework is the Multi Criteria Decision Analysis methodology. An MCDA is a decision making tool where a set of alternatives (in this case, circular innovations) are assessed on numerous criteria (in this case, mechanical properties, circular properties, lifecycle emissions, costs, availability) to rank their performance and/or select the most suitable solution for the given Decision Making Problem (DMP). Research by Cinelli et al. (2022) allows us to accurately define the DMP and choose an MCDA method that best suits the problem objectives for the assessment of alternatives. The criteria in the MCDA can be quantitatively or qualitatively measured through the aggregate values of one or more indicators, for example, the MKI is an indicator to measure the environmental impact of materials through CO₂ emissions, and is thus part of the lifecycle emissions criteria. The MCDA method selected to make the numerical model for this framework is the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution), which has been explained in further sections.

Alternatives

The alternatives refers any of the options, for example, circular innovations, materials, services, suppliers or even types of contracts, that are presented as choices to the decision maker. These alternatives are used in the MCDA to measure their performance, so that the decision-maker can choose the most suitable option for their purpose.

Criteria

The term criteria refers to the characteristics or parameters that are used to check and measure the performance of the alternatives in the MCDA. This is determined by the decision-maker from their objectives, that are either project objectives or organizational objectives, to define the aspects that the alternatives will be tested on when the choice is being made between them. The decision maker also assigns weights to the criteria. A higher weight means the criteria will have a bigger influence on the final score of an alternative, and is thus more important to the decision-making process.

Indicators

Indicators are used within criteria to quantitatively measure the performance of an alternative. For example, if lifecycle emissions is a criteria in the MCDA, the indicators used can be MKI. Indicators carry raw data and the data collected should be measured in the same units for all the alternatives within one criteria.

1.1.2 Theoretical Basis for MCDA Structure- TOPSIS

As mentioned earlier, the TOPSIS method is used to create the MCDA, through the method described by Chakraborty (2021b). The first step of the process is to normalize the data collected through the indicators. The purpose of normalization is to represent the performance of the alternative, as a ratio of the total performance of alternatives, as a way to compare them to each other on a uniform scale. This ensures the only parameter used to compare performance is a ratio, and it negates the possible effects of repetition and connection between different criteria.

Step 1- Normalized Data. i refers to the material, j refers to the criteria

In the TOPSIS method of the MCDA, the normalization formula remains the same for all criteria, and is as follows:

$$y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^I x_{ij}^2}$$

where x_{ij} is each data point corresponding to a material, within one criteria and y_{ij} is the normalized value (normalized performance rating). Thus, each data point is normalized to express a fraction of the sum of the squared values.

Step 2- Integrate Weight with Normalized Performance Rating

Simple multiplication. The weight for each criterion is obtained from the interviews with stakeholders that have diverse circularity experience, and decision makers from the municipality are giving double the influence as the other respondents. The weighted normalized data is given by:

$$v_{ij} = W_j * y_{ij} \quad (i = 1, 2, \dots, I ; j = 1, 2, \dots, J)$$

where W_j is the weight of the criteria and y_{ij} is the normalized data from the previous step.

Step 3- Find the positive and negative ideal solutions.

The ideal and anti-ideal solutions are determined by slightly different formulae for cost and benefit criteria. Cost criteria are where having higher values are a negative outcome for the decision maker and benefit criteria are where high values are a positive outcome. The formulae are given by:

A^* and A^- are denoted as the positive and negative ideal solution sets respectively which can be detected from the previous equation as

$$A^* = [v_1^*, v_2^*, \dots, v_J^*]$$

$$A^- = [v_1^-, v_2^-, \dots, v_J^-]$$

Where,

$$v_j^* = \begin{cases} \max v_{ij}, & \text{if } j \text{ is a benefit attribute} \\ \min v_{ij}, & \text{if } j \text{ is a cost attribute} \end{cases}$$

$$v_j^- = \begin{cases} \min v_{ij}, & \text{if } j \text{ is a benefit attribute} \\ \max v_{ij}, & \text{if } j \text{ is a cost attribute} \end{cases}$$

In the Excel, the MIN/MAX formulae are used to determine the ideal and anti ideal solutions. These formulae are thus modified according to whether the criterion is a cost or benefit criterion.

