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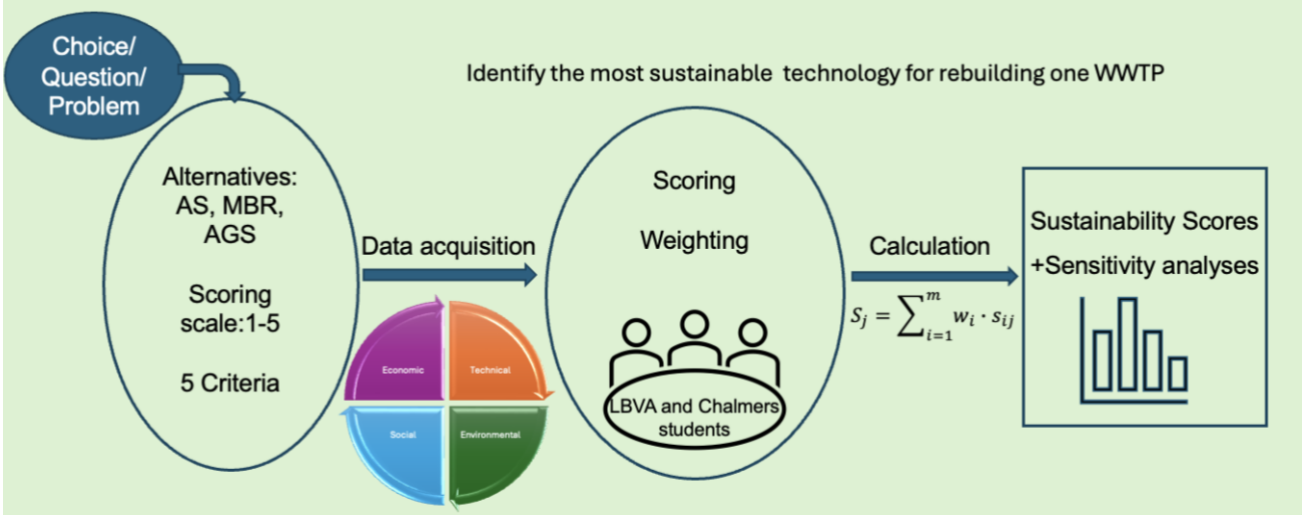

Sustainability assessment using multicriteria analysis for wastewater handling

Master's Thesis in Infrastructure and Environmental Engineering

Shiyun Huang

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Gothenburg, Sweden 2025

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ABSTRACT

This study presents a sustainability assessment of three wastewater treatment technologies—Activated Sludge (AS), Membrane Bioreactor (MBR), and Aerobic Granular Sludge (AGS)—using the case of the Västra Stranden Wastewater Treatment Plant (WWTP) in Halmstad, Sweden. A Multi-Criteria Decision Analysis (MCDA) approach was applied to evaluate and compare the technologies across environmental, economic, technical, and social dimensions. Two different weighting methods were tested: a traditional percentage-based model and a value-based model using Weighted Score Ratios (WSR). Data collection included quantifiable performance indicators, expert judgment from professionals at Laholmsbuktens VA (LBVA), and input from students in an advanced wastewater engineering course.

The value-based model assigns monetary values to each sustainability criterion, helping to clarify trade-offs and improve transparency in the decision-making process. Results from both workshops showed that the value-based approach was more effective in identifying which criteria had the greatest influence on overall sustainability.

This study highlights the strengths of combining technical data with structured stakeholder input and suggests that value-based MCDA models can support more robust and balanced decisions in wastewater planning.

Key words: Sustainability assessment, wastewater treatment, MCDA, weighted score ratio, activated sludge, membrane bioreactor, aerobic granular sludge, stakeholder evaluation.

SAMMANFATTNING

Denna studie presenterar en hållbarhetsbedömning av tre avloppsreningstekniker – Aktivt Slam (AS), Membranbioreaktor (MBR) och Aerob Granulärt Slam (AGS) – med Västra Strandens avloppsreningsverk (ARV) i Halmstad som fallstudie. En flerkriterieanalys (MCDA) användes för att utvärdera och jämföra teknikerna utifrån miljömässiga, ekonomiska, tekniska och sociala dimensioner. Två olika viktningstekniker testades: en traditionell procentbaserad modell och en värdebaserad modell som använder viktade poängförhållanden (Weighted Score Ratios, WSR). Datainsamlingen omfattade kvantifierbara prestandaindikatorer, expertbedömningar från yrkesverksamma vid Laholmsbuktens VA (LBVA) samt synpunkter från studenter på en avancerad kurs i avloppsteknik.

Den värdebaserade modellen tilldelar monetära värden till varje hållbarhetskriterium, vilket bidrar till att tydliggöra avvägningar och öka transparensen i beslutsprocessen. Resultat från båda workshopparna visade att den värdebaserade metoden var mer effektiv för att identifiera vilka kriterier som hade störst påverkan på den övergripande hållbarheten.

Studien framhäver fördelarna med att kombinera tekniska data med strukturerad intressentmedverkan och föreslår att värdebaserade MCDA-modeller kan stödja mer robusta och balanserade beslut i planering av avloppsrening.

Nyckelord: Hållbarhetsbedömning, avloppsrening, MCDA, viktade poängförhållanden, aktivt slam, membranbioreaktor, aerob granulärt slam, intressentutvärdering.

ACKNOWLEDGEMENTS

I have always believed that there is a gap between what we learn in academia and how things are actually done in the industry. This belief is what motivated me to choose this thesis project—to explore how real-life stakeholders approach real-world challenges in wastewater management.

I would like to express my sincere gratitude to Laholmsbuktens VA (LBVA) and Envidan for providing the essential data used in this study. Special thanks to Carina for organizing the LBVA workshop, introducing the topic, and sharing critical data with me—your support was central to this thesis. I am truly grateful for the opportunity to collaborate with Envidan and professionals from LBVA. It has been an inspiring and eye-opening experience.

I am especially thankful to my supervisor, Ann Mattsson, whose guidance has been invaluable throughout this project. As a senior consultant, she not only helped me structure the methodology and research design but also offered practical advice on planning and time management—skills I will carry with me into future projects.

I also appreciate the support of my examiner, Oskar, for organizing the student workshop at Chalmers, which served as a key part of the data collection. It was a pleasure to work alongside peers and hear their perspectives. Their input and ideas added great value to the thesis.

Lastly, heartfelt thanks to my friends Max and Yifan for their emotional support and creative input throughout this journey. Your encouragement made a big difference.

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1 Introduction

Environmental challenges such as climate change, resource depletion, and pollution are placing increasing pressure on industries to reduce their ecological footprint. Decision-making in these contexts must now go beyond traditional economic considerations to also include environmental and social impacts. Multi-Criteria Analysis (MCA), also known as Multi-Criteria Decision Analysis (MCDA), provides a structured way to compare alternatives based on a broad range of criteria. However, a key challenge in MCA lies in how to assign appropriate weights to these criteria.

This study applies a weighted score ratio (WSR) approach to address this challenge. By expressing the weighting of criteria in economic terms, the WSR method provides a more transparent and interpretable decision-making process. The focus of this study is to evaluate the effectiveness of the WSR-based weighting within an MCA framework.

Data from the Västra Stranden Wastewater Treatment Plant (WWTP) in Halmstad, Sweden whereas the case study. The analysis involves comparing three wastewater treatment technologies: Activated Sludge (AS), Aerobic Granular Sludge (AGS), and Membrane Bioreactor (MBR). The goal is to assess how different weighting methods influence sustainability evaluations across these three alternatives.

1.1 Background

Sustainability analysis using MCA has become a fundamental approach in environmental management and infrastructure planning. MCA enables the integration of economic, environmental, and social dimensions which widely recognized as the three pillars of sustainability into structured decision-making processes (Neth, 2023). Its flexibility allows practitioners to incorporate case-specific indicators and address the complexity of real-world decisions in the water and sanitation sectors.

In wastewater treatment planning, MCA is particularly useful due to the diversity of operational challenges. For instance, WWTPs must often deal with constraints related to limited physical space, energy consumption, treatment of emerging pollutants, and public acceptance. Technologies such as AGS and MBR present promising alternatives to traditional activated sludge, but they must be assessed not only on technical performance but also on lifecycle cost, environmental impact, and long-term adaptability (Awawdeh, 2019; Al Nasiri N. , 2023)

MCA is beneficial in these contexts because it supports decisions where objectives may conflict or be expressed in different units—such as monetary costs, greenhouse gas emissions, or qualitative assessments of workplace safety. Reducing such complex, multi-objective problems into a single-objective framework is often neither feasible nor desirable. In participatory settings, particularly, decision-makers must account for diverse stakeholder preferences, values, and levels of influence. MCDA methods such as weighted sum models or AHP help quantify how alternatives perform under multiple criteria. One of the strengths of MCDA is its ability to incorporate both technical evaluations and stakeholder input in a transparent and reproducible manner

This combination supports not only technically sound decisions but also ones that are socially acceptable and politically defensible.

In this study, the sustainability performance of the three selected wastewater treatment technologies will be evaluated using MCA, comparing results from two groups: university students and a group of local wastewater experts (LBVA). The analysis builds upon a methodology previously developed by Neth, 2023 with modifications to better reflect the context-specific needs and criteria relevant to the Västra Stranden WWTP.

1.2 Aim

The aim of this study is to enhance the MCA process for evaluating sustainability in wastewater treatment operations and achieve the following goals:

- To gain knowledge on applying MCA in the wastewater decision-making process through a case study and literature review.
- To develop and compare two different MCA models – specifically investigating how incorporating monetary values affects key indicator criteria.
- To enhance the weighting model and improve the accompanying Excel spreadsheet to be more user-friendly for stakeholders

1.3 Specification of the issue being investigated

Selection of the Three Alternatives: the technologies—AS, AGS, and MBR—were selected to address specific challenges faced by the Västra Stranden WWTP (LBVA). These challenges include meeting strict effluent quality requirements, operating within space constraints, and implementing energy-efficient processes.

Improving the Analytical Tool: this study aims to enhance the current Excel-based MCA tool to make it more user-friendly for stakeholders. Simplifying the interface and functionalities will facilitate easier data input, manipulation of weighting parameters, and interpretation of results, thereby lowering barriers to conducting comprehensive sustainability assessments.

Evaluation Using Student and Professional Data: to test the effectiveness and validity of the MCA method, the study will use data gathered from students and professionals' data from LBVA. This approach will particularly assess the use of Monetary-based model versus traditional percentage-based weighting methods.

1.4 Limitations

This study is designed to analyze and interpret existing data within the framework of MCDA and weighting score ratios. A key boundary condition of research approach is the decision not to undertake new data collection efforts, instead, analysis will focus on the comprehensive examination of previously gathered data from company Envidan, applying MCA and WSRs methodologies to assess sustainability in wastewater treatment operations.

2. Literature review

Sustainable wastewater management requires balancing multiple objectives – from environmental protection and public health to economic feasibility and social acceptance (Attri, 2022). Traditional decision-making approaches often fall short when they only focus on one single aspect, such as cost or treatment efficiency, while neglecting others.

To address this limitation, MCDA has become a key approach for evaluating and comparing wastewater treatment technologies across a comprehensive set of criteria. MCDA integrates technical, economic, environmental, and social aspects, making it a dependable tool for complex sustainability decisions (Stojčić, 2019).

Over the past decade, researchers have increasingly applied MCDA methods to support wastewater treatment decisions. These applications range from selecting optimal treatment processes for new facilities to comparing upgrade alternatives for existing plants under sustainability criteria. In the sections below, we review recent peer-reviewed studies that use MCDA for wastewater technology assessment. The key MCDA methods and concepts used, how different sustainability criteria are incorporated and weighted, the role of stakeholder participation in the decision process was identified in the literature.

2.1 What is multi-criteria decision analysis?

Multi-Criteria Decision Analysis (MCDA), also known as multi-criteria decision-making (MCDM), is a family of methods designed to help decision-makers in evaluating options against multiple, often conflicting criteria. Stojčić (2019) said that if decisions are based on a single criterion (like cost alone), it can lead to suboptimal decisions. Instead, MCDA enables the explicit consideration of trade-offs among factors such as cost, environmental impact, and social benefits. Based on that MCDA has become a necessary tool in contemporary engineering because many real-world problems involve complex trade-offs and stakeholder values (Štilic, 2023).
The evolution of MCDA methods has been propelled not only by diverse real-world problems that necessitate the consideration of multiple criteria but also by practitioners' aspirations to refine decision-making techniques through advancements in mathematical optimization, scientific computing (Wiecek, 2008; Zou, 2024). Complex problems often involve conflicting factors like cost, performance, reliability, safety, productivity, and affordability. Given that multiple criteria are at play, one singular optimal decision sometimes is best for all parameters or several viable options (Achillas, 2013).

2.2 The classifications of MCDA

There are many MCDM methods with different characteristics that can be related to many aspects from the quality of answers to the type of the problem these methods solve. Figure 1 shows the whole structure about different multi-criteria decision making types (Taherdoost, 2023; IPCC, 2014).

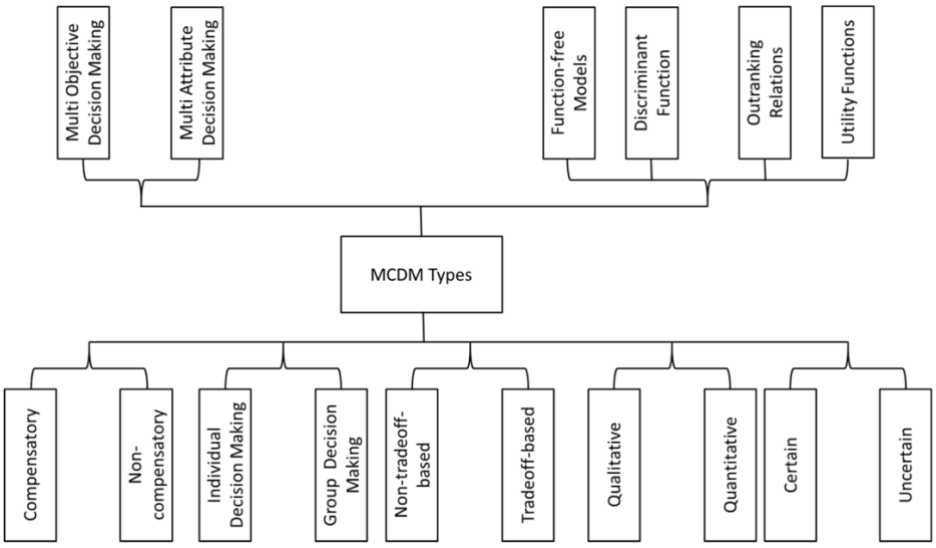


Figure 1 Different classifications of multi-criteria decision making (MCDM). Reproduced from Taherdoost, H.

In the classification figure, the top section of the figure shows different types of MCDA based on decision-making logic approach. These can reflect how decisions are reasoned. Methodology can be used to evaluate and choose between options when the decision process is formulated. This lower section shows the types and nature data and input processing used by the MCDA method.

Based on the classification, there are a variety of MCDA techniques have been employed. These can be broadly classified based on how they aggregate criteria and the decision-making philosophy they follow. Classical methods such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), ELimination Et Choix Traduisant la REalité (ELECTRE), VIšeKriterijumska Optimizacija i Kompromisno Rešenje (VIKOR), Multi-Attribute Utility Theory (MAUT) and Preference Ranking Organization method for Enrichment Evaluations (PROMETHEE) are commonly reported (Sharma, 2023).

For example, value measurement or utility-based methods like the AHP or MAUT assign weights and scores to each criterion and compute an overall value for each option (Cinelli, 2014). These methods are compensatory. They allow high performance in one criterion to offset weaker performance in another. One trade-off approach often aligned with “weak sustainability” where some environmental losses might be offset by economic gains (Cinelli, 2014). In contrast, outranking methods such as ELECTRE and PROMETHEE use pairwise comparisons and thresholds. They are following a non-compensatory logic. Non-compensatory approaches can enforce “strong sustainability”. By preventing an alternative that fails a threshold on a crucial criterion from being preferred, no matter how well it scores on other criteria.

Each method has their own strengths: AHP breaks down complex decisions into an intuitive hierarchy of criteria and sub-criteria with pairwise comparisons to derive weights. Whereas TOPSIS and VIKOR offer straightforward computational procedures to rank alternatives against idealized best or worst solutions. PROMETHEE provides a pairwise outranking approach using preference functions, and ELECTRE uses outranking with concordance or discordance tests (Wei, 2025).

Given the diversity of available methods, several studies have compared or combined MCDA techniques to ensure robust results. For instance, Attri et al. (2022) compared six wastewater treatment technologies using a hybrid fuzzy MCDA approach: they employed Fuzzy Stepwise Weight Assessment Ratio Analysis (Fuzzy SWARA) to derive criteria weights, then applied both Fuzzy MULTI-Objective Optimization by Ratio Analysis (Fuzzy MOORA) and Fuzzy TOPSIS to rank the alternatives. By using three methods in parallel, their study cross-validated the rankings, results were "somewhat predictable," confirming the reliability of the approach (Attri, 2022). This combined methodology exemplifies how researchers handle methodological uncertainty: if different MCDA techniques converge on a similar top-ranked option, decision-makers gain confidence in the choice.

The aggregation produce type is considered a key aspect of MCDA classification. According to Zopounidis, 2002 classificated methods in the compensatory model allows poor performance in one criterion can be offset by strong performance in another. Since the weighting process is used to aggregate the criteria to an overall sustainability score, it allows trade-offs for compensations between different criteria through weighted scores. For example, if one wastewater treatment alternative has a high CO_2 footprint but lower life cycle cost, the decision model accounts for both and balances them accordingly.

When evidence suggests that one alternative is as good as another, the outranking method can help assess the options by evaluating their outranking degree. According to Zopounidis, the utility function method assigns a numerical score to each alternative based on its performance across multiple criteria. This process often includes normalizing and aggregating values to produce a final ranking. In the literature and thesis models aggregated criterion evaluations generate a single utility score for each alternative. Normalized weights and scoring formulas allow each alternative's performance to be quantified into a single, comparable score (Zopounidis, 2002).

2.3 MCDA in sustainable engineering

Sustainable engineering focus on creating solutions that are environmentally sound, socially acceptable, and economically practical. To achieve these goals, decision makers must carefully weight various factors such as conserving resources, reducing pollution, improving energy efficiency, maintaining economic viability, ensuring social equity and involving stakeholders throughout the process. These factors often conflict which makes decision-making in sustainable engineering especially challenging. MCDA offers a structured approach to manage these trade-offs, helping to identify the most balanced and effective outcomes (Andelka Štilic, 2023, Banasik, 2018).

In the infrastructure development, for example, MCDA is commonly used to compare different alternatives based on environmental impacts, economic costs, and social acceptance. Decision models may evaluate various energy sources by looking at their carbon emissions, affordability, and how well they are accepted by the community. Similarly, in the field of water resource management, MCDA helps planners select options that ensure good water quality, minimize costs, and support long-term sustainability (Guarnieri, 2019).

These include the use of systems thinking and environmental impact assessments, protecting and enhancing natural ecosystems, and applying life cycle perspectives when evaluating technologies and materials (Abraham, 2006). Sustainable engineering also emphasizes the use of clean and safe materials and energy, minimizing the use of non-renewable resources, and reducing waste at every stage. Cultural, geographic, and local conditions are also considered important when designing engineering solutions, along with the encouragement of innovation and inclusive collaboration. Involving stakeholders and local communities in decision-making is a central principle, ensuring that solutions are grounded in local realities and supported by those they affect.

2.3.1 Integration of sustainability criteria

Recent studies consistently emphasize a interconnected criteria set in their assessments. For example, Hasan et al. (2021) evaluated 13 wastewater treatment plants in Iraq using 31 indicators grouped into four categories: Environmental (En), Social (S), Economic (E), and Technical (T) (Omran, 2021). In the Iraq study, environmental factors had the greatest influence on overall MCDA scores (the authors noted the effect order as Environmental > Economic > Social > Technical (Omran, 2021).

Similarly, Kanchanapiya & Tantisattayakul (2023) built a four-dimensional scorecard (economic, social, health, and environmental criteria) to prioritize water reuse options for Thailand (Kanchanapiya, 2023). In their case, health impacts were considered separately from general social factors which criteria definitions can be tailored to specific concerns (e.g. public health risk from water reuse). MCDA helps make these trade-offs explicit. Interesting patterns do emerge, though several case studies report that environmental criteria tend to receive the highest priority in sustainability assessments.

Modern studies on wastewater treatment selection emphasize multi-dimensional sustainability criteria. Instead of evaluating options on cost or performance alone. Now researchers build

frameworks that consider environmental, economic, social, technical and resource recovery dimensions side by side. Each sustainability dimension is further broken down into specific indicators or sub-criteria. This can enable to assess of tradeoffs. For instance, the DMsan decision-analysis package introduced by Lohman et al. (2023) defines five top-level criteria – technical, resource recovery, economic, environmental, and social – which collectively have 28 quantitative indicators. By defining these categories and indicators, MCDA frameworks can ensure that all key sustainability facets are quantified. Integrating results from methods like LCA and life-cycle cost into MCDA allows a balanced consideration of environmental, economic, social, and technical factors. This can lead to more well-rounded decisions. Gherghel et al. (2020) similarly evaluated alternative plant designs against six criteria (e.g. greenhouse gas emissions, energy use, operational cost, land footprint, required landfill area, and the facility's ability to function as a "biorefinery" for resource recovery).

So, some common criteria categories and examples reported in the literatures (Omran, 2021, Lohman, 2023) include:

- Environmental criteria:

Greenhouse gas emissions, energy use, effluent quality indicators (BOD, nutrient removal), sludge generation, ecological impact. These are often quantified via Life Cycle Assessment or compliance with regulatory standards.

- Economic criteria:

Capital and operational costs, cost-benefit ratio, economic savings from resource recovery, affordability for communities. Many studies incorporate life-cycle cost analysis or techno-economic analysis to inform these criteria.

- Technical criteria:

Treatment efficiency, reliability and robustness, ease of operation, land footprint, process flexibility, and innovation potential.

- Social criteria:

Public acceptance, social benefits (job creation, local development), impacts on health and sanitation, odor and noise nuisance, and alignment with stakeholder values or cultural preferences. Social criteria are sometimes harder to quantify and may be evaluated by stakeholder scoring or proxies (like the number of complaints).

- Resource recovery criteria:

Potential for water reuse, energy recovery from biogas, nutrient recovery from sludge. This has emerged as an additional category as circular economy principles are applied to wastewater systems.

Findings across studies generally show that no single option dominates all criteria. This is one of reasons why using MCDA in sustainable engineering. Most of scenarios are often about trade-offs. For example, an energy-intensive treatment might score high on effluent quality in environmental benefit criterion. But it was low on cost and carbon footprint in economic and environmental drawback dimensions. As Attri et al. (2022) argue, even a technically and economically sound solution can fail if social. Therefore, modern MCDA frameworks for wastewater strive to keep the

evaluation balanced, often through iterative refinement of the criteria set with expert or stakeholder input.

2.3.2 General procedure for MCDA in sustainable engineering

The application of Multi-Criteria Decision Analysis (MCDA) methods in sustainable engineering has grown in recent years. This is driven by advances in computing data availability, and increased emphasis on stakeholder engagement (Tseng, 2021). As global concerns over resource conservation, pollution prevention, and community involvement grow. MCDA methods have become essential tools for addressing complex sustainability challenges in engineering. Details of the MCDA process adapted for sustainable engineering can be structured into three main stages as per Esmail and Geneletti (2018):

Decision Context and Structuring:
This initial stage involves defining the decision problem, including its objectives and constraints, to establish a clear understanding of the context. It requires identifying and formulating the criteria against which alternatives will be evaluated, encompassing environmental, social, economic, and technical dimensions. Developing a set of feasible alternatives or options to address the decision problem is also crucial. Engaging relevant stakeholders during this phase ensures that diverse perspectives and values are considered, enhancing the legitimacy and acceptance of the decision process (Gregory, 2012). This stage lays the foundation for a comprehensive analysis by structuring the problem effectively

Analysis:
In this phase, each alternative's performance is evaluated against the established criteria using appropriate quantitative and qualitative measures. Assigning weights to each criterion reflects their relative importance in the decision-making process. The weighted criteria assessments are then aggregated to derive an overall performance score or ranking for each alternative. Conducting sensitivity analysis is vital to examine how variations in criteria weights or assessments affect the outcomes, thereby testing the robustness of the results (Belton, 2002). This analytical phase provides a systematic evaluation of alternatives, facilitating an understanding of trade-offs and highlighting options that best align with sustainability objectives

Decision:
The final stage integrates information from the previous analyses to make informed and transparent decisions. Alternatives are ranked based on the aggregated assessments, leading to the selection of the most suitable options that align with sustainability goals. Communicating the findings to stakeholders is essential, providing a transparent rationale for the chosen alternative. Developing an action plan for implementing the selected alternative involves considering practical aspects such as resource allocation, timelines, and monitoring mechanisms. Engaging stakeholders throughout the process ensures that the decisions are well-understood and broadly supported, facilitating smoother implementation (Esmail B. A., 2018).

2.4 MCDA in wastewater management and application

MCDA has been applied to a variety of wastewater treatment decision scenarios worldwide, reflecting different regional priorities and contexts. This is because decisions often involve balancing technical performance, economic costs, environmental impacts, and social criteria. A variety of MCDA methods – from classical techniques like the analytic hierarchy process (AHP) and TOPSIS to more advanced fuzzy and hybrid models – have been applied in this domain. These methods provide a systematic framework to compare alternative solutions (e.g. treatment technologies, reuse options, facility locations). By quantifying diverse criteria and incorporating stakeholder preferences. Recent studies from different regions illustrate how MCDA can support transparent and rational decision-making in wastewater management.

Cicekalan et al. (2023) used AHP to select an optimal wastewater treatment upgrade for a municipality in North Macedonia. Their analysis compared three alternative treatment solutions against criteria such as upfront investment, operating costs, and management complexity, ultimately recommending the construction of a new moving bed biofilm reactor (MBBR) plant as the most suitable option. At a broader planning level, Yahya et al. (2020) applied the TOPSIS method to rank several common wastewater treatment technologies in terms of cost, energy usage, maintenance requirements, and other factors. In this study, which also tested a fuzzy PROMETHEE approach for comparison, found that the conventional activated sludge process was the top-performing technology, followed by a nano-filtration method.

Omran et al. (2021) conducted a comprehensive sustainability assessment of wastewater techniques across 13 operating plants in Iraq. This study involved 52 experts from the Ministry of Municipalities and Public Works in evaluating four types of treatment systems – conventional activated sludge, oxidation ditch, aerated lagoon, and membrane bioreactor. Using a weighted-sum MCDA framework, they aggregated 31 indicators covering environmental, social and technical dimension. This is a structured way to identify which technologies delivered the best overall sustainability performance.

In water-scarce regions of Asia, MCDA has been used to plan water reuse and augment water supplies. Kanchanapiya and Tantisattayakul (2023) applied MCDA to evaluate wastewater reuse options for Phuket, a tourism-driven island in Thailand. They formulated three reuse scenarios which are domestic reuse, agricultural reuse, and using reclaimed water as raw feed for thwater treatment plant and assessed each on economic, social, health, and environmental criteria (Kanchanapiya, 2023).

MCDA techniques have also been integrated with spatial analysis for infrastructure siting. For instance, a recent study in Oman combined AHP with Geographic Information System (GIS) tools to evaluate suitable sites for new sewage treatment plants (Al Nasiri, 2023). The researchers weighted eight locational factors which is including terrain slope, proximity to built-up areas, distance from roads, and environmental buffers. By using the AHP and then generated GIS suitability maps to pinpoint optimal zones. Their results showed a few coastal areas in Muscat as the most suitable locations which is only about 1% of the study area. These results can provide planners with a clear rationale for prioritizing those sites.

In Europe, where stringent environmental regulations and sustainability goals are in place, MCDA has be into both planning new infrastructure and corporate decision processes. A study by Gherghel, (2020) found with the sustainable design of large wastewater treatment plants in Romania, in collaboration with experts in Italy. They considered various design and upgrade strategies for large municipal plants, explicitly including criteria such as greenhouse gas emissions and land use which are often marginal in traditional engineering design. Stakeholder involvement was through workshops, they gathered input not only from engineers but also from environmental regulators and local authorities. Using an MCDA framework, they combined AHP for criteria weighting with a weighted sum composite index to rank design alternatives (similar to the approach described by Ling et al. (2021)). When sustainability criteria, like carbon footprint or space footprint, are given sufficient weight alongside cost and technical performance, the optimal design solutions for a wastewater plant can change. For example, a configuration that might be slightly more expensive upfront but yields lower emissions and sludge byproducts could outrank a traditionally favored, cheaper design. Gherghel et al.'s results showed that broader sustainability-oriented decision-making can lead to different priorities, emphasizing long-term environmental and social benefits in plant design.

Taken together, these international examples underscore the adaptability and impact of MCDA in wastewater management. Whether selecting treatment technologies, comparing reuse strategies, or exploring new system configurations. Meanwhile, it also supports participatory planning, helping align infrastructure choices with diverse stakeholder values and long-term sustainability goals. As the literature shows, MCDA offers not only analytical structure but also transparency and legitimacy. This is because qualities increasingly essential for guiding wastewater decisions in a one growing environmental and social complexity.

2.5 Use of Weighted Score Ratio in MCDA

The weighted score ratio method is a recent extension of the simple additive weighting approach in MCDA. In WSR, decision-makers first score alternatives on each criterion (often on a normalized scale) and then assign weights to reflect criteria importance. Unlike conventional weighted-sum methods, WSR introduces an extra: calculating the WSR between criteria to reveal the implicit trade-offs being made. These ratios have real-world units (e.g. cost per unit of environmental impact), making the consequences of weight choices transparent.

Neth et al. (2023) investigated the sustainability of different methods for removing pharmaceuticals from wastewater using the Weighted Score Ratio. The study systematically classified key sustainability factors, including climate impact, energy use, annual costs, work environment, and security risks, assigning them weighted scores based on their perceived importance. This allowed stakeholders to compare their implicit trade-offs to societal reference values (such as carbon prices), greatly increasing the objectivity and clarity of the decision process . The final assessment integrated these weighted scores to determine the most and least sustainable technologies, aligning with projected sustainability standards for 2050.

2.5.1 How to calculate the Weighted Score Ratio

Participants in the weighting group assign weighting coefficients on a 1–20 scale, which are then converted to percentages. The 1–20 scale allows participants to focus on whether a criterion should have high or low priority rather than assigning an exact percentage, simplifying the decision-making process. Weighting coefficients represent that decision-makers attribute to performance variations in each criterion (e.g., from 'neutral' to 'good').

This is directly linked to how performance fluctuations impact sustainability outcomes. Participants are also encouraged to define minimum and maximum weights for each criterion to facilitate sensitivity analysis (Brattebø, 2013; Brattebø, 2013; Brattebø, 2013; Brattebø, 2013). When the weights are set, relationships between the criteria emerge, demonstrating each criterion's contribution to the total sustainability score. The weighted score ratios (WSRs) between criteria are calculated using the follows the formula in

$$WSR(unitA/unitB) = \frac{V_A}{V_B} \cdot \frac{W_B}{W_A}$$

Where:
$WSR(unitA/unitB)$: in units such as €/CO2e, €/kWh or kWh/CO2e.
V_A/V_B: value per score step of criterion A and B
W_A/W_B: weights of criterion A and B

These WSR values can be expressed in different units, such as €/CO_2e, €/kWh, or kWh/CO_2e. To ensure consistency, it is recommended to start the weighting procedure by setting the weight for 'annual cost' and keeping it constant as a reference value.

For non-quantifiable criteria, the value per weighted score step can be expressed in terms of any quantifiable criterion by using the relationship between their weights.

The formula used in Neth et al. 2023:

$$Value\ per\ weighted\ score\ step(unitC/weightedscore\ step) = \frac{W_D}{W_C} \cdot V_c$$

Where:
V_c: the value per score step for criterion C
W_C/W_D: weights of criterion C and D

For example, if annual cost (C) and work environment (D) are compared, this equation quantifies how much additional annual cost an organization would accept to improve work environment by one score step.

2.5.2 Result: what total sustainability score for each alternative has been calculated

The total sustainability score for each alternative was calculated using the following formula from Maria Neth's (2023) study:

$$S_j = \sum_{i=1}^{m} w_i \cdot S_{ij} \ (4.5)$$

Where:
S_j: the total sustainability score for alternative j
m: the number of criteria included in the analysis
w_i: the weight of criteria i
sij: the score of alternative j on criteria i

2.5.3 Comparison of WSR with other MCDA methods: Benefits and limitations

The WSR method shares some similarities with well-known MCDA methods like the AHP and MAUT, but there are important differences that affect how these methods are used in sustainability assessments.

AHP, as mentioned earlier, is a widely used MCDA method that derives criteria weights through pairwise comparisons in a hierarchy. It uses pairwise comparisons to derive weights for each criterion, helping decision-makers think clearly through each trade-off. One key benefit of AHP is its ability to break down complex problems into smaller, easier-to-understand steps. This makes it useful in contexts like wastewater planning, where stakeholders can compare the importance of factors like environmental impact versus cost. However, AHP can be mentally demanding because it requires many comparisons. It can also lead to inconsistencies in judgment. For example, if someone says A is better than B, B is better than C, but then says C is better than A (e.g. A > B, B > C, but then C > A, which is inconsistent). While AHP can flag these inconsistencies, managing them can be difficult, especially with many criteria

WSR avoids these cognitive challenges. It does not rely on pairwise comparisons and works with direct scoring and weighting. WSR also makes trade-offs more transparent. For example, it can show how much cost increase a decision-maker is willing to accept for a one-point improvement in environmental performance. These "exchange rates" between criteria (e.g., €/kg CO_2 or €/kWh) help make abstract trade-offs more concrete and easier to explain to stakeholders.

MAUT is another common MCDA method that works by building utility functions for each criterion and then combining them using weights. In many cases, this results in a weighted sum similar to WSR. However, MAUT has an added strength: it can reflect decision-makers' risk preferences. For example, it can model situations were avoiding the first 10 units of pollution is more valuable than avoiding the next 10. This kind of non-linear thinking is not built into WSR, which typically assumes that each point of improvement is equally valuable. In that sense, WSR can be seen as a simpler, linear version of MAUT that focuses more on transparency and ease of use than on modeling complex preferences.

Other MCDA methods include outranking techniques like PROMETHEE and ELECTRE, and compromise-ranking methods like VIKOR. These approaches compare alternatives in pairs and apply preference thresholds to decide if one option "outranks" another. Unlike WSR, they do not produce a single final score. Instead, they allow decision-makers to define cut-off points for acceptable performance. This can be useful when strong sustainability is required—where a bad score in one criterion cannot be balanced out by good scores in others. However, these methods are harder to explain and can become confusing for stakeholders. They may also run into problems with inconsistent rankings or comparisons that don't yield a clear winner. In contrast, WSR uses a continuous, weight-based system without thresholds, so every criterion can always be traded off, which helps keep the process straightforward.

In summary, WSR offers a clear and easy-to-follow method for combining criteria. It does not require complex comparisons or mathematical models. Scores and weights are applied directly, and total performance is calculated through addition. This makes it highly accessible and transparent for both experts and non-experts. However, WSR does not have built-in checks for

inconsistencies or errors in the weights. If the weights are misjudged. For example, if a stakeholder unintentionally gives too little importance to a critical factor. WSR can reflect that directly in the final outcome. This makes the process highly dependent on good facilitation. Without careful guidance, there is a risk that poor input leads to poor decisions—a classic case of "garbage in, garbage out."

2.6 Stakeholder and sensitivity analysis in MCDA

Stakeholder analysis plays an important role in MCDA because it helps identify who the key actors are, what their interests might be, and how their perspectives can shape the decision-making process. While most MCDA methods do not include built-in tools for stakeholder identification, successful applications in practice show that stakeholder input improves both the legitimacy and relevance of the analysis (Reed, 2009).