Step 4- Finding the separation values

Separation Values are calculated from the distance of each performance rating from the positive and negative ideal solution, within criteria. Separation values are calculated **for each material, to represent its performance across all the criteria.**

$$S_i^* = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^*)^2} \quad ; \quad S_i^- = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^-)^2}$$

where S_i^* is the overall performance of the material in relation to the positive ideal solution in each criteria, and S_i^- is the overall performance in relation to the negative ideal solution.

Step 5- Calculate the overall preference score

The following formula is used to calculate the overall preference score:

$$V_i = \frac{S_i^-}{S_i^- + S_i^*}$$

The overall preference score is V_i for each alternative i . It is the relation of the distance from the anti-ideal solution to the sum of both distances for each alternative. This is the final score of the alternative, to represent its performance. This is a straightforward formula, and the higher the score for the material, higher the ranking, the more preferred it is.

The above steps have been modelled using the fundamental formulae in Excel, and those steps have been described in Part 2 of this document. The phases and activities related to setting up the framework are just as crucial, if not more important, than the MCDA itself, which have been explained in the next section.

1.2 Main Phases and Process

The main phases of decision-making for this process were created to embody the data collection and MCDA set up activities. As depicted, the full process consists of the follow phases:

Part 1: Qualitative Data Collection

- Phase 1: Setting up of the DM Model
- Phase 2: Data Collection

Part 2: Quantitative Decision Analysis and Result

- Phase 3: MCDA Using the Excel Tool
- Phase 4: Multiple Prioritization Scenarios
- Final Ranking of Innovations

Remaining Processes for Project Implementation

- Project Compatibility Study, Feasibility Analysis, Material Flow Analysis, End-of-Life Scenario Planning
- Test Project (Field Labs)
- Implementation of Innovation in Project

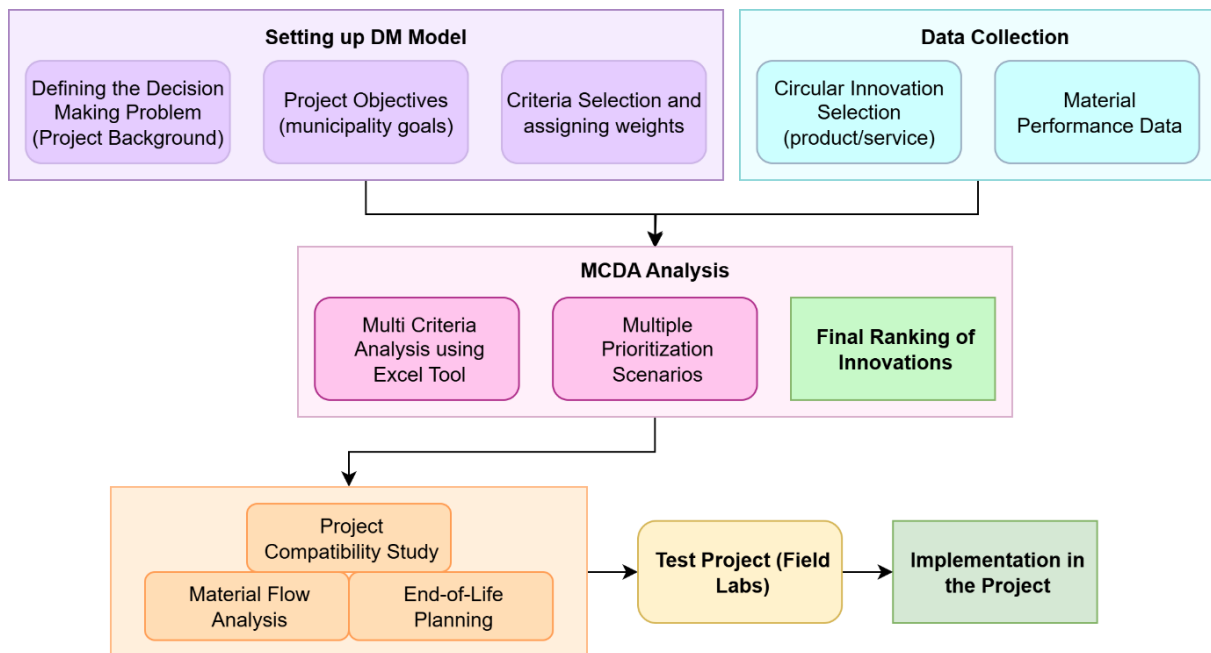


Fig x: Phases of the Decision Making Framework

1.2.1 Activities of Phase 1: Setting up the DM Model

Every organization has its own strategic objectives that shapes the pathway to the future and motivates ambitions to be more sustainable, improve processes and grow. These are translated into the different types of projects at the lowest functional level, which all contribute to building the organization towards those goals for the future. The main objectives can change drastically for every project, and the Excel tool allows decision makers to map their objectives across measurable indicators and criteria with weights for the importance.