Recent studies from participatory MCDA frameworks have enhanced decision-making outcomes by directly involving stakeholders. For instance, Ngubane et al. (2024) introduced a framework in South Africa where stakeholders, including local residents and municipal representatives, collaboratively identified and prioritized best management practices to mitigate river pollution risks. This inclusive approach ensured that the selected strategies affected with the community's environmental, economic and social priorities.

Beutler et al. (2024) applied a participatory MCDA approach in Swiss municipalities to explore transitions from centralized sewer systems to decentralized sanitation solutions. Local stakeholders were invited to co-define evaluation criteria and assess options under uncertain conditions. Environmental protection emerged as the most important criterion across all groups, and decentralized systems. Especially for those with urine separation which were identified as the most sustainable. Participants found the process informative and trustworthy, reinforcing the value of inclusive MCDA in reaching consensus, even on complex infrastructure choices.

In wastewater planning, stakeholder involvement often occurs during the criteria weighting phase. This is because the relative importance assigned to each criterion has a direct impact on the final ranking of alternatives. Ling et al. (2021), in collaboration with Thames Water in the UK, involved 14 internal stakeholders in a structured process to derive weights using the AHP. Individual weightings were then aggregated into a final group weight set. Similarly, Omran et al. (2021) engaged 52 municipal experts in Iraq to score the sustainability of 13 treatment plants. Their wide participation helped ensure that results were credible and relevant to local needs. To address this, some studies use group decision-making tools. Such as averaging, voting, or consensus facilitation in order to build a fair and inclusive model.

The main advantage of involving stakeholders is the increased transparency and ownership of the decision process. Stakeholder involvement is not just helpful. It is often necessary to ensure that decisions are accepted and implemented. While it can lengthen the process and sometimes lead to disagreements, many studies report that participants value the opportunity to discuss trade-offs and understand different perspectives. Even if a stakeholder's preferred option is not selected, they are more likely to accept the outcome if the process is seen as open and evidence based.

A second important is sensitivity analysis. After calculating scores, it is common to test how robust the results are to changes in inputs. For example, if the weight on environmental criteria increases or decreases by 10%, does the top-ranked alternative stay the same? In the Thames Water case, Ling et al. compared rankings based on group weights versus individual stakeholder weights and a previous default ranking. They found that the selected option remained stable across scenarios, increasing confidence in their results.

Some studies take a scenario-based approach, adjusting weight profiles to reflect different decision priorities. For instance, Kanchanapiya et al. (2023) used a budget-allocation task to simulate how weights might shift under financial constraints. Similarly, Neth et al. (2023) used WSR to make trade-offs explicit. If the resulting ratios seemed implausible. Such as like an excessive willingness to pay for marginal environmental benefits which can be refined the weights accordingly. This iterative process, though informal, serves as a practical sensitivity test.

Generally, stakeholder involvement and sensitivity analysis are two inevitable elements of MCDA process. Stakeholder inputs allow that the model can reflect real-world values, while the sensitivity analysis confirms that conclusions are reliable under a range of assumptions.

3 Case study: Västra Strandens WWTP

In this section, a case study presents of the Västra Strandens WWTP to illustrate the application of the enhanced MCA method developed in this research. The WWTP serves as an example. The purpose of the study is to evaluate the weighting method used for the MCA and not to determine which treatment method should be used at a specific WWTP. The planning process for Västra Stranden is ongoing and new or revised data as well as changed circumstances can further change the results in this specific case. By applying the MCA method to this case, the study aims to showcase how decision-makers can systematically compare alternative technologies considering multiple sustainability criteria.

3.1 Case study background

Västra Strandens WWTP, located in Halmstad, Sweden, was originally constructed in 1962 and has since played a central role in treating wastewater for both residents and industries in the region. As the largest treatment facility in the area, it currently serves approximately 80,000 inhabitants. Its service network extends to several surrounding districts, including Trönninge, Eldsberga, Påarp-Laxvik, and Gullbranna, as well as the western zones of Görvik-Sandhamn, Frösakull, and Tylösand, and eastern areas such as Skedala, Holm, and Kvibille (DHI and Envidan and Akvedikt Miljö & Media på Kivik and Medins Havs och Vattenkonsulter , 2022-10-31) (Åkerblom, 2022).

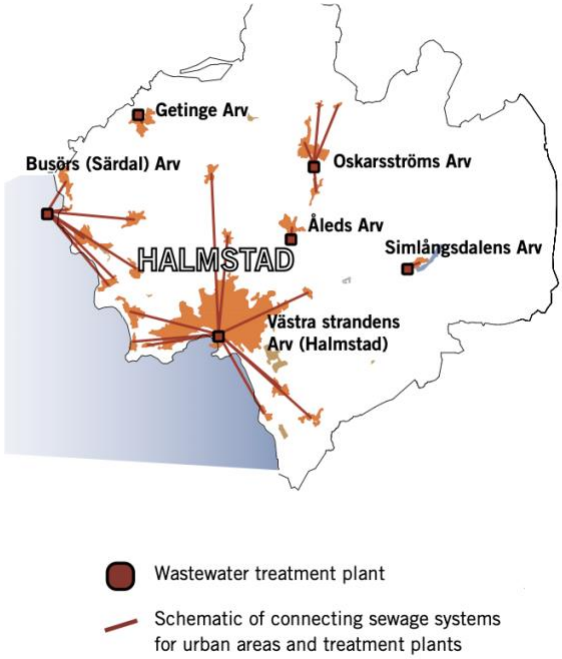


Figure 2 Map and schematic of the service network at Västra Strandens WWTP *(Åkerblom, 2022)*

3.2 Historical development

The plant has undergone several strategic upgrades to meet evolving environmental standards and operational needs. Key milestones include:

- 1962: Establishments of the WWTP to manage wastewater for local and industries.
- 1990s: The introduction of nitrogen removal systems.
- 2004: Improvements in overflow water management systems.
- 2005-2006: Implementation of enhanced biological phosphorus removal (EBPR)
- 2015: Increase use of chemical phosphorus removal processes due to the deterioration of EBPR. (Eriksson, 2018)
- 2016: Introduction of primary sludge hydrolysis in the pre-sedimentation process to enhance Volatile fatty acid (VFA) production.
- 2020: New strategic plan for supplemental water planning from Envidan was adopted by LBVA.
- 2021: The Slättåkra wastewater treatment plant was shut down, and the wastewater that it used to treat was redirected to Västra Strandens Wastewater Treatment Plant.

3.3 Wastewater treatment process

At Västra Strandens WWTP, the wastewater treatment begins with a mechanical cleaning stage where wastewater first passes through two grates with a slot width of 2 mm, effectively removing coarse material. The residues from these grates are subsequently washed and dewatered, then transported to an incineration facility for disposal. Sand and gravel are segregated in an aerated grit chamber, washed, and repurposed as filling material. At the same time, fats separated in the grit chamber are also directed to the incineration plant.

Following mechanical preprocessing, the wastewater progresses to the primary sedimentation stage where primary sludge is extracted and conveyed to a thickener for concentration. The pretreated water is then advanced to the biological treatment stage, specifically for the removal of nitrogen and phosphorus. This stage is a Slamox-anoxic tank which means it treats return sludge and reject water at the same time and the excess sludge is extracted. The water undergoes a flotation process where chemicals for precipitation are added based on the phosphorus levels after biological treatment in sludge oxidation and thinkers. The wastewater treatment process at Västra Strandens WWTP consists of the process steps seen in Figure *3* below.

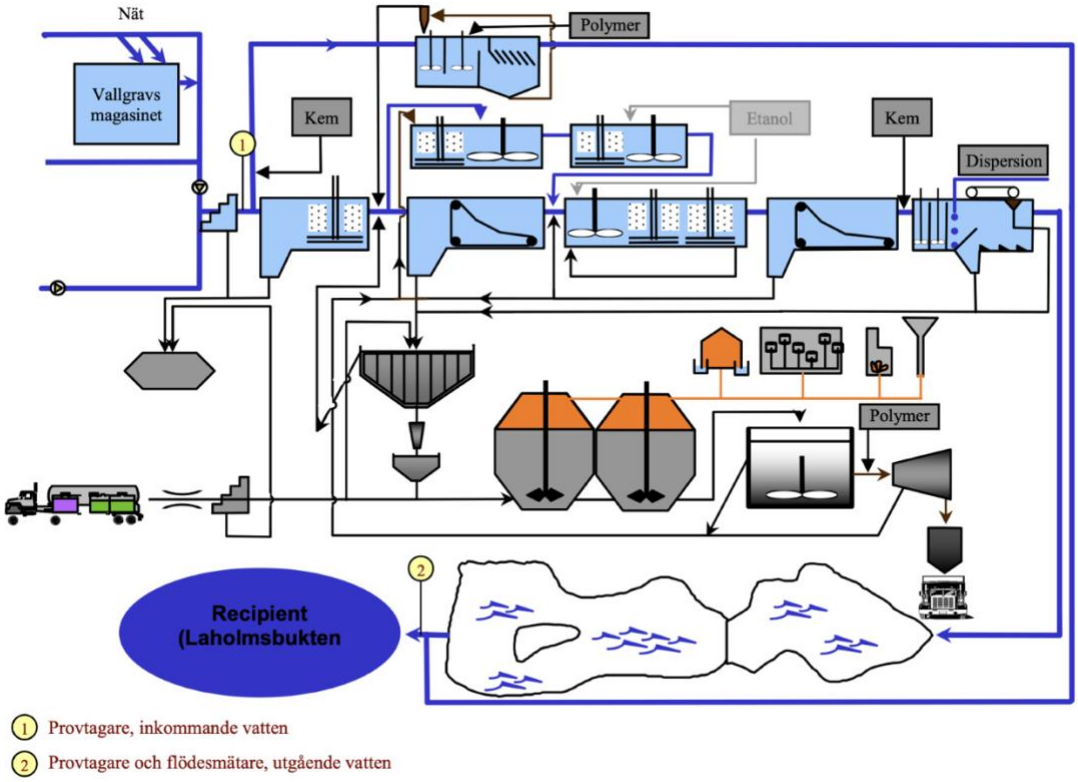


Figure 3 Process schematic of the wastewater treatment process At Västra Strandens WWTP *(Åkerblom, 2022; Aqua-Aerobic Systems, Inc., 2021)*

3.4 Flow capacity and expansion needs

Currently, the plant is designed to handle wastewater loads equivalent to a population of approximately 102,000 people. However, population growth and the decommissioning of smaller treatment plants are projected to increase this number to 154,000 by 2050. This sharp increase will place substantial pressure on the plant's treatment capacity. Additionally, more stringent discharge requirements from future environmental permits will necessitate process upgrades to ensure compliance. As shown in

Figure 4, this anticipated growth will significantly impact the flow capacity requirements of the WWTP. Simultaneously, stronger limitations are expected to be imposed through new environmental permits, necessitating upgrades and expansions to comply with stricter regulations while accommodating higher capacity demands.

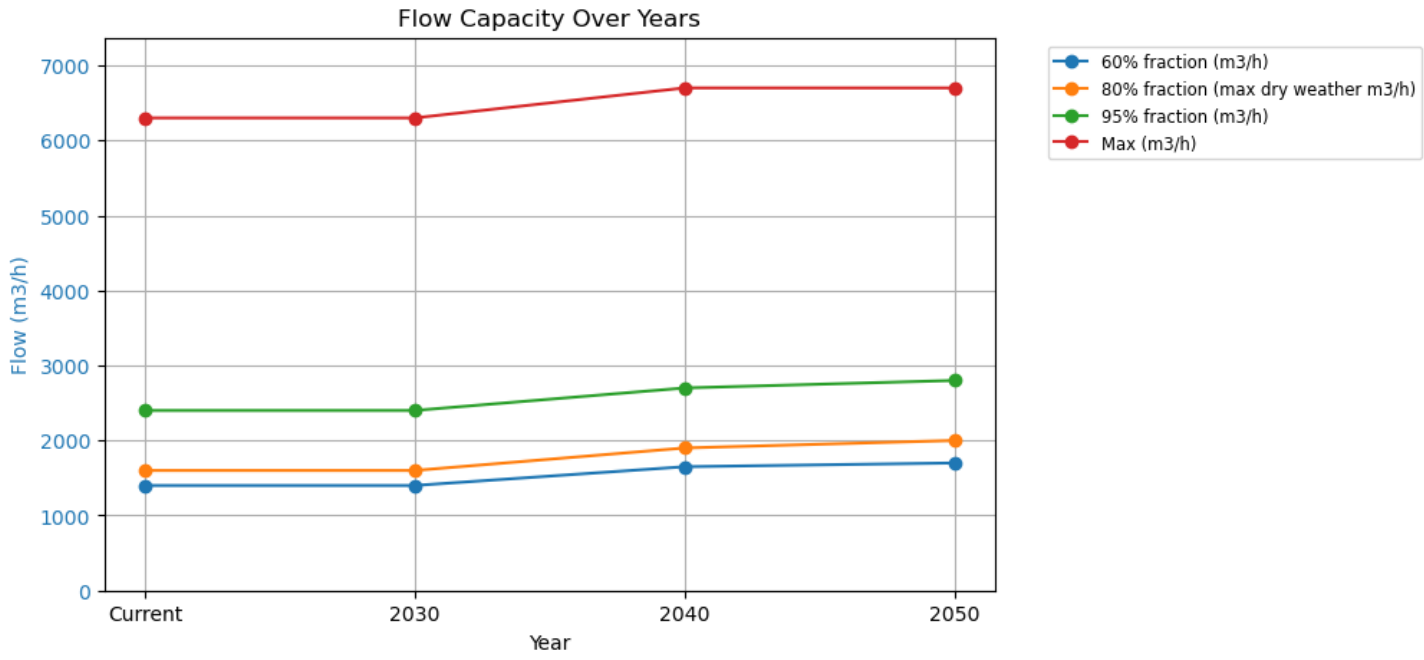


Figure 4 The current and future loadings and flow capacity At Västra Strandens WWTP

The combination of increased load and stricter regulations underscores the need for systematic planning and evaluation of treatment alternatives. This context makes the Västra Strandens WWTP a relevant and timely case for applying MCA in support of sustainable and informed decision-making.

3.5 Three different technologies as alternatives for case study

3.5.1 Activate sludge, AS

AS is a conventional and widely used wastewater treatment technology. It operates by using suspended aerobic sludge consisting of flocs of active bacteria, which consume and remove aerobically biodegradable organic substances from screened or screened and pre-settled wastewater (Tilley, 2014). Activated sludge systems can treat blackwater, brown water, greywater and industrial wastewater if the pollutants to be treated are biodegradable.

This established method is familiar to Västra Strandens WWTP and offers several benefits and considerations for scalability, nutrient removal, space requirements and future adaptability. AS processes can be optimized for biological phosphorus removal, enhancing nutrient management. This capability makes AS a robust solution for meeting stringent nutrient discharge regulations. However, AS requires significant space due to the low concentration of suspended solid. This necessitates additional separation stages which can increase spatial and infrastructure demands. AS systems can be upgraded to Membrane Bioreactor systems if higher treatment capacity or better effluent quality is needed.

3.5.2 Membrane bioreactor, MBR

MBR technology combines biological treatment with membrane filtration, providing high-quality effluent with reduced particle concentrations and improved removal of micropollutants (Beddow, 2010). MBR systems achieve very high levels of purification, resulting in low particle concentrations. This facilitates the removal of micropollutants, such as pharmaceuticals. Due to the high efficiency of the process, MBR systems are very compact and do not require extensive secondary or tertiary treatment stages (Chapman, 2004).

The system can be optimized for biological phosphorus removal, provided chemical precipitation does not dominate the process. If excessive precipitation occurs, it may hinder Bio-P, necessitating additional post-precipitation stages and potentially undermining the compactness advantage of MBR (GE, 2011). Otherwise, MBR systems require significant energy input due to extensive pumping, return flow, and recirculation requirements. Strong chemicals are often needed for membrane cleaning and maintenance (Radjenovic, 2008).

MBR combined with conventional biological treatment (AS) processes can provide an advanced level of organic and suspended solids removal. When designed accordingly, these systems can also provide an advanced level of nutrient removal (GE, 2011). This level of filtration allows for high quality effluent to be drawn through the membranes and eliminates the sedimentation and filtration processes typically used for wastewater treatment. Because the need for sedimentation is eliminated, the biological process can operate at a much higher mixed liquor concentration. This dramatically reduces the process tankage required and allows many existing plants to be upgraded without adding new tanks (Radjenovic, 2008; Reed, 2009).

3.5.3 Aerobic granular sludge, AGS

AGS is an advanced biological wastewater treatment technology known for its compact, dense microbial granules that improve settling and treatment efficiency. These granules consist of stratified microbial communities. It can allow multiple biological processes to occur simultaneously within the same biomass. This structure enables enhanced phosphorus removal, along with simultaneous nitrification and denitrification, all within a single reactor (Zou, 2024).

Unlike conventional activated sludge systems, which rely on flocculent biomass and require large clarifiers, AGS systems promote faster settling and higher biomass concentrations. The reactor biomass concentration in AGS systems typically exceeds 8–10 kg MLSS/m³, which contributes to a smaller footprint and higher treatment efficiency (Wang, 2022). This process occurs within a single tank, creating optimal conditions to develop and maintain a stable granular without needing supplemental carriers (Aqua-Aerobic Systems, Inc., 2021). The layered aerobic and anaerobic zones within the granule allow for simultaneous processes to take place in the granular biomass, including enhanced biological phosphorus reduction and simultaneous nitrification and denitrification.

The AGS system is especially effective in meeting the stricter discharge regulations now seen in many regions. Traditional activated sludge often struggles to maintain stable effluent quality, particularly during load fluctuations or under tighter nutrient discharge limits (Devos, 2023). In contrast, the self-aggregating nature of AGS offers superior resilience and effluent stability, making it a promising alternative to traditional technologies.

AGS System uses an optimized batch cycle structure as follow in Figure 5. There are three main phases of the cycle to meet advanced wastewater treatment objectives. The duration of the phases will be based upon the specific waste characteristics, the flow and the effluent objectives.