The MCDA Model grants decision makers the flexibility to define their own criteria and weights per project, with no interference with the functioning of the model. The following are the steps of this phase:

Activities for this phase

1. Defining the Decision Making Problem (in this case, the project background)
2. Final Project objectives aligned with organizational strategies
3. Selecting the criteria and assigning weights.

In case the purpose is to improve an existing process, the following steps would be required:

1. Current state assessment of the process
2. Identification of pain points through SWOT and risk analysis
3. Definition of project objectives and Decision Making Problem
4. Selecting criteria and assigning weights

1.2.2 Activities of Phase 2: Data Collection

Decision makers need to select the alternatives or circular innovations that they want to compare and sort through the MCDA, and then obtain data to measure each alternative's performance. At least one of the alternatives in the MCDA has to be the reference material. Thus, when considering circular innovations, the reference material can be conventional materials. This serves as a benchmark to understand the criteria in which innovations perform better or worse than the traditional materials in use today.

The innovations to be selected for the MCDA have to be determined by the decision maker through a preliminary selection process with an initial set of parameters or boundary conditions, that the innovation must fulfil, to qualify for the MCDA. This is also set by the DM, based on the project requirements.

Poor performance by innovations in the MCDA for some criteria does not mean an automatic elimination, rather the weights assigned to the criteria allow the decision maker to choose which criteria they think are more important, and poor performance in important criteria along with better performance in others will still result in an overall bad score for the alternative. In the same line of thinking, better performance in one criteria does not mean an automatic success of the innovation from the MCDA.

Activities for this phase

- Circular Innovation Selection (products or services) through fulfilment of boundary conditions
- Data that measures performance of the alternatives in each criteria

1.2.3 Activities of Phase 3: Multi Criteria Decision Analysis

Decision makers can now proceed to the quantitative decision analysis and results. This part is composed of performing the MCDA, applying different scenarios and finalizing the results from the MCDA, to determine the best and worst performing alternatives. The transparency of the MCDA model and simple, user-centric build allows decision makers to also retrace the processes in the MCDA that led to certain outcomes, and recalculate the input data if needed.

Activities for this phase

- Input of MCDA criteria and weights, along with influence level of decision makers if necessary
- Input of alternatives and data in each criteria sheet
- Calculation of final rankings of alternatives

1.2.4 Activities of Phase 4: Multiple Prioritization Scenarios

Once the MCDA is complete, the results need to be thoroughly analyzed by the decision maker to identify strengths and weaknesses of the alternatives and reevaluate weights of the criteria, or the criteria themselves. Different scenarios and project objectives can be modelled in the excel to

observe how the performance of alternatives changes. The changing objectives are simply defined into new criteria or different weights for existing criteria to build alternate scenarios.

Activities for this phase

- Analyzing the strengths and weaknesses from the full result calculation process in the MCDA
- Adjusting criteria weights or introducing new criteria and indicators to study different scenarios
- Defining the most suitable scenario for the project which may be in terms of accuracy, efficiency, data availability, data visualization, etc. from the indicators and criteria.

The final output from Part 2 and the MCDA analysis is thus :

- Ranking of alternatives
- Most suitable criteria
- Best approach for the indicators selected and input data
- Most useful comparisons of alternatives.

1.2.5 Remaining Processes for Project Implementation

The compatibility of the innovation with the current construction process and technology in the project must be checked (feasibility analysis), and planning for the end-of-life scenarios of the innovation must be executed. This can be done through a material flow analysis to learn about the potential of the material to be reused and what the quality of the material may look like in the future. The innovation may also need specialized skillsets or equipment to be applied in a project, which the decision makers may not be prepared with. The decision maker must thus ensure they have the resources to accommodate the new technology in their project.

Following the compatibility study, the innovation must be tested in pilot projects to gather experimental data that further reinforces the decision to implement it, and prepares it to perform in an actual project. If it succeeds, it is then ready for application in a new project. The MCDA Excel tool can be applied before and after the pilot projects for the final decision about innovations.

Activities for this phase

- Feasibility and compatibility analysis of innovation
- End-of-Life scenario planning to close the material loop
- Testing through pilot projects to observe performance, for criteria that needs experimental data

1.3 Connecting the DMF with Construction Phases

The Decision Making Framework is applied in three construction phases:

1.3.1 Operation and Use and End of Life

To be able to successfully select innovations for the field labs, test their performance and actually implement them in real projects, especially in road infrastructure, decisions about the need for

projects should be made at least years in advance. Five years is approximately the amount of time that is used to test the performance of innovations in the field labs, and when it comes to road infrastructure, the municipality keeps records of when roads need renovations based on the foot traffic and material of a street. Thus, the municipality should recognize the need to implement circularity in the renovation of these roads, select innovations, test them in the field labs, and keep these circular options ready for when the renovations begin and they are needed, to ensure a more continuous circular economy, by projecting their future need and supply.

1.3.2 Initiation and Planning Phase

The idea and decision to start a project thus happens much earlier and on an organizational level, based on the projected requirements for renovations and new construction, that is determined from the end-of-life phase. The initiation and planning phase is thus scaled up to a larger, strategic level and more stakeholders are involved.

1.3.3 Design and Procurement Phase

When the client owner does not have an inventory but is interested in seeking circular materials directly from the industry and circular suppliers, the client can acquire and network with companies that have a supply of secondary materials through their activity in the circular economy, through sourcing secondary material from circular demolition companies creating new circular materials that incorporate recycled materials, and producers of new materials that have greater durability and functional lifetime.