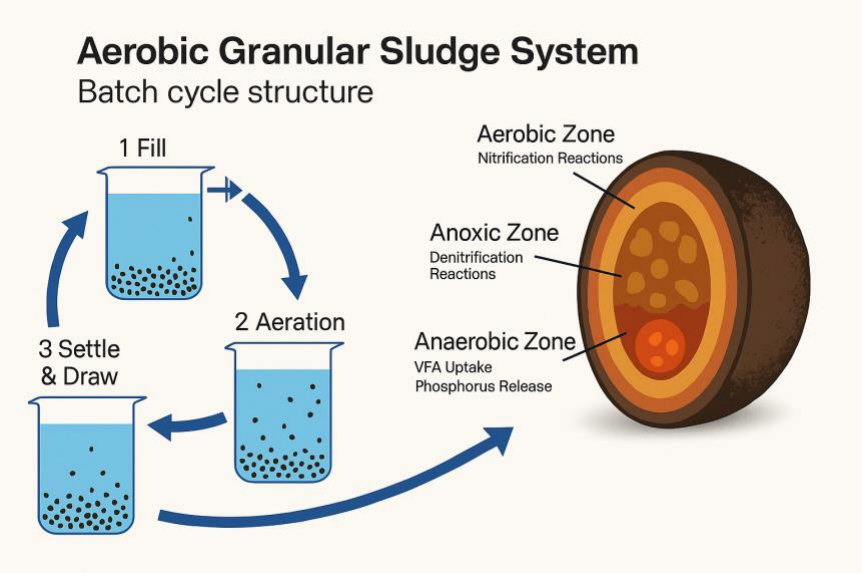


Figure 5 Aerobic granular sludge system and batch cycle structure reproduced from Aqua-Aerobic Systems, Inc., 2021.

The operation of an AGS system follows a structured sequencing batch reactor (SBR) cycle, typically divided into three main phases: fill and draw, reaction, and settling based on Figure 5 and AquaNereda, 2022.

Step one involves the simultaneous fill and draw phase. In this stage, influent wastewater enters the reactor along with readily biodegradable carbon sources. This influx creates anaerobic and anoxic conditions within the biomass, which helps to prepare the microbial granules for effective nutrient removal. During this phase, phosphorus is released from the biomass, supporting enhanced biological phosphorus removal. At the same time, treated water from the previous cycle is discharged from the top of the reactor.

Step two is the reaction phase, where the input of new wastewater is paused. The biomass is now exposed to alternating aerobic and anoxic conditions. These conditions enable simultaneous nitrification and denitrification to occur within the granular structure. Oxygen supports the conversion of ammonia to nitrate in the outer layers, while the inner anoxic zones support the reduction of nitrate to nitrogen gas. Because of this internal diffusion, AGS eliminates the need for large internal recycle flows, which are typically required in conventional systems.

Step three is the settling phase. The dense granular biomass rapidly settles to the bottom of the reactor, effectively separating it from the treated effluent. Any excess sludge is removed at this stage to maintain optimal biomass concentrations. Once the granules have settled, the system is ready to begin a new cycle.

3.6 Data collected for case study

Before the workshop, relevant data were collected Envidan and LBVA to support the evaluation of wastewater treatment technologies. This data focused on quantifiable sustainability criteria commonly used in the wastewater sector, including life cycle cost, CO_2 emissions, and energy consumption. The analysis was limited to the water line of the WWTP and followed four main sustainability dimensions: economic, technical, environmental, and social. These were further divided into six specific evaluation criteria:

Economy: Life Cycle Cost (kr/year)
Technical: Stable Operation (measured by reliability and downtime), Flexibility (ability to adapt to future demands and regulatory changes)
Environment: CO2 Footprint (Ton CO2e/year), Energy Consumption (kWh/year)
Social: Working Environment and Safety (improvements in workplace innovation and safety)
These criteria were thoroughly analyzed to guide the selection of the most suitable technology.

Table 1 collected that AGS exhibited the lowest life cycle cost, CO2 emissions, and energy consumption among the alternatives, making it a potentially favorable option. Conversely, MBR ranked highest in terms of cost, CO2 output, and energy use.

Table 1 Input Data for quantifiable sustainability criteria

Criteria	Unit	Input data		
		AS	MBR	AGS
life Cycle Cost	kr/year	22 000 000	26 000 000	16 000 000
Stable Operation	-	-	-	-
Flexibility	-	-	-	-
CO2 Footprint	ton CO2e/year	16 900	17 700	16 800
Energy Consumption	kWh/year	1 500 000	2 900 000	1 300 000
Working Environment and Safety	-	-	-	-

For the qualitative part of the assessment, professionals from LBVA were asked to evaluate each criterion by assigning grades from 1 to 5. These expert scores were used in the value-based model to reflect how well each technology aligns with long-term sustainability targets, particularly those set for 2050. The grading description was summarized into Table 2.

Table 2 Description of grading scale used by LBVA experts

Grade	Grade description
1	Significantly worse than future acceptable level
2	Worse than future acceptable level
3	Future acceptable level
4	Better than future acceptable level
5	Close to optimal level

The score of 3 was used as the reference point for ‘acceptable future performance’ for each criterion. This grading system allowed all criteria (quantifiable and non-quantifiable) to be compared on the same normalized scale. This is done by ranking the scenarios for each criterion according to the scoring criteria in Table 3. which is based on the data and information given for each criterion. Comparisons can be facilitated by converting the data and information for the different criteria into comparable ratings that reflect the same scale.

Table 3 Expert grades assigned to each alternative

Criteria	Unit	Grade from experts (1-5)		
		AS	MBR	AGS
life Cycle Cost	kr/year	3,6	3,1	5,0
Stable Operation	-	4,0	3,0	5,0
Flexibility	-	2,0	5,0	4,0
CO2 Footprint	ton CO2e/year	5,0	4,8	5,0
Energy Consumption	kWh/year	4,3	2,2	5,0
Working Environment and Safety	-	4,0	2,0	5,0

4 Methodology

This section outlines the methodological approach used to assess the sustainability of wastewater treatment alternatives using the Weighted Score Ratios (WSR) method. The methodology involves conducting two workshops—one with Chalmers students and another with experts—to evaluate three wastewater treatment technologies. Two different weighting models were applied to assign importance to the selected criteria in assessing the sustainability of wastewater treatment options:

Percentage-based weighting model: A traditional Multi-Criteria Analysis (MCA) approach, where criteria are assigned weights on a predefined scale. This method ensures straightforward quantification of relative importance.

Value-based weighting model: A cost-based approach, where monetary values are assigned to each criterion, allowing for a cost-effectiveness comparison.

4.1 Percentage-based weighting model: input weights for each criterion

Percentage-based weighting model is the most basic and commonly used in MCA analysis. In this model, weights are assigned to each criterion using a scale ranging from 1-20. This scale allows participants to prioritize criteria effectively, focusing on the importance rather than numerical values. Under the decision-making process, the scale's range show a clear demarcation between high and low priority criteria which means 1 is the less important criterion and 20 is the most important criterion.

4.1.1 Normalization of weights

Weights assigned to criteria are normalized to ensure their summative contribution equates to 100%, enabling comparability across different criteria and treatment alternatives.

The normalization process is described mathematically as follows:

$$W_{N1} = \frac{W}{\sum W_{All\ Criteria}} \times 100\% \ (4.1)$$

Where:

W: the weight assigned to a criterion.
W_{N1}: the normalized weight, expressed as a percentage

4.2 Value-based model: input monetary for each criterion

The Value-based model gives a different perspective for MCA by incorporating monetary values into the weighting process. Instead of assigning percentage-based weights, students evaluate sustainability criteria based on the economic impact. Monetary values can be assessing the sustainability criteria, providing a quantifiable economic perspective that aids in decision-making. "Monetary value" refers to the financial quantification assigned to each criterion within the MCA. When assessing the economic impact of different sustainability criteria on various wastewater treatment options, ranging from direct costs to non-quantifiable criteria values.

Monetary values are directly compared to benchmarks set for the model. The financial quantification of each criterion follows specific units:

- CO2 footprint: SEK per kg CO2 equivalent (SEK/kg CO_2eq)
- Energy consumption: SEK per kilowatt-hour (SEK/kWh).
- Non-quantifiable criteria converted into economic terms (e.g., environmental, flexibility) SEK per grading step.

4.2.1 Calculating Weighted Economic Impact

The economic impact of each criterion is calculated using linear regression, where the value per grading step V_p represents the monetary change per unit increase in grading.

The monetary input for each criterion is given by:

$$C_q = |C_p \times V_p| (4.2)$$

Where:

C_p: cost per unit for the quantifiable criterion.
V_p : value per grading step, determined through linear regression.
C_q: cost per unit, the criterion's weghted economic impact.

Table 4 Example from LBVA to calculate the weighted economic impact

Criteria	Unit	Cp	Vp	Cq
life Cycle Cost	fixed	1	-5051546,392	5051546,392
Stable Operation	SEK/yr/Grade	3 500 000		3500000
Flexibility	SEK/yr/Grade	750 000		750000
CO2 Footprint	SEK/kg CO2eq	1,5	-4250000	6375000
Energy Consumption	SEK/kWh	1,000	-593406,5934	593406,5934
Working Environment and Safety	SEK/yr/Grade	175 000		175000

Table 4 provides an example of this calculation based on input data from LBVA. In this example, the C_p value is defined by stakeholders as the estimated cost required to improve a criterion by one grading step. The corresponding V_p value is taken from earlier analysis (see Table 1). Using Equation 4.2, the product of these values gives C, the economic weight of the criterion.

4.2.2 Normalization of Economic weights

To ensure comparability across different criteria, the weighted economic impacts C_q normalized by using the cost (for example LLC) as a baseline reference:

$$W_{N2} = \frac{\frac{C_q}{Cost}}{\left(\sum \frac{C_q}{Cost}\right)_{All\ Critrtia}} \times 100\% (4.3)$$

Where:

C_q: cost per unit, the criterion's weighted economic impact.
$Cost$:in this case is the life cycle cost, as the baseline
W_{N2}: normalized weight, expressed as a percentage in value-based model.

4.3 Calculation of weighted scores for both models

To evaluate each technology effectively, two sets of normalized weights (W_{N1} and W_{N2}) are used, corresponding to the Percentage-Based and Value-Based Weighting Models respectively. Each technology is graded (G) based on how well it meets the specified criteria. The score for each criterion (S_c) is then calculated by multiplying the normalized weight by the grading for this selected technology. The specific equations used are outlined below:

$$S_c = W_N \times G \quad (4.4)$$

Where:

S_c: Score for selected criterion

W_N: Normalized weight as a percentage (from either W_{N1} or W_{N2}, depending on the model used)

G: Grading of the technology for each criterion, typically on a scale from 1 to 5, where 1 represents poor performance and 5 represents excellent performance.

Eq (4.4) means when calculate the individual contribution of each criterion to the overall assessment of one technology based on its performance. The grading G reflects how well a technology achieves the goals set within a particular criterion, multiplied by the importance of the selected criterion as established by W_N.

For the final score for each technology, to summarize all the scores for each criterion as Eq (4.5).

$$S_T = \sum (S_c)_{all\ criteria} \quad (4.5)$$

Where:

S_T: Total score for all technology

S_c: Score for selected criterion, calculated as per Eq 4.4

An example from the Chalmers workshop is shown in Table 5.

Table 5 Example of Percentage-based weighting model from Chalmers workshop

Criteria	Group1	Normalized weighting(%)	Scores Alt. 1	Scores Alt. 2	Scores Alt. 3
			AS	MBR	AGS
life Cycle Cost	15	23%	3,6	3,1	5,0
Stable Operation	18	28%	4,0	3,0	5,0
Flexibility	8	12%	2,0	5,0	4,0
CO2 Footprint	8	12%	5,0	4,8	5,0
Energy Consumption	10	15%	4,3	2,2	5,0
Working Environment and Safety	6	9%	4,0	2,0	5,0
Total Score			3,8	3,3	4,9

The six sustainability factors were used to evaluate the wastewater treatment alternatives. The percentage-based weights were assigned to each criterion, ensuring they sum to 100%. Each alternative receives a performance score for each criterion. To calculate the final weighted score for each alternative, the normalized weight of each criterion is multiplied by the respective alternative's score. The total weighted scores for each alternative are then summed to determine the overall performance ranking. In Table 5, alternative AGS (Alt.1) has a final score of 4.9, which suggests it performed best among the alternatives. A higher score presents a better overall sustainability performance based on the assigned criteria and weights.

4.4 Workshops Overview

To test and validate the application of the WSR method in enhancing the decision-making process, two workshops were conducted. The first workshop involved students from an advanced wastewater engineering course, while the second engaged wastewater experts from LBVA. These workshops aimed to compare the effectiveness of the WSR method against traditional percentage-based and value-based models. The graded results of the Västra Stranden case study were used as an example.

4.4.1 Workshop with Chalmers students

This workshop was designed to introduce participants to MCA process and to test different weighting models in a controlled educational setting. Eighteen students from the ACE040 Advanced Wastewater Engineering course were divided into nine groups of two.

Workshop Structure and Activities:
The workshop was structured into two main sessions: an introductory presentation on MCDA concepts and a hands-on application of two weighting models as shown in the flow chart.

Session 1 Introduction to MCA and case study:
Students were introduced to MCA concepts based on the methodology described by Maria Neth, 2023. A detailed presetation was delivered on Västra Stranden WWTP case study, which focused on three alternative wastewater treatment technologies: Activated Sludge (AS), Membrane Bioreactor (MBR), and Aerobic Granular Sludge (AGS).

Students received comprehensive background information on the differences among the treatment process. Also including factors such as footprint reduction (e.g., Integrated fixed film Activated Sludge (IFAS) offers a 60% reduction, while MBR and AGS offer 25% reductions), land area requirements, electricity demand, and chemical consumption. Emphasis was placed on the importance of assessing technologies from multiple sustainability perspectives-social, environmental and economic to make the most informed decision.

Session 2 Application of weighting models
Following the introduction, students engaged in applying the two weighting models to the criteria established for Västra Stranden WWTP case study. This session allowed students to practically for the Västra Stranden WWTP case study. In this session was designed to allow students to apply the theoretical knowledge they learned to real life scenarios through exercise. Before start session, each group received data on six criteria spanning the sustainability dimensions. Quantitative metrics provided included life cycle cost, CO_2 footprint, and energy consumption. The whole workshop process is summarized in Figure 6.

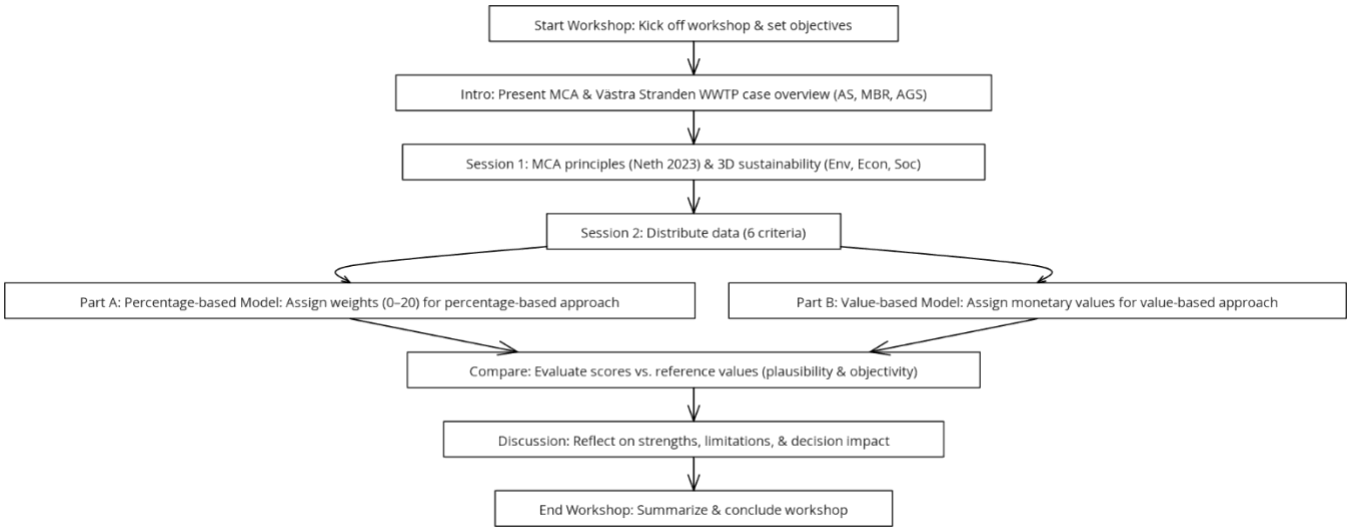


Figure 6 Workshop flowchart – Chalmers. Students' MCDA exercise

4.4.2 Part A: Percentage-based weighting model

In this part of the workshop, students were introduced to the percentage-based weighting model. A classic MCA approach weights are assigned directly to each sustainability criterion. Students rated weights from 0 to 20 to each sustainability criterion, without reference to external benchmarks. Before starting the hands-on task, students were shown an illustrative example to help them understand the model. In Figure 7 , it means how weights were initially assigned across three sustainability dimensions—Environmental, Economic, and Social—with each criterion evenly weighted at 16.7%, totaling 100%. This served as a neutral baseline for comparison.

Dimension	Criteria	Weight	Scores Alt. 1	Scores Alt. 2	Scores Alt. 3
Environmental	Crit. 1	16.7%	2	3	4
	Crit. 2	16.7%	4	3	2
Economic	Crit. 3	16.7%	2	1	5
	Crit. 4	16.7%	2	5	3
Social	Crit. 5	16.7%	4	3	4
	Crit. 6	16.7%	1	3	2
		Total score	***2.5***	***3***	***3.3***

Figure 7 Example of Percentage-based weighting model across three sustainability dimensions

After reviewing the example, students engaged in a hands-on activity where they determined and assigned weights to each criterion based on their own assessments of importance. To facilitate this process, each group of students received a blank weighting template (Table 6). Students were instructed to assign weights from 0 (no importance) to 20 (highest importance). This scale was selected to simplify the allocation process and allow for detailed prioritization of the criteria. Additionally, they also had to provide a short justification in the "Comment (why)" column, explaining why they gave each criterion a specific weight.