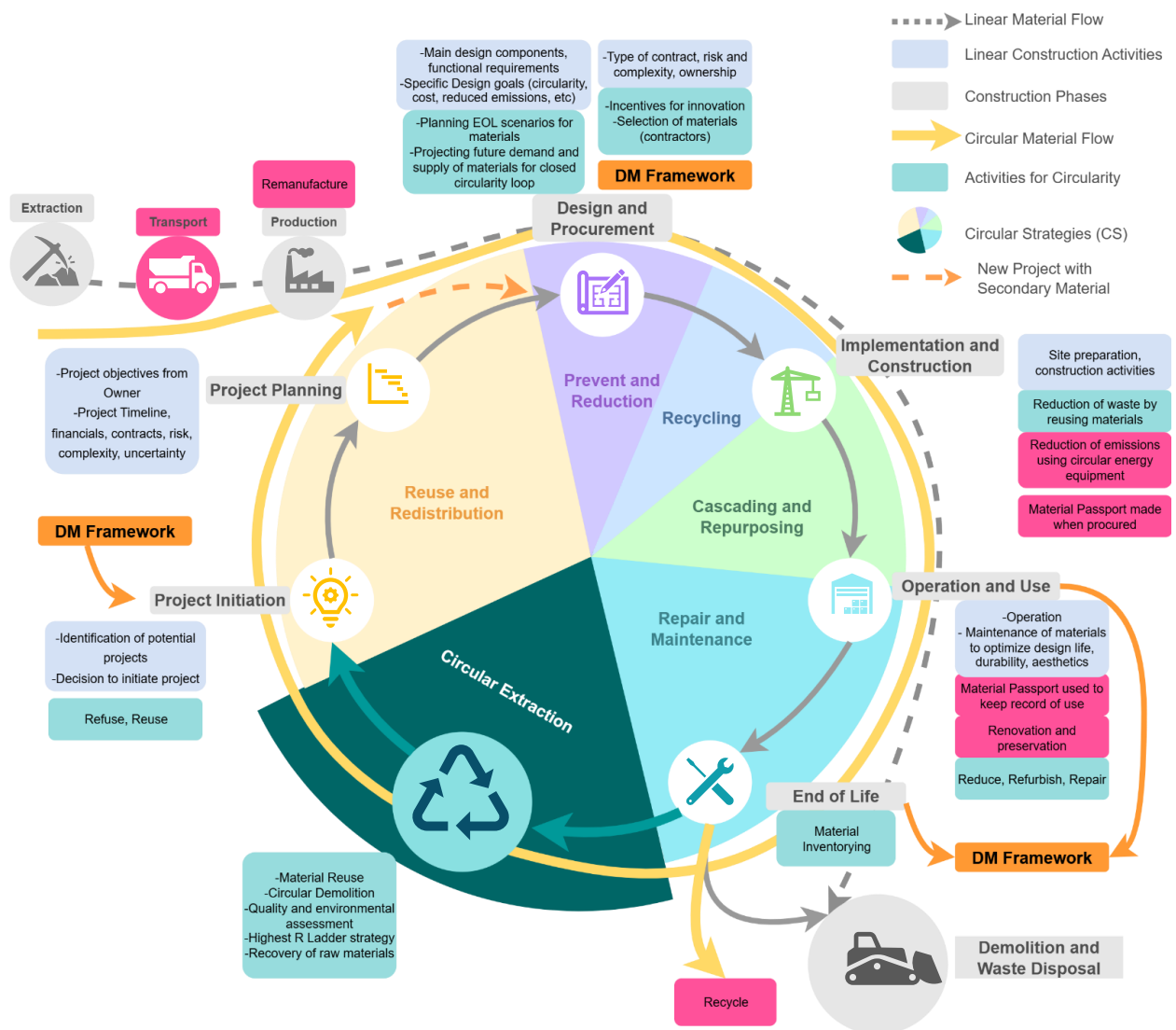


Fig x: Circularity in Construction Phases and DM Framework (author)

The DM Framework has the best applicability in the pre phase (Project Initiation) and the Design and Procurement phase, but it receives majority of its input in the Operation and Use phase and the End of Life phase. The circular material flow creates a closed material loop to reduce the manufacture of new materials and thus reducing emissions. The construction phases of the linear economy can be followed, but it is important to always carry out these activities with the circular strategies in mind, and that can be done through the activities for enhancing circularity that have been mentioned in the blue boxes. The field labs and testing materials is a crucial step in the circular economy as its results have multiple applications in the closed material loop.

1.4 Stakeholders to be Involved

Operation and Use

Required: Client, Maintenance Contractors

Highly Recommended: Surveys from Residents, Designers

End of Life Phase

Required: Client, Circularity Experts (Consultants), Circular Demolishers (Contractors), Circular Quality Surveyors

Highly Recommended: Clients from other projects

Project Initiation and Planning

Required: Client, Circularity Experts, Designers

Highly Recommended: Innovation Team, Project sponsors

Design and Procurement Phase

Required: Client, Circularity Experts, Designers, Contract Managers, Suppliers with Circular Materials and Innovations

Highly Recommended: Process Managers, Building contractors

Part 2- MCDA Excel Manual

The following section explains the formulae used in the Excel and the process of setting it up with the data of the alternatives to obtain a ranking from the highest performing to lowest performing innovation.

Step 1. Criteria Weights and Spreadsheets

A separate sheet has been created for each criteria, as well as one sheet for the final calculation, and one for the criteria weights, as seen in Fig 2a. The first step is to assign weights to the criteria in that sheet. If there are multiple decision makers with differing opinions for the weights, they are asked to assign their own weights to the criteria, and the average is taken. The weights are assigned in percentages, and the sum of the weights should add up to 100% or 1, which is displayed in the last column. This is also shown in Fig 2a. The names of the sheets can also be changed.

D5								
	A	B	D	E	F	G	H	I
1	SI No	Interview Respondent	Weights	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5
2	1	Respondent 1	1	0.2	0.35	0.1	0.05	0.3
3	2	Respondent 2	1	0.3	0.24	0.3	0.08	0.08
4	4	Respondent 3	1	0.4	0.24	0.25	0.1	0.01
5	5	Respondent 4	1	0.22	0.15	0.26	0.13	0.24
6	3	Respondent 5	1	0.07	0.26	0.16	0.28	0.23
7	7	Respondent 6	2	0.34	0.25	0.23	0.05	0.13
8	6	Respondent 7	1	0.05	0.3	0.05	0.3	0.3
9	8	Respondent 8	1	0.14	0.2	0.05	0.16	0.45
10	9	Respondent 9	2	0.25	0.25	0.25	0.12	0.13
11	10	Respondent 10	2	0.25	0.2	0.25	0.05	0.25
12	11	Respondent 11	1	0.1	0.1	0.1	0.1	0.6
13	12	Respondent 12	1	0.6	0.1	0.2	0.05	0.05
14	13	Respondent 13	2	0.3	0.2	0.2	0.2	0.1
15	14	Respondent 14	1	0.3	0.35	0.2	0.05	0.1
16	Average Weights			0.26	0.23	0.20	0.12	0.20
17								
18								

Fig 2a- Assigning weights to criteria

If it is required to combine results from many respondents, the influence that they should have on the decision can be quantified by also assigning weights to the respondents, as seen in Fig 2a.