Table 6 Workshop criteria weighting template for part A: input weighting to evaluate each criterion

Group number:

Part A: input Weighting to evaluate each Criteria

Criteria	Weightng (0-20)	Comment(why)
life Cycle Cost		
Stable Operation		
Flexibility		
CO2 Footprint		
Energy Consumption		
Working Environment and Safety		

4.4.3 Part B: Value-based weighting model

In Part B, students worked with the Value-Based Weighting Model, focusing on monetary weighting of each sustainability criterion. Unlike Part A, which used a scale from 0–20, this part required assigning monetary values to represent the cost or impact of each criterion. Each group completed Table 7, where the criteria were listed alongside suggested units (e.g., SEK/kg CO_2eq for CO_2 emissions, SEK/kWh for energy consumption).

Table 7 Workshop criteria weighting template for part B: input costs per criterion

Group number:

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost		Fixed	
Stable Operation		SEK/year/Grade	
Flexibility		SEK/year/Grade	
CO2 Footprint		SEK/kg CO2eq	
Energy Consumption		SEK/kWh	
Working Environment and Safety		SEK/year/Grade	

To help students critically assess the financial impact of each criterion, they were prompted with guiding questions during the session, such as: “How much does CO2 emission cost in the current carbon market?"; "What financial considerations are involved if an employee is paid to enhance workplace safety?"; "What is the current cost of electricity per kWh in Sweden?". These questions encouraged students to link sustainability criteria with real-world market values.

Meanwhile, students were encouraged to refer to current market data or reliable databases. For example, a reference value for CO2 emissions was shown during the workshop, based on the European Emissions Trading System (ETS). According to the ETS:

- 1 kg of CO_2 ≈ **0.089 EUR**
- 1 EUR ≈ **12 SEK**
- Therefore, 1 kg of CO_2 ≈ **1.068 SEK/kg**

4.4.4 Workshop with LBVA

A workshop was held with professionals from Laholmsbuktens VA (LBVA), the regional authority responsible for wastewater management. The purpose of the workshop was to test and refine the MCA model in a real-world setting, using the case of Västra Strandens WWTP in Halmstad. The workshop focused on applying the value-based weighting model to support decision-making regarding future technology choices for the plant's upgrade. Three alternative technologies were evaluated during the session. The key objective was to determine which option was most aligned with long-term sustainability goals while also being practical and cost-effective.

The workshop process involved assigning monetary values to each sustainability criterion. This was done through a structured discussion among LBVA professionals, who shared insights based on their operational experience, knowledge of the wastewater sector, and awareness of market trends. Each participant contributed by referencing national benchmarks, historical project data, and LBVA's internal sustainability targets.

Through group discussions, the experts agreed on minimum and maximum values for each criterion. These values were intended to reflect both current costs and anticipated future developments, helping to ensure the model remained relevant and forward-looking. The goal was to capture not only present market conditions but also expected regulatory and operational changes up to 2050.

Table 8 was gave to the LBVA when during the workshop.

Table 8 Value Ranges for Sustainability Criteria from LBVA Workshop

Criteria	Units	Weighting	Min	Max
Stable Operation	SEK/yr/Grade			
Flexibility	SEK/yr/Grade			
CO2 Footprint	SEK/ton CO2eq			
Energy Consumption	SEK/kWh			
Working Environment and Safety	SEK/yr/Grade			

It summarizes the criteria used during the workshop, including the unit of measurement and the value ranges (minimum and maximum) determined by the expert group.

During the session, LBVA experts reviewed reference data and aligned their inputs through consensus. The final set of values and weightings were shaped by both practical experience and shared understanding of the sector's trends and needs. This helped ensure that the model outputs were grounded in realistic assumptions and could support robust sustainability decisions for the Västra Strandens upgrade.

Figure 8 Photo from LBVA workshop when grading each criterion.

4.5 Comparison with reference values

This section presents reference values used to guide the value-based weighting model. This can ensure assigned costs are aligned with market prices, national goals, and industry standards. These values also support the sensitivity analysis by establishing minimum and maximum weighting boundaries for each criterion. Reference values for criteria such as SEK/CO2e, SEK/kWh, were sourced from national and local sustainability goals; previous MCA studies; European and Swedish government agencies, Market data and investment benchmarks.

4.5.1 Climate impact

The EU Emissions Trading Scheme (EU ETS) sets the market price for carbon emissions. As of 2024, the price reached 868.5 SEK/ton CO_2 (Carbon credits , 2024). Various estimates from previous multi-criteria analyses and local and national goals also provide valuable reference points for assessments.

For example, Sweden has set targets for carbon pricing and emissions reductions. According to recent data, the cost per ton of CO2 in Sweden ranges from 550 SEK for large volumes, as per IPCC standards, to 7,000 SEK for long-term strategies proposed by the Swedish Transport Administration (Trafikverket, 2020).

The detail of climate impact for CO2 is shown in Table 9.

Table 9 Reference Values – Climate Impact of CO_2 (SEK/ton)

Climate impact for CO2	SEK/ton CO2
Large volume according to IPCC	550
Emission rights	1000
Investments today	1500
More expensive measures globally	2200
Long-term measure	3000
More expensive measures in Sweden?	4400
Long-term strategies proposed by Swedish Transport Administration (Trafikverket, 2020)	7000

4.5.2 Energy consumption

While energy use is included in overall operational costs, its additional environmental and efficiency value justifies separate consideration. The cost of producing electricity varies depending on the source.

Table 10 Reference Values – Energy Cost (SEK/kWh)

Using Renewable energy	SEK/kWh	Future
New nuclear power	1	?
New wind power	0,3	?

In Table 10, new nuclear power is estimated to cost around 1 SEK per kWh, while new wind power is significantly cheaper at 0.3 SEK per kWh. These costs are subject to change based on future technological advancements and policy changes.

4.5.3 Working environment and safety

Workplace costs were based on annual staff salaries, assuming a typical worker earns 700,000 SEK/year. Costs are then scaled based on the degree of improvement (grading difference between alternatives). Table 11 presents reference values for different shares of worker cost. The final cost is divided based on the grading between AS and MBR for the work environment.

The reference values for the work environment are detailed in Table 11 below.

Table 11 Work Environment Cost Comparison

Share of Annual Worker (%)	SEK/year	1 Step	2 Steps
200	1400000	1 400 000	700 000
100	700 000	700 000	350 000
50	350 000	350 000	175 000
10	70 000	70 000	35 000
5	35 000	35 000	17 500
2	14 000	14 000	7 000

4.5.4 Flexibility

Flexibility is assumed to represent a percentage of the total life cycle cost (LCC), estimated at 20 MSEK/year. Table 12 shows reference values per grade step, while Table 13 adds land cost estimates as an alternative basis for calculating flexibility costs.

Table 12 Reference Values – Flexibility Cost (Based on LCC)

LCC (%)	MSEK/year	MSEK/year per Grade
20	4	1,33
10	2	0,67
5	1	0,33
0,5	0,1	0,03

For the flexibility, the space requirement and land price can be considered as well. The land Market price for 600 SEK/m2 in Sweden. The price of each area can be calculated in Table 13. Moreover, due to only AS evaluated by experts is 2, so price per step divided by 3.

Table 13 Reference Values – Land Market Cost for WWTP Expansion

Area	Area m2	Price (SEK)	Price per step (SEK)
A	4 600	2 760 000	1 380 000
B	3 000	1 800 000	900 000
C	7 100	4 260 000	2 130 000
D	2 500	1 500 000	750 000

4.5.5 Stable operational

We assume the whole life cycle cost (LCC) to be 20 MSEK/year. Stable operation is measured by how much percentage of the total cost it occupies. The reference values for stable operation are detailed in Table 14.

Table 14 Reference Values – Stable Operation Costs

How much of LCC (%)	MSEK/year	MSEK/year per Grade
20	4	1,33
10	2	0,67
5	1	0,33
0,5	0,1	0,03

5 Result

This chapter presents the results from the data preparation for selected criteria, the weighting assigned to each criterion by different student groups, their commentary on each criterion, and expert evaluations from the LBVA group.

5.1 Results from Chalmers students in percentage-based model

This section summarizes the outputs from student exercise described in sections 4.2.1 and 4.2.2. Specifically, it evaluates the weighting distributions from the Percentage-Based Model (discussed in section 4.1.1) applied by the students during the Chalmers Workshops.

5.1.1 Overview of Percentage-based Weightings

The weightings assigned by student groups to each criterion varied, reflecting diverse priorities and perspectives on sustainability. Students assigned a numerical number from 1- 20 which means 1 is the less important, 20 is the best case. The raw scores from the nine student groups are presented in Table 15.

Table 15 Raw weightings assigned by student groups in Part A

Criteria	Weighting (1-20)								
	G1	G2	G3	G4	G5	G6	G7	G8	G9
life Cycle Cost	16	15	10	19	17	16	7	17	16
Stable Operation	19	18	16	18	18	14	13	16	19
Flexibility	15	8	8	12	15	12	9	8	12
CO2 Footprint	10	8	11	15	20	15	12	15	17
Energy Consumption	18	10	15	20	17	16	10	12	16
Working Environment and Safety	20	6	18	14	19	18	19	5	18

To enable fair comparison across groups, the raw scores were normalized to express each criterion's weight as a percentage. The normalized results are shown in Table 16. Each group's normalized weighting shows how they distributed the total 100% importance across all six criteria. This allows the differences between group preferences to be compared on a consistent scale.

Table 16 Result from nine groups students after normalized weighting

Criteria	Weighting(1-20)								
	G1	G2	G3	G4	G5	G6	G7	G8	G9
life Cycle Cost	16%	23%	13%	19%	16%	18%	10%	23%	16%
Stable Operation	19%	28%	21%	18%	17%	15%	19%	22%	19%
Flexibility	15%	12%	10%	12%	14%	13%	13%	11%	12%
CO2 Footprint	10%	12%	14%	15%	19%	16%	17%	21%	17%
Energy Consumption	18%	15%	19%	20%	16%	18%	14%	16%	16%
Working Environment and Safety	20%	9%	23%	14%	18%	20%	27%	7%	18%

5.1.2 Weighting distribution and Student comments

Integrating insights from Figure 9, Table 16 and selected group comments, the summary as follow.

Life Cycle Cost range from 10% to 23%, showing varied assessments of economic sustainability. G1 (16%) and G2 (23%) highlighted the importance of minimizing operational and total lifecycle costs, respectively. G1 focused on keeping operational costs low, while G2 emphasized avoiding frequent large investments.

Stable Operation received high weightings, up to 28% by G2, reflecting its perceived importance for ensuring uninterrupted plant operation. G2 commented that a stable operation reduces maintenance costs and prevents malfunctions, which is crucial for the plant's continuous performance.

Flexibility ranged from 10% to 15%, indicating different views on the need to adapt technologies to future demands and regulatory changes. The moderate emphasis suggests that while important, flexibility is secondary to more immediate operational concerns.

CO2 Footprint emphasized with weightings from 10% to 21%, reflecting growing environmental concerns. G4 (15%) specifically noted that CO2 emissions are a critical factor due to their environmental impact, advocating for it to be considered significantly in decision-making.

Energy Consumption received consistent attention with weightings between 14% to 20%. G9 highlighted the importance of sustainable energy usage, suggesting the use of energy from sludge waste as a sustainable practice.

Working Environment and Safety showed the widest range in weightings from 7% to 27%, with G9 emphasizing safety and the minimization of environmental impact on the nearby community as paramount. They stressed that processes should not adversely affect the surrounding environment through odor, noise, or pollution.

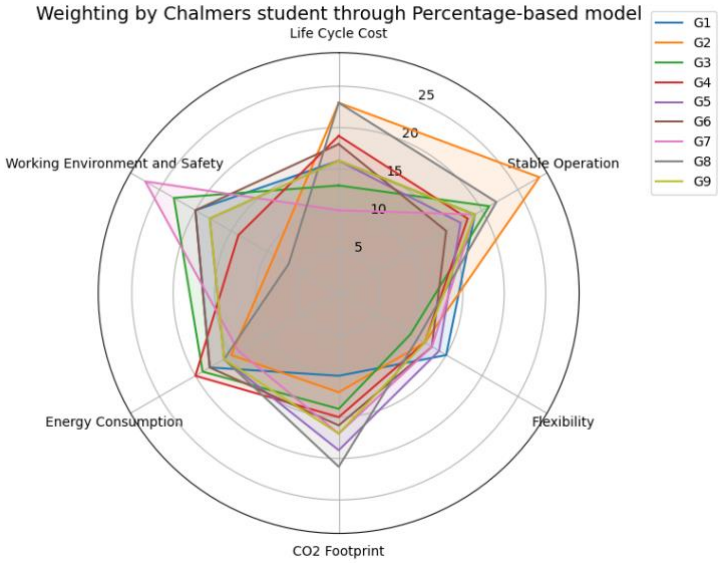


Figure 9 Radar chart for Chalmers students by using the percentage-based model

5.1.3 Percentage-based model performance evaluation

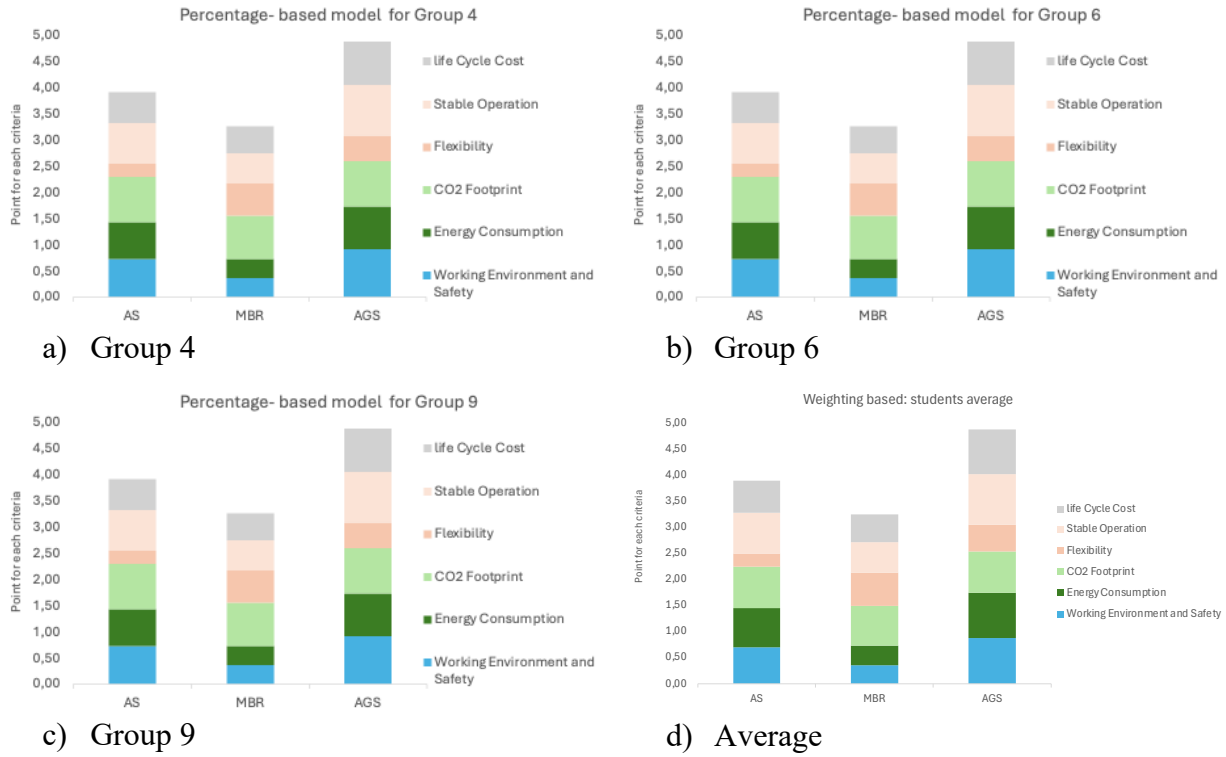
The final scores for all alternatives (AS, MBR, AGS), based on the weighting and grading provided by the student groups, are summarized through a series of composite figures. These are summarized in Table 17.

Table 17 Final Weighted Scores for Alternatives (Percentage-Based Model)

	Score (weigting*grade)				
Alternatives	AS	MBR	AGS	Highest	Lowest
G1	3,8	3,2	4,8	AGS	MBR
G2	3,8	3,3	4,9	AGS	MBR
G3	3,9	3,1	4,9	AGS	MBR
G4	3,9	3,2	4,9	AGS	MBR
G5	3,9	3,3	4,9	AGS	MBR
G6	3,9	3,2	4,9	AGS	MBR
G7	3,9	3,2	4,9	AGS	MBR
G8	3,9	3,4	4,9	AGS	MBR
G9	3,9	3,3	4,9	AGS	MBR
Average	3,9	3,2	4,9	AGS	MBR
Median	3,9	3,2	4,9	AGS	MBR

Figure 10 shows the application of the Percentage-based model across different perspectives, including Groups G4, G6, G9 and average. These charts help to see how each group's weightings change the total scores. The y-axis shows the six criteria. The x-axis shows the three technology options. Each color shows how much a criterion affects the result.

Even though the groups gave different weights to the criteria, the final results for each alternative are not very different. The changes in ranking are small. All groups used the same grading scale and had similar ideas about what matters most. That kept the results from being too different.



a) Group 4 b) Group 6

c) Group 9 d) Average

Figure 10 Comparison of percentage-based weightings across selected student groups (G4, G6, G9) and average

Group 4 talked about the Life Cycle Cost. They said that large, frequent investments should be avoided. Group 6 said that high-cost technologies may not work in the long run. Group 9 said that the project should stay affordable and efficient.

For Stable Operation, Group 4 said that the system should need little maintenance and run reliably. Group 6 linked stability to long-term savings. Group 9 said that if the plant fails, it could cause environmental and financial problems.

Flexibility was seen as useful, but not the most important. Group 4, Group 6, and Group 9 all agreed that being able to handle future changes is a benefit.

Group 4 said that CO_2 emissions are a big environmental concern. Group 6 and Group 9 said that carbon impact matters when thinking about long-term sustainability.

Group 4 and Group 6 said that energy use is tied to cost and efficiency. Group 9 said that using energy from waste, like sludge, is a smart way to save resources.

Group 4 and Group 9 said that safety and health at work are very important. They said that the plant should not harm workers or nearby people. Group 6 also said safety matters and that no group should be put at risk.

5.2 Results from Chalmers Students and LBVA in Value-based model

This section evaluates the economic considerations of various sustainability criteria, as weighted by Chalmers students and LBVA experts using the Value-based model discussed in section 4.1.2. Presented through a series of box plots, this analysis visualizes the range and distribution of value-based assessments applied during the Chalmers workshops, detailing the methodology outlined in section 4.1.

5.2.1 Overview of Value-Based Weightings

Based on the values and reference points for each criterion in Session 4.5 Comparison with reference values, each student group and LBVA assigned their unique value-based weightings. These weightings reflect diverse economic valuations of operational and environmental factors across different student groups and expert assessments. Table 18 collates these weightings, offering a detailed comparative view.

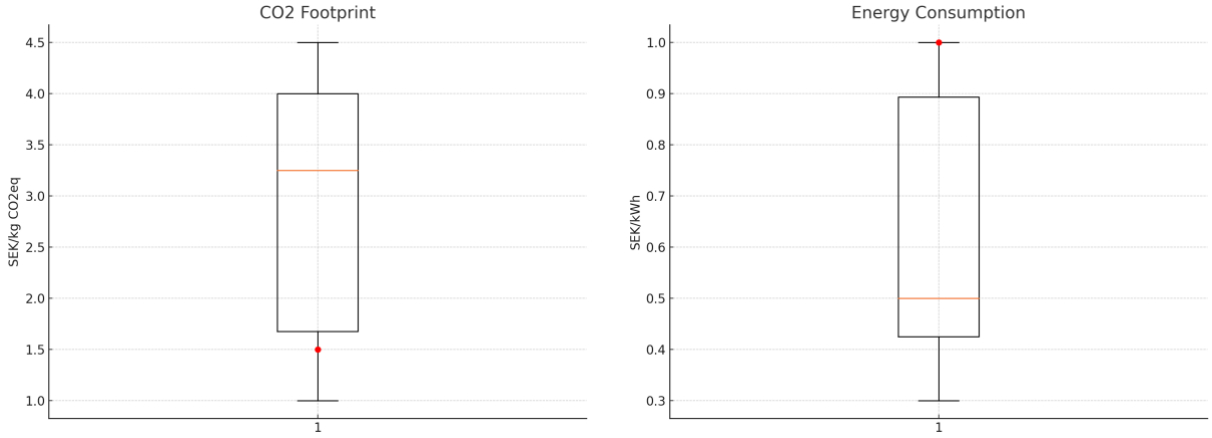
Table 18 Value-based weightings assigned by Student groups and LBVA

Group	Stable Operation	Flexibility	CO2 Footprint	Energy Consumption	Working Environment and Safety
Unit	SEK/yr/Grade	SEK/yr/Grade	SEK/kg CO2	SEK/kWh	SEK/yr/Grade
1	2 000 000	670 000	2,2	0,300	525 000
2	2 000 000	1 000 000	3,5	0,650	200 000
3	1 340 000	15 000	1,0	0,975	4 000 000
4	1	1	4,0	0,400	200 000
5	1 000 000	30 000	1,5	0,500	117 000
6	1 000 000	330000	4,0	0,500	350 000
7	4 000 000	3 000 000	4,0	1,000	15 000
8	670 000	330 000	3,0	0,500	175 000
9	1 000 000	670 000	4,5	0,300	175 000
LBVA	3 500 000	750 000	1,5	1,000	175 00

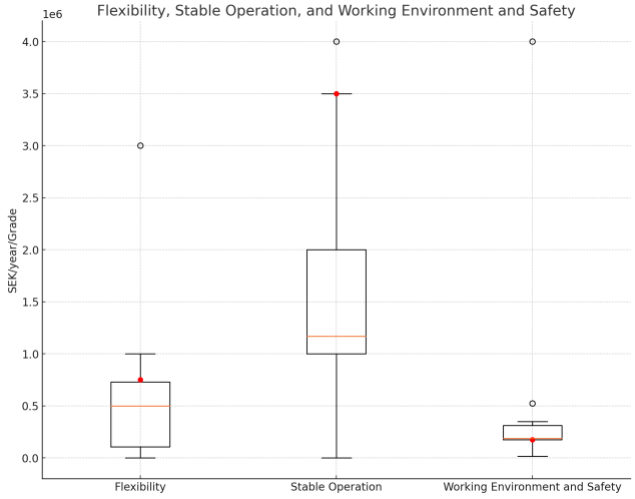
These numbers show that student groups had very different ideas. Some focused more on environmental impact. Others gave higher cost to workplace safety or reliability. LBVA gave high values to stable operation and energy use, which shows they value long-term stability and cost-saving. Each group used the same units, which makes it easy to compare. All weights are in SEK and follow a cost-per-impact format. For example, CO_2 is priced in SEK per kg. Energy use is priced per kWh. Safety and technical values are priced per year and per grade level.

5.2.2 Comments in the value-based model

Based on how students and LBVA experts assigned economic values to five criteria in the Value-Based Model. The box plot in Figure 11 a-c provides the distributions of cost estimates vary across the criteria (in SEK per grading step per year) assigned by students and LBVA experts to five criteria: Stable Operation, Flexibility, CO_2 Footprint, Energy Consumption, and Working Environment and Safety. LBVA values are marked with red dots, and outliers are indicated. observe that the distributions of cost estimates vary across the criteria. These box plots show how much student input varied. Some groups gave much higher or lower values than others. The red dots show where expert opinion stands in comparison.



a.) CO2 Footprint b.) Energy Consumption



c.) Flexibility, Stable Operation, and Working Environment and Safety

Figure 11 a-c Box plots showing distribution of value-based weights across all groups

Stable operation ranged from 1 to 4,000,000 SEK/yr/Grade. Group 7 gave the highest value. They said that stable operation is important to avoid both environmental and technical problems. Group 4 gave the lowest value. They believed that current systems are already stable and do not need more investment. Group 1 gave 2,000,000 SEK. They said that following regulations and protecting the environment are important. Group 9 gave 1,000,000 SEK. They wanted to make sure the system runs continuously without issues. Group 3 said that stable systems need less maintenance.

Flexibility ranged from 1 to 3,000,000 SEK/yr/Grade. Group 7 again gave the highest value. They said that being able to adjust for future changes is very important. Group 4 gave the lowest value. They thought that no extra flexibility is needed now. Other groups talked about future needs. These include changes from climate effects, population growth, and new rules.

CO2 Footprint ranged from 1 to 4.4 SEK/kg CO2eq. Group 9 gave the highest value. They said that meeting climate rules is very important. Group 3 gave the lowest value. They placed less focus on CO_2 because they had other concerns. Group 1 gave 2.2 SEK per kg. They said that climate change matters, but budgets are limited.

Energy Consumption ranged from 0.3 to 1 SEK/kWh. Group 7 assigned the highest weighting of 1 SEK/kWh, recognizing the significant costs associated with energy usage which was also relative to energy efficiency. Groups 1 and 9 both assigned the lowest weighting of 0.3 SEK/kWh, indicating a focus on maintaining energy costs at a manageable level. Group 9 assigned 0.3 SEK/kWh, emphasizing the importance of sustainable energy consumption, such as using energy from sludge waste.

Working Environment and Safety: weights for working environment and safety ranged from 15,000 to 4,000,000 SEK/yr/Grade. Group 3 assigned the highest weighting of 4,000,000 SEK/yr/Grade, showing a strong commitment to improving workplace safety and conditions. Group 7 assigned the lowest weighting of 15,000 SEK/yr/Grade, possibly indicating that existing safety measures are deemed sufficient. Group 1 and 9 assigned 525,000 and 175,000 SEK/yr/Grade, prioritizing compliance with laws and the protection of workers which also have impact with the nearby society.

5.2.3 Normalized weighting analysis

After collecting the weightings from both the student groups and LBVA, the next step was to normalize the data. This helped to make the values easier to compare. Each criterion had different units and scales. Normalization allowed them to be put on the same level.

The method followed the value-based model. For quantifiable criteria, the cost was multiplied by the value per grade step. For non-quantifiable criteria, the cost was used directly. The results were then scaled in relation to the cost value used for the life cycle cost. This step gave a set of percentages showing how much weight each criterion received. The normalization showed priority between LBVA and the student groups and is summarized in Table 19.

Table 19 The weights distributed to each criterion, resulting in weight distribution percentages for value-based model.

Criteria	unit	LBVA	Normalized weighting(%)	Student average	Normalized weighting(%)
life Cycle Cost	Fixed	1	24%	1	31%
Stable Operation	SEK/year/Grade	3 500 000	21%	1 400 000	7%
Flexibility	SEK/year/Grade	750 000	5%	710 000	3%
CO2 Footprint	SEK/kg CO2eq	1,5	39%	3,1	62%
Energy Consumption	SEK/kWh	1	4%	0,6	2%
Working Environment and Safety	SEK/year/Grade	175 000	1%	640 000	3%

There is a clear difference in how some criteria were valued. LBVA gave more weight to stable operation. This shows that experts believe reliability is key. Students, on the other hand, gave more weight to the CO_2 footprint. This suggests students focused more on the environmental side. The results show different ways of thinking between students and professionals.

5.2.4 Final score

To get the final scores for each alternative, we used the cost values from each group. For quantifiable criteria, we multiplied the cost by the value per grade step. For non-quantifiable criteria, the cost was used directly as the weight. After that, each value was normalized by dividing it by the value of the grade step for life cycle cost. This gave a set of weighted scores for each group and each technology. The final scores for each alternative based on cost input are shown in Table 20.

Table 20 Final scores for alternatives in value-based model

Score = Weightings*Grade					
Alternatives	AS	MBR	AGS	Highest	Lowest
G1	4,3	4,0	5,0	AGS	MBR
G2	4,5	4,2	5,0	AGS	MBR
G3	4,2	3,2	5,0	AGS	MBR
G4	4,7	4,4	5,0	AGS	MBR
G5	4,3	3,9	5,0	AGS	MBR
G6	4,6	4,3	5,0	AGS	MBR
G7	4,3	4,2	4,9	AGS	MBR
G8	4,5	4,2	5,0	AGS	MBR
G9	4,6	4,4	5,0	AGS	MBR
LBVA	4,2	3,8	5,0	AGS	MBR
Student average	4,4	4,1	5,0	AGS	MBR

The results show that AGS received the highest score in every group. It was rated 5.0 by most groups, including LBVA. AS had a moderate score. The average score for AS was 4.4 from students and 4.2 from LBVA. MBR got the lowest score. It received 3.8 from LBVA and an average of 4.1 from students.

5.2.5 Value-based model performance

Table 21 shows the value-based model results for both LBVA and student groups. It includes their average, minimum, and maximum weightings. This helps compare how each group thinks about the importance of each sustainability criterion.

Table 21 Comparison of value-based weightings between LBVA and students

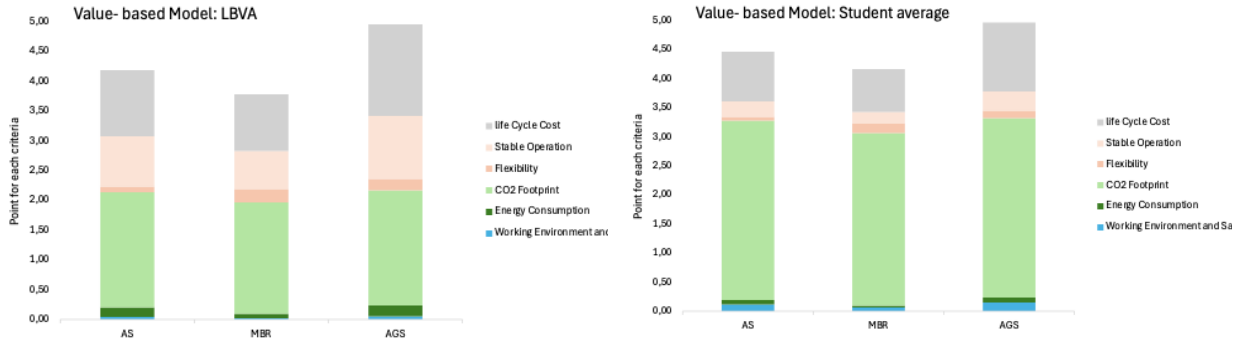
Criteria	unit	LBVA	LBVA max	LBVA min	Student average	Student max	Student min
Stable Operation	SEK/year/Grade	3 500 000	3 500 000	2 500 000	1 400 000	4 000 000	1
Flexibility	SEK/year/Grade	750 000	2 000 000	200 000	710 000	3 000 000	1
CO2 Footprint	SEK/ton CO2eq	1 500	3 000	500	3 100	4 500	1 000
Energy Consumption	SEK/kWh	1	3	0	0,6	1	0,3
Working Environment and Safety	SEK/year/Grade	175 000	250 000	25 000	640 000	4 000 000	15 000

To have a horizontal comparison of selected data as shown in Figure 12. It includes panels for average, best-case, and worst-case values from both LBVA and the student groups. This setup facilitates a direct comparison across several dimensions:

In the average weighting panels (Figure 12 a and b), both LBVA and students gave the most weight to the CO_2 footprint. This is shown by the green bars. After that, both groups also gave importance to life cycle cost. The main difference is in the smaller criteria. Students gave more weight to the working environment. LBVA gave more weight to energy consumption. This shows a difference in priorities.

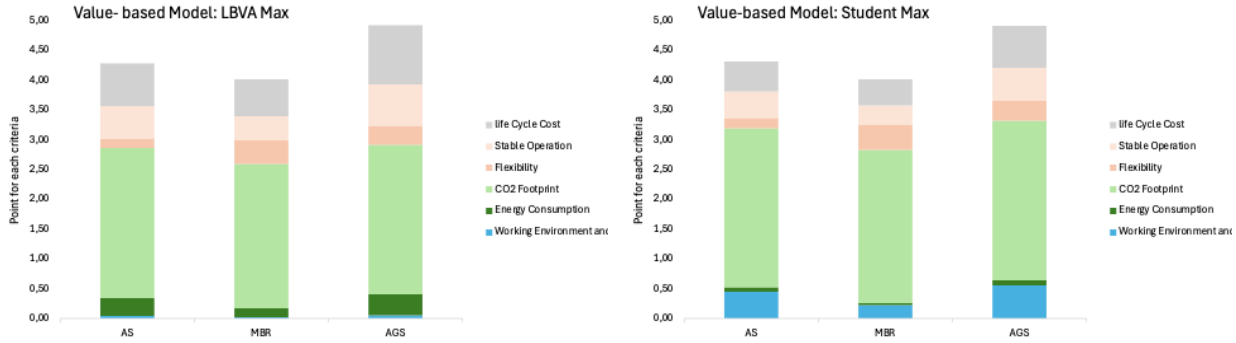
In the worst-case weighting panels (Figure 12 c and d): these scenarios reflect the highest potential economic impacts across all criteria. These panels show the conditions where the financial consequences of each criterion are the maximized. While both LBVA and students showed the similar weighting patterns for most criteria. The main differences appeared in the importance given to energy consumption and working environment. These two criteria were weighted differently between the groups. This means LBVA and students weighted these two areas differently when thinking about high-cost situations.

In the best-case weighting panels (Figure 12 e and f): these scenarios reflect where cost impacts are minimized, under this case, both groups consider life cycle cost as the most dominant criterion. Which means when everything else is considering low cost, long-term cost becomes the main concern. LBVA also gave more weight to stable operation, which mean they value reliability. On the other hand, students cared more about environmental impact and saving energy. This means they focused on green outcomes when money was less of a problem.



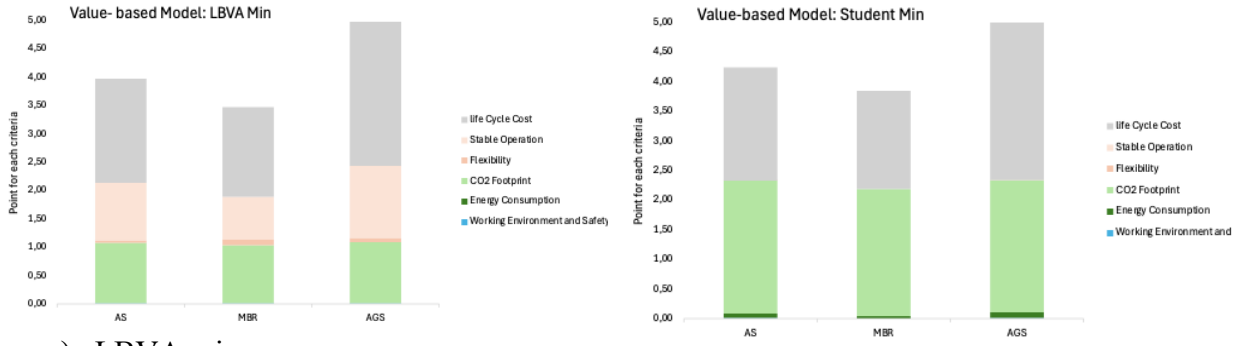
a) LBVA

b) Student average



c) LBVA max

d) Student max



e) LBVA min

f) Student min

Figure 12 a-e Different criteria panel chart for selected data in Comparison of Value-Based weightings Between LBVA and Students

6 Sensitivity analysis

This chapter presents the sensitivity analysis for the results of the study. The purpose is to check how the results change when the input data changes. This helps to see how stable and reliable the findings are. The analysis is done by changing the input costs while keeping the grading fixed.

6.1 Sensitivity analysis for LBVA data

During the LBVA workshop, experts gave not only the weightings but also the minimum and maximum cost values for each criterion. These are used here for the sensitivity test.

To do this, we test each alternative one at a time. The steps are as follows:

1. One technology is selected at a time for the analysis.
2. Criteria grading: identify which criteria the selected alternative scored higher than the other two alternatives.
3. Cost input adjustment: For the criteria where the selected alternative scored higher, we apply the maximum cost from LBVA. For the criteria where it scored lower, we apply the minimum cost. The life cycle cost is fixed and does not change in this analysis.