Step 2. Input of Alternatives and Raw Data

The alternatives that successfully passed the preliminary selection are then used in the MCDA. Data measuring the performance of the alternatives in each criteria is collected and converted to a uniform scale, ready for normalization. As seen in Fig 2b, the Criteria Weight gets filled in automatically, and the raw data is filled in the left columns. For the analysis, it helps to also fill reference data like the suppliers (manufacturers), the unit used in the raw data, etc

When the raw data is complete, the tool automatically applies the formulae to calculate the remaining data and provide the ranking of alternatives. The formulae and step-wise calculation in the MCDA is as follows:

Normalization:

$$y_{ij} = x_{ij} / \sqrt{\sum_{i=1}^I x_{ij}^2}$$

The square root of the sum of the raw data points is calculated in the Denominator field.

Each raw data point is divided by this denominator to be expressed as the ratio of the whole.

The weights are then multiplied by the normalized data in the next column.

Ideal and Anti-Ideal Solution:

The MIN and MAX functions are applied to the weight normalized data to retrieve the ideal and anti-ideal solution, and then the distances from each are calculated for each alternative.

These distances are then squared in preparation for the final formula.

Alternatives Final Score:

The Separation Values and the Overall Preference Score are calculated in the final sheet to obtain the final rankings for the alternatives.

Separation Values:

$$S_i^* = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^*)^2} \quad ; \quad S_i^- = \sqrt{\sum_{j=1}^J (v_{ij} - v_j^-)^2}$$

To calculate this, the squared distances from each criteria sheet are combined into one table in the final sheet. Their sum is calculated, and the square root values are obtained. This is seen in Fig 2d.

Overall Preference Score:

$$V_i = \frac{S_i^-}{S_i^- + S_i^*}$$

The Separation Values from each alternative are used to calculate their Overall Preference Score using a Division formula in the third table of the sheet.

Following that, the alternatives are arranged based on their rank in the green table, which is the final output of the MCDA. The above two steps are also seen in Fig 2d. In this example, a blank criteria (Criteria 3) has been included to demonstrate how the values are copied in the Excel and applied in the final formula.

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Fig 2d: Calculating the Final Rankings of Alternatives

This step marks the end of the MCDA Excel calculations. The results need to be thoroughly analyzed by the decision maker to identify strengths and weaknesses of the alternatives and reevaluate weights of the criteria, or the criteria themselves. Different scenarios and project objectives can be modelled in the excel to observe how the performance of alternatives changes. The changing objectives are simply defined into new criteria or different weights for existing criteria to build alternate scenarios.

Conclusion

This framework was built in consultation with researchers, project decision makers, process experts and circularity experts, with diverse professional backgrounds and experiences with circularity, to capture a variety of perspectives and explore methods to combine ideas. The construction industry and the circular economy is a large, complex machine with many moving parts, all with a unique, defined purpose, that ensure the proper functioning of the machine. To enable the circular economy, increased collaboration between stakeholders is necessary, and the non-participation of any of them in decision making processes will disrupt the functioning of the overall machine.

Through the decision-making process defined in this framework, the client or owner of the project receive timely input from all the involved stakeholders in the process who have unique expertise, from the operation and end-of-life phases to initiation, design and procurement. This reduces the uncertainty of the performance of circular innovations and the risk of additional costs from change management.

At first glance, the most important part of the framework seems to be the MCDA tool, but through research it was discovered that the data collection and MCDA set up activities are far more impactful in this process, and the MCDA tool is as useful as the research put into it. Although this is a preliminary method, it must be improved on by future research to optimise on the limitations and scale up the tool for wider applications.

The critical change that needs to be applied in the current industry is the creation of demand and motivation to innovate by government institutions. Through mandates that define what is needed from circular innovations and how they must perform to be implemented in projects from the government, market players are incentivized to build innovations accordingly, and with greater competition, more suppliers with similar and improved products are available, which causes a significant shift in the circular economy. This is not easily done, but frameworks like this tool are small steps and changes that slowly and surely shift the dynamic of the circular economy in the right direction. The initiatives taken by multiple municipalities in the Netherlands in pursuit of circularity have already impacted the industry immensely, and it is crucial to continue this pursuit of protecting our environment from the harmful effects of the construction industry.