Table 22 Grading from experts for sensitivity analysis with green maker

Criteria	Betyg/grade from expert(1-5)		
	AS	MBR	AGS
life Cycle Cost	3,6	3,1	5
Stable Operation	4	3	5
Flexibility	2	5	4
CO2 Footprint	5	4,8	5
Energy Consumption	4,3	2,2	5
Working Environment and Safety	4	2	5

Table 22, as shown with the green marker, the criteria will be input as the maximum cost. The life cycle cost is fixed and not engaged in the sensitivity analysis. For AS, only the CO2 criterion will use the maximum cost from LBVA, while other criteria will use the minimum cost.

4. Evaluation: adjust the input data for each alternative based on the criteria and recalculate the final scores. Table 23 below shows the input data used for the sensitivity analysis

Table 23 Input data for sensitivity analysis

Criteria	Input data for sensitivity analysis				
	Min	Max	input for AS	input for MBR	input for AGS
life Cycle Cost	1	1	1	1	1
Stable Operation	2 500 000	3 500 000	2 500 000	2 500 000	3 500 000
Flexibility	200 000	2 000 000	200 000	2 000 000	200 000
CO2 Footprint	0,55	3	3	0,55	3
Energy Consumption	0	3	0	0	3
Working Environment and Safety	25 000	250 000	25 000	25 000	250 000

6.2 Result and discussion of sensitivity analysis for LBVA data

The sensitivity analysis checks how changing the input costs affects the final scores of each technology: AS, MBR, and AGS. Table 24 and Figure 13 below summarized the final scores for each alternative under different sensitivity scenarios and illustrate the differences between AGS and AS, and AGS and MBR.

Table 24 Final scores and differences under sensitivity scenarios

Sensitivity Scenario	AS	MBR	AGS	AGS-AS	AGS-MBR
original value	4,2	3,8	4,9	0,77	1,11
Best for AS	4,5	4,2	4,9	0,49	0,83
Best for MBR	3,7	3,7	4,8	1,14	1,10
Best for AGS	4,5	4,1	4,9	0,52	0,90

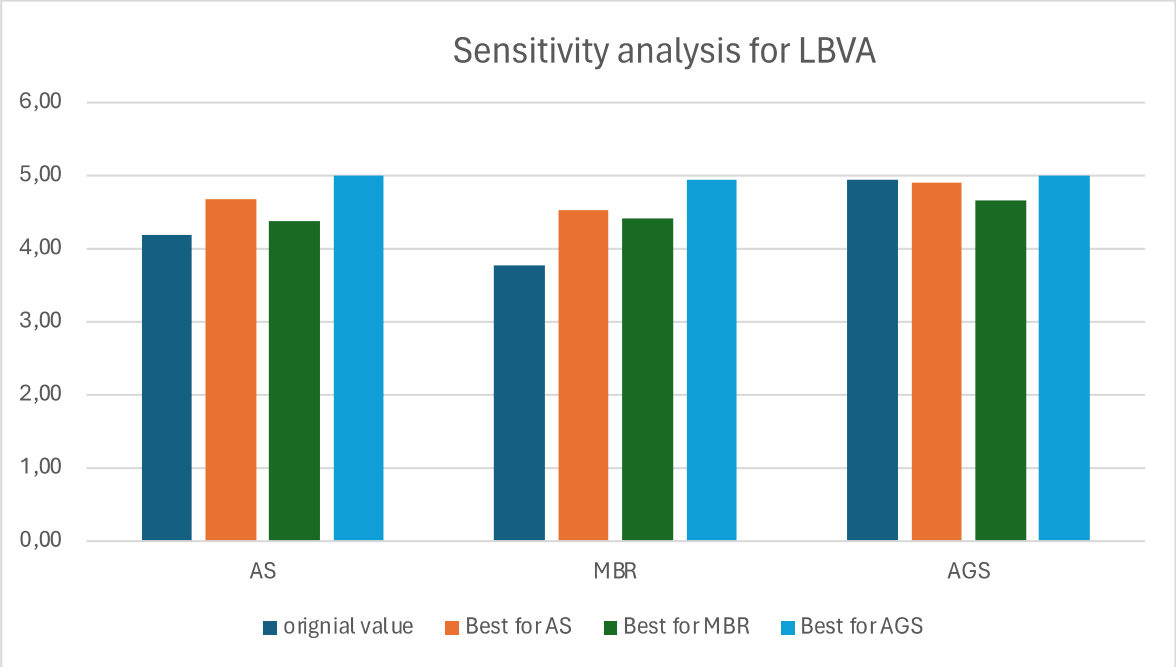


Figure 13 Sensitivity analysis for LBVA data

The sensitivity analysis shows how changing the cost inputs for each criterion affects the overall scores of the alternatives (AS, MBR, AGS). When the best-case scenario for AS is considered in Figure 14, the CO2 footprint criterion is assigned the maximum cost, while minimum costs are assigned for the other criteria. The adjustment increases AS's score from 4.2 to 4.7. In particular, the scores for MBR also increase, while AGS's score decrease slightly. This is because when the cost for CO2 is higher, AGS's advantage diminishes due to its higher CO2 emissions. Conversely, MBR and AS both benefit from this scenario, which means their relative efficiency in CO2 management when cost constraints are relaxed.

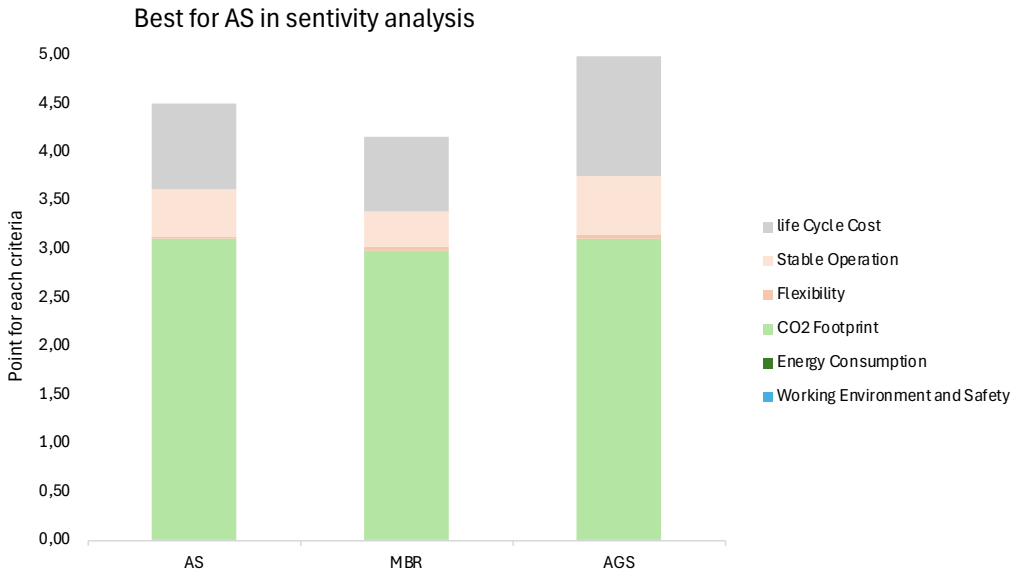


Figure 14 Sensitivity analysis_ when Activated sludge considered as best case.

In the best-case Figure 15 for MBR, we apply the highest cost to flexibility. The other criteria use the lowest cost. MBR's score goes up to 4.2. This is because flexibility becomes more important. If more cost is given to improve flexibility, MBR becomes more effective. AGS loses some advantage here because its lead in flexibility becomes smaller.

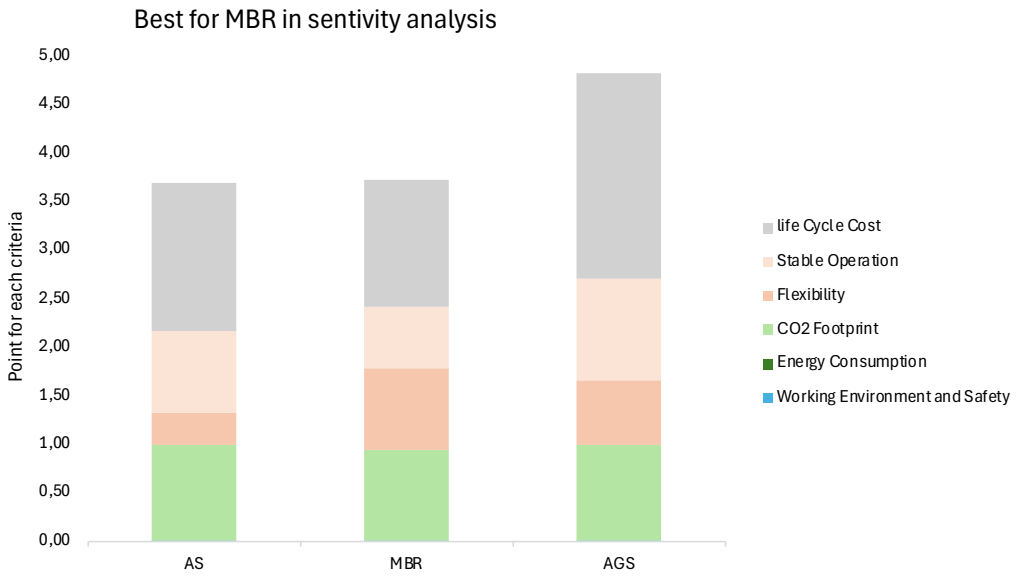


Figure 15 Sensitivity analysis_ when Membrane bioreactor considered as best case.

Figure 16 involves assigning maximum costs to the stable operation, energy consumption, and working environment and safety criteria, with minimum costs for remaining criteria. This results in AGS's score increasing from 4.95 to 5.00 which show AGS is reaching out to the highest score (best case). Interestingly, MBR and AS's scores also increase under this scenario, but not surpass AGS. As if the investment is good enough for all criteria, which make all alternatives show the same priority to each other.

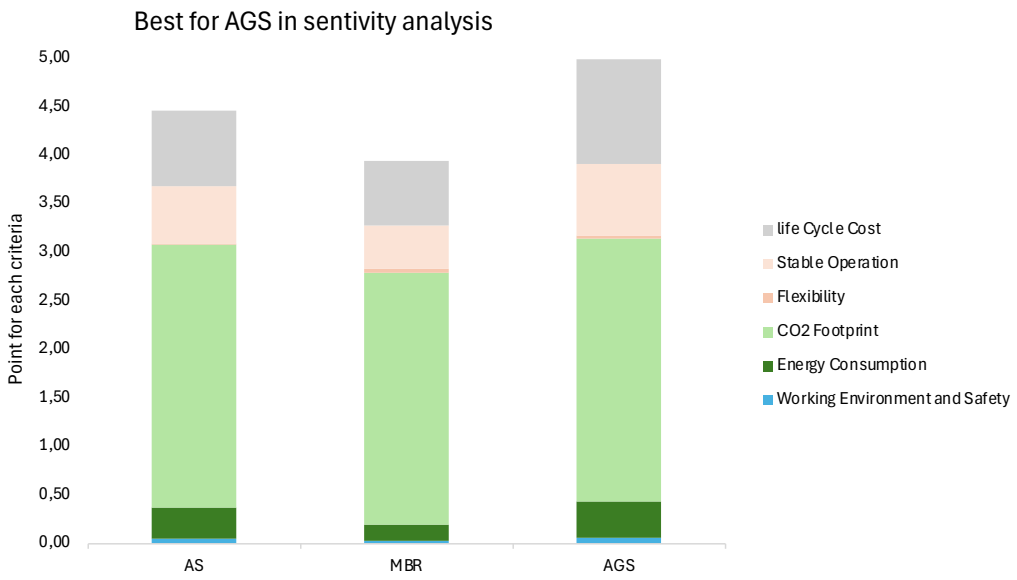


Figure 16 Sensitivity analysis_ when Aerobic Granular Sludge considered as best case.

In the end, AGS consistently emerges as the most optimal alternative, even when the costs for different criteria are adjusted. The "Best for AS" scenario shows AS can improve significantly, reducing the gap with AGS. The "Best for MBR" scenario indicates that MBR can become more competitive with targeted investments in flexibility.

7 Discussion

This chapter presents discussion on the overall results and the details of how the results were developed. It also includes a discussion regarding the accuracy of data, limitations, and assumptions.

7.1 Percentage-based vs. Value-based Models

The normalized weighting differences between the two models (percentage-based and Value-based) as shown in Table 25. In the percentage Model (Student Average): treats all criteria with relatively balanced importance, making it difficult to distinguish which criteria are the most critical. But in Value-based Model (Student Average), CO2 footprint is the most significant criterion as the major cost factor. The table indicates that the percentage-based model tends to treat all criteria as relatively equally important, whereas the valued-based model reveals clear differences in the importance of each criterion.

Table 25 Normalized weighting between percentage- based and valued- based model from LBVA and student average

Criteria	Normalized weighting(%)		
	Percentage	Value-based	
	Student average		LBVA
life Cycle Cost	18%	24%	31%
Stable Operation	20%	7%	21%
Flexibility	13%	3%	5%
CO2 Footprint	16%	62%	39%
Energy Consumption	17%	2%	4%
Working Environment and Safety	17%	3%	1%
sum	100%	100%	100%

Based on the Figure 17 and Table 18, the main difference observed between the two models is the carbon footprint criterion, which increased from 15% in the percentage-based model to 61% in the value-based model (student average). This shift shows that when students think in terms of cost, they see CO_2 reduction as a big priority. This may reflect concern about climate change or the high cost of reducing emissions. The value-based model helps to reveal what students and experts see as more impactful when cost is part of the decision.

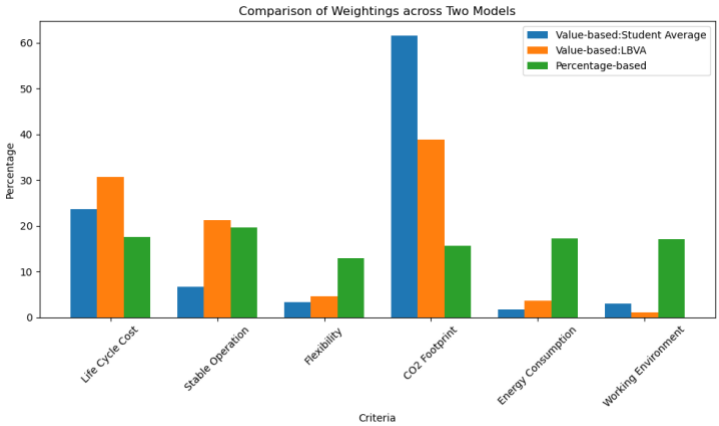
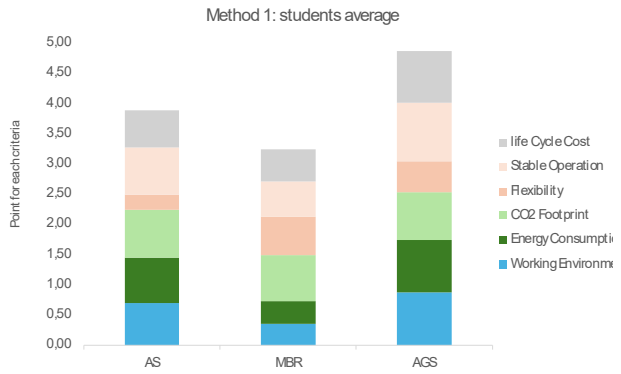
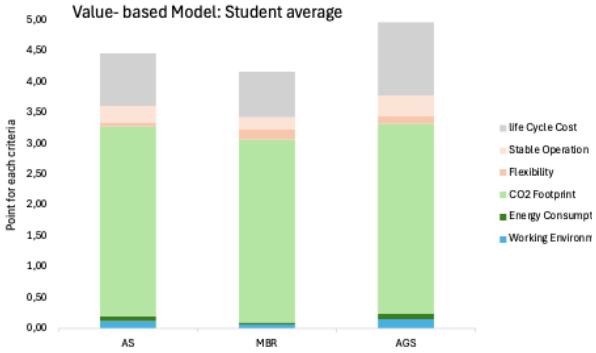


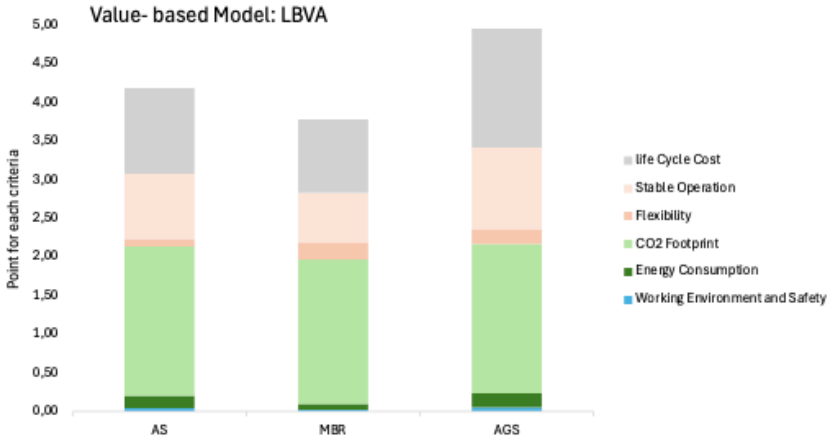
Figure 21 Comparison of weightings between percentage-based and value-based model.



a.) Percentage-based model performance from student average



b.) Value-based model performance from student's average



c.) Value-based model performance from LBVA

Figure 17 a-c Combined with the percentage -based and value-based model performances for student's average and LBVA

In the percentage-based model shown in Figure 17a, the range of inputs (1-20) did lead to a spread across various criteria. This produced an even distribution. But the results do not clearly show which criteria are most important. All the values look similar. This means the model cannot highlight clear priorities. Without cost added, students may see all criteria as equally important. This can make it harder to focus on what matters most when making decisions. This could suggest that when criteria are weighted without direct monetary implications, students perceive all factors are comparably significant potentially diluting the focus needed for more strategic decision-making.

In the value-based model shown in Figure 17b-c, these results are clearer. The CO2 footprint and life cycle cost energy are clearly as top priorities. This is because the value-based model includes cost. When people see real prices, it becomes easier to understand which criteria have the biggest impact. The model connects environmental and operational factors to money. That helps both students and experts make stronger decisions.

Students and LBVA can see the financial implications of each criterion, making it easier to recognize which factors carry more weight in real-world applications. The lesser present on

working environment and energy consumption which does not mean they are not important. These areas are viewed as less immediately impactful on a cost basis compared to direct environmental and operational costs. But from a cost point of view, they have less direct impact. CO_2 emissions and life cycle cost affect budgets more. So, they get more attention in this model.

This difference between the models shows something important. When we add cost, people can better see which choices matter most. The value-based model helps show this. It is more useful for planning in the real world. It gives a clearer picture of the financial side of sustainability. It can help both students and professionals make better decisions.

Some assumptions in this model are that the integration of cost increase transparency and, by extension, the effectiveness of decision-making. The assumptions could be further explored by conducting qualitative studies to understand reasoning in model selection and criteria weighting. A follow-up study could ask students and experts why they chose their weightings and what influenced their thinking.

7.2 Comparison with LBVA and students in Method 2: Value-Based

Figure 18 shows how both LBVA experts and student groups ranked the criteria in the value-based model. The comparison is based on average values from students and expert input from LBVA. This model allows for a detailed examination of how both groups assess the importance of various factors.

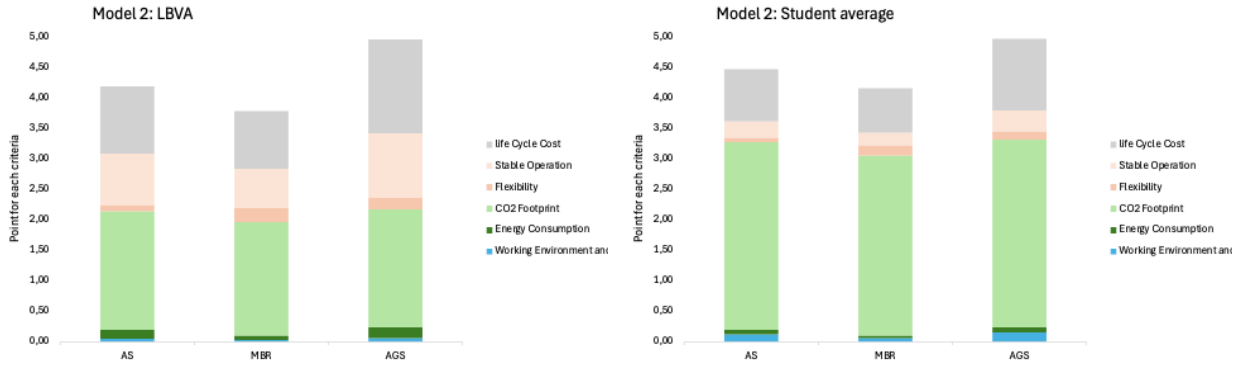


Figure 18 Combined with the Value-based model for student's average and LBVA

In the value-based model, both students and LBVA consistently rated the CO2 footprint as the most critical criterion. This uniformity underscores a shared recognition of the importance of reducing environmental impact as a first concern. The emphasis on CO2 footprint concerns on the need to add global climate challenges issue directly through sustainable practices in industry operations.

The second most important criterion was life cycle cost. Both groups agreed on this. It shows that economic performance is also a key part of sustainability. A technology must not only be effective but also affordable in the long run. Cost-efficient systems are more likely to be used widely and stay in operation over time.

Life cycle cost as the second most vital criterion for both groups. This reflects be economically viable over the long term. This pattern addressed within the frameworks of reducing CO_2 emissions and managing costs. A perception which improvements in the primary criteria could inherently lead to gains in these secondary areas. By ranking life cycle cost highly, both students and LBVA recognized cost-effective operations are not only for financial sustainability but also for the broader adoption and feasibility of treatment solutions.

The value-based model clearly separates the most important factors from the less important ones. This helps decision-makers see where to focus their efforts. It also makes the process more transparent by showing the cost impact behind each choice. The model supports strategic planning that fits both environmental and economic needs.

7.3 Accuracy of data, limitations and assumptions

This study used input data from student groups and experts to apply multi-criteria decision analysis and weighting score ratios to assess sustainability in wastewater treatment. While the results offer useful insights, there are some important limitations and assumptions to consider.

One limitation is the variability in student input. The weights provided by each group reflect their individual understanding and preferences. As different groups may prioritize different criteria based on their academic or personal inclinations. This variability can influence the final results. Some students may have placed more value on environmental concerns, while others focused more on technical or economic aspects. Due to the workshop had a limited time frame, some students might have encountered errors or misunderstandings in interpreting and applying the reference values when conducting their weightings. Especially in part two of the exercise. This could affect the reliability of their results.

Another limitation involves the calculation of the weighting score ratio. The calculation of weighting score ratios is heavily reliant on the grades provided by experts. These grades reflect expert judgment. While based on experience, they can still introduce bias. If more detailed or updated information becomes available, the grades and final results may need to be adjusted.

There is also a limitation in the research approach itself. A fundamental assumption of this study is the decision not to undertake new data collection efforts. The study did not include any new data collection. Instead, it relied on existing data from the case study and reference values. This assumes that the current data is complete and strong enough to support both MCDA and WSR analysis. This may not always be the case.

For future research, it could be useful to collect more data. This includes adding more expert opinions, using different case studies, and testing the model in other contexts. Doing so could help validate the method further and explore how well it works in different settings.

8 Conclusion

This study evaluated three wastewater treatment technologies—AS, MBR, and AGS—using two different MCDA models: a percentage-based model and a value-based model. The comparison helped identify differences in how sustainability criteria are weighted and how these differences affect the final evaluation of each alternative. Based on the results, AGS consistently as the most sustainable option in both models. AS ranked second, while MBR was the least favorable. This ranking was consistent across all assessments and reflects the strong performance of AGS, particularly in terms of cost, energy use, and environmental impact.

The use of two weighting models provided additional information about how criteria are prioritized. The percentage-based tended to treat all criteria as equally important, which made it difficult to identify which factors had the greatest influence on the final results. In contrast, the value-based model clearly showed differences between each criterion. CO2 footprint and life cycle cost were identified as the most criterial factors in this case. Other criteria, such as energy consumption and working environment and safety, were shown to have less influence on the overall outcome.

One important benefit of the value-based model is it enable to express the importance of each criterion in monetary terms. This approach can enhance the transparency of decision-making process. Meanwhile it can encourage participants to think more carefully about trade-offs between sustainability aspects, rather than treating all factors as equally important. It also helped clarify how improvements in one area might justify additional cost in another.

The value-based model improved the transparency of the decision-making process. By linking weights to real-world values, such as actual costs or environmental impacts. The model made the reasoning behind each decision more explicit. This transparency can improve stakeholder communication, build trust in the evaluation process, and support more balanced and evidence-based decisions in sustainability planning.

Overall, the study shows that integrating monetary-based weighting in MCDA can help identify that the most sustainable solution while also providing a clearer picture of the trade-offs involved in complex infrastructure decisions.

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Appendix A: Percentage-based to evaluate each Criterion for nine students' groups

Session one: blank table handed into students

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost		
Stable Operation		
Flexibility		
CO2 Footprint		
Energy Consumption		
Working Environment and Safety		

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost		Fixed	
Stable Operation		SEK/year/Grade	
Flexibility		SEK/year/Grade	
CO2 Footprint		SEK/kg CO2eq	
Energy Consumption		SEK/kWh	
Working Environment and Safety		SEK/year/Grade	

Group number: 1
Part A: input Weighting to evaluate each Criterion

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	16	Reduce operation cost, keep it functional as low as possible
Stable Operation	19	To ensure to stay in the guideline, protect environment and avoiding fees in penalty
Flexibility	15	Climate change leads to more extra weather changes lead to unpredictability, population increase
CO2 Footprint	10	Environment protection, but vague with no “direct” impact match laws. WWTP is necessary for environmental protection.
Energy Consumption	18	Highest cost factor
Working Environment and Safety	20	Required by laws, protect people lives and stay lovely

Group number: 2

Part A: input Weighting to evaluate each Criterion

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	15	
Stable Operation	18	Important that the treatment works at all times
Flexibility	8	
CO2 Footprint	8	
Energy Consumption	10	
Working Environment and Safety	6	Shouldn't choose treatment options after this design safe work method after.

Group number: 3

Part A: input Weighting to evaluate each Criterion

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	10	
Stable Operation	16	A more stable operation implies a more stable performance of the treatment plants, with malfunction and spend less maintain cost
Flexibility	8	
CO2 Footprint	11	
Energy Consumption	15	The WWTP can run 24 hours, non-step every day. Energy consumption, thus cost could be high if no methods to save energy are applied.
Working Environment and Safety	18	Safety is the most important thing!

Group number: 4

Part A: input Weighting to evaluate each Criterion

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	19	Considering cost involved for the set-up from start to end of life, if it is low there might be large investment frequently which might not be ideal
Stable Operation	18	The treatment method should have less maintenance and no breakdown to have antipirate operation of the plant.
Flexibility	12	Availability of latest technology will be considered while investment change of technology might cost more or may not be even aware of what future holds.
CO2 Footprint	15	It gives the amount of CO2 equivalent generation in a year due to operation. Hence considering environment, it should also be considered as an important factor.
Energy Consumption	20	Involves cost of operation. Increased cost will make it less efficient.
Working Environment and Safety	14	Health and safety are vital. No factor costing human/environment risk is good.

Group number: 5

Part A: input Weighting to evaluate each Criterion

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	17	Money is a deciding factor on of it can be implemented or not.
Stable Operation	18	If it isn't technically reliable it can cause economic, environmental or safety issues.
Flexibility	15	It should already be designed for a long time in the future. Maybe it is not possible to consider.
CO2 Footprint	20	Important to care for the environment.
Energy Consumption	17	It depends on how the energy is produced. For example, if it is green energy, it could be weighted lower.
Working Environment and Safety	19	The safety of the workers should be a priority.

Group number: 6

Part A: input Weighting to evaluate each Criterion

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	16	If the project is too expensive, it will not be possible to perform
Stable Operation	14	Important for economics and reliability
Flexibility	12	Important, but not as important as the other criterions
CO2 Footprint	15	Important environmental criteria
Energy Consumption	16	Environmental and economic and reliability related
Working Environment and Safety	18	Safety comes first, no one should be harmed.

Group number: 7

Part A: input Weighting to evaluate each Criteria

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	7	Important, but it can depend on where in the world the WWTP is constructed
Stable Operation	13	
Flexibility	9	
CO2 Footprint	12	It is important, but if the water is treated well, it can perhaps compensate
Energy Consumption	10	Depends on the energy source, e.g. green energy or carbon energy
Working Environment and Safety	19	

Group number: 8

Part A: input Weighting to evaluate each Criteria

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	17	most important
Stable Operation	16	
Flexibility	8	
CO2 Footprint	15	
Energy Consumption	12	
Working Environment and Safety	5	

Group number: 9

Part A: input Weighting to evaluate each Criteria

Criteria	Weighting (0-20)	Comment(why)
life Cycle Cost	16	Sustainable approach. Spaced should be utilized when new technology arises, the structures must be accessible. Economic perspective, too.
Stable Operation	19	Important because if operation does not occur causes more problems to the environment (untreated effluent) as well as in economic perspective.
Flexibility	12	If the treatment process is more efficient then it is to occupy more space. If the technology is not efficient enough then obviously. We need space for the future technologies.
CO2 Footprint	17	Cannot make efficient practically possible towards sustainable approach climate change is happening a lot so need some concentration
Energy Consumption	16	However, energy will be consumed but it would be better if we consume those energy in sustainable way like energy from the sludge waste which will turn into kind of s
Working Environment and Safety	18	Safety, health is more important to consider (since they have the glass chemicals somehow). The process should not affect the nearby society in environment by means of order, noise, water, pollution.

Appendix B: Value-based to evaluate each Criterion from nine student groups

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost		Fixed	
Stable Operation		SEK/year/Grade	
Flexibility		SEK/year/Grade	
CO2 Footprint		SEK/kg CO2eq	
Energy Consumption		SEK/kWh	
Working Environment and Safety		SEK/year/Grade	

Group number: 1
Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	2,000,000	SEK/year/Grade	
Flexibility	670,000	SEK/year/Grade	
CO2 Footprint	2.2	SEK/kg CO2eq	The WWTP usually don't have that much money available
Energy Consumption	0.3	SEK/kWh	
Working Environment and Safety	525,000	SEK/year/Grade	Safety gear, upgrade technology in office (PC, software) Working space – bigger plant, more people, bigger building safer

Group number: 2

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	2,000,000	SEK/year/Grade	choose 20%
Flexibility	1,000,000	SEK/year/Grade	15% of life cycle cost
CO2 Footprint	3.5	SEK/kg CO2eq	
Energy Consumption	0.65	SEK/kWh	
Working Environment and Safety	200,000	SEK/year/Grade	

Group number: 3

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	1,340,000	SEK/year/Grade	
Flexibility	15,000	SEK/year/Grade	
CO2 Footprint	1	SEK/kg CO2eq	
Energy Consumption	0.975	SEK/kWh	
Working Environment and Safety	4,000,000	SEK/year/Grade	

Group number: 4

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	SEK/year/Grade	Fixed
Stable Operation	1	SEK/year/Grade	Most important while functioning the treatment plant and the operation
Flexibility	1	SEK/year/Grade	Not ideal to change technology in middle of operations
CO2 Footprint	4	SEK/kg CO2eq	Ideally to protect the environment
Energy Consumption	0.4	SEK/kWh	More sustainable energy and less carbon foot of we align towards wind energy
Working Environment and Safety	200,000	SEK/year/Grade	If the WWTP is at good operation the work needed by the personal will be compensability less

Group number: 5

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	1,000,000	SEK/year/Grade	10% of LCC
Flexibility	30,000	SEK/year/Grade	0.5% of LCC
CO2 Footprint	1.5	SEK/kg CO2eq	
Energy Consumption	0.5	SEK/kWh	Focus on green energy
Working Environment and Safety	117,000	SEK/year/Grade	Choose 50%

Group number: **6**

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	1,000,000	SEK/year/Grade	10% of LCC
Flexibility	330,000	SEK/year/Grade	5% of LCC
CO2 Footprint	4	SEK/kg CO2eq	More expensive in sweden
Energy Consumption	0.5	SEK/kWh	WWTP produce its
Working Environment and Safety	350,000	SEK/year/Grade	100%, 2 steps

Group number: 7

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	4,000,000	SEK/year/Grade	
Flexibility	3,000,000	SEK/year/Grade	
CO2 Footprint	4	SEK/kg CO2eq	
Energy Consumption	1	SEK/kWh	
Working Environment and Safety	15,000	SEK/year/Grade	

Group number: 8

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	670,000	SEK/year/Grade	10% of LCC
Flexibility	330,000	SEK/year/Grade	5% of LCC
CO2 Footprint	3	SEK/kg CO2eq	
Energy Consumption	0.5	SEK/kWh	
Working Environment and Safety	175,000	SEK/year/Grade	

Group number: 9

Part B: input weights as costs for each criterion

Criteria	Weighting	Unit	Comment(why)
life Cycle Cost	1	Fixed	
Stable Operation	1,000,000	SEK/year/Grade	To avoid untreated effluent that causes environmental pollution
Flexibility	670,000	SEK/year/Grade	If the treatment is efficient spending money is fine if not its waste
CO2 Footprint	4.4	SEK/kg CO2eq	Environmental concern
Energy Consumption	0.3	SEK/kWh	Need to use sustainable way to create energy in a comparative way
Working Environment and Safety	175,000	SEK/year/Grade	

Appendix C: Value-based to evaluate each Criterion from LBVA

Criteria	Unit	Weighting	Max weighting	Min weighting
life Cycle Cost	Fixed	1	1	1
Stable Operation	SEK/year/Grade	3 500 000	3 500 000	2 500 000
Flexibility	SEK/year/Grade	750 000	2 000 000	200 000
CO2 Footprint	SEK/kg CO2eq	1.5	3	0,5
Energy Consumption	SEK/kWh	1	3	0
Working Environment and Safety	SEK/year/Grade	175 000	250 000	25 000

Appendix D: Mathematical Equations Used in the Analysis

Table A1 List of Equations and Descriptions

Equation	Description	Model
$W_{N1} = \frac{W}{\sum \mathrm{W}_{\mathrm{All}\ Criteria}} \times 100\%$	Based on the input weightings (1-20), normalized weighting as percentage	Percentage-based
$C_q = \lvert C_p \times V_p \rvert$	Based on the input monetary value and excel valuate value per grading step to calculate the criterion's weighted economic impact	Value-based
$\mathrm{W_{N2}} = \frac{\frac{C_q}{\mathrm{Cost}}}{\left(\sum \frac{C_q}{V_{LCC}}\right)_{All\ Critrtia}} \times 100\%$	In the Value-based model, based on the weighted economic impact for each quantifiable criterion, normalized weighting as percentage based on life cycle cost.	Value-based
$S_c = W_N \times G$	Based on the selected criterion, calculate the score of criteria	Percentage-based And Value-based
$S_{\mathrm{T}} = \sum (S_c)_{\mathrm{all\ criteria}}$	Summary up all the criteria we have to get alternative's final score	Percentage-based And Value-based

Table A2 Definitions and Descriptions of Parameters

Parameter	Definition
W	The weight assigned to a criterion.
W_{N1}	Normalized weight, expressed as a percentage. This is calculated as the weight of a criterion divided by the total weight of all criteria, multiplied by 100%.
C_p	Cost per unit for the quantifiable criterion. This represents the cost associated with each unit increase in the grading step of the criterion.
V_p	Value per grading step, determined through linear regression. This value quantifies the incremental benefit or cost associated with each step change in a criterion's evaluation.
C_q	Cost per unit, the criterion's weighted economic impact. This is calculated by multiplying the cost per unit by the value per grading step.
W_{N2}	Normalized weight in the value-based model, expressed as a percentage. This is calculated as the ratio of C_q to V_{LCC} for a criterion, divided by the sum of such ratios for all criteria, then multiplied by 100%.
S_c	Score for a selected criterion. This is calculated by multiplying the normalized weight (W_N, either W_{N1} or W_{N2} by the grading of the technology.
G	Grading of the technology for each criterion, typically on a scale from 1 to 5, where 1 represents poor performance and 5 represents excellent performance.
S_T	Total score for all technologies. This is the sum of scores for all criteria (S_c), providing an aggregate measure of a technology's performance based on the weighted evaluation of all criteria.