UNIVERSITY OF TWENTE.

Faculty of Behavioural, Management and Social Sciences

Department of Industrial Engineering and Business Information Systems

Bachelor Thesis

Evaluating the sustainability of a technology by performing a supply chain analysis

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Abstract

The present study is aimed at solving the problem of insufficient understanding of the sustainability performance of the Archimedean Drum Screen (ADS) biomass and plastic waste clean-up technology. To do so, a specifically tailored for this problem theoretical framework is developed and a deductive research approach, relying on a mix of qualitative and quantitative data collection methods is embraced. As a result, this study establishes that further technological improvements are needed to ensure high ADS sustainability performance and that the post-collection handling of the waste plays only a marginal role in the achieved level of sustainability. More specifically, the research goal of this study: *"Evaluate the sustainability performance of the Archimedean Drum Screen biomass and plastic waste clean-up technology by performing a supply chain analysis"* is reached by executing a meticulously crafted solution. Firstly, a systematic literature review sets the context by providing guidelines on how to measure sustainability and by operationalizing the concept through the triple bottom line perspective. Secondly, comprehensive criteria of 12 key performance indicators meant to collectively encompass supply chain sustainability is formulated. Thirdly, to ensure sufficient scope of analysis, three different supply chain scenarios for handling the biomass and plastic waste stemming from the ADS are constructed, quantified (via input-output models) and evaluated. A commonality between all scenarios is the assumed Power Plant and ADS industrial symbiosis, established early on during the research as the most suitable technology integration strategy. Ultimately, although none of the supply chain scenario scores sufficiently high across all sustainability dimensions to posit that the ADS is holistically sustainable, the most promising scenario is waste pelletizing – characterized by comparatively lower CO_2 emissions, complete (100%) waste reuse, significant expected increase in annual demand of finished products and strong commercial competitiveness on the economic front.

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List of Acronyms

Acronym	**Meaning**
ADS	Archimedean Drum Screen
AHP	Analytical Hierarchy Process
BMS	Behavioral, Management and Social
CAGR	Compound Annual Growth Rate

CO_2	Carbon Dioxide
DEA	Data Envelopment Analysis
IEM	Industrial Engineering and Management
In-No-Plastic	EU-funded project for innovative approaches towards prevention, removal, and reuse of marine plastic litter
SDG	Sustainable Development Goal
SLR	Systematic Literature Review
KPI	Key Performance Indicator
kWh	Kilo-Watthour
LCA	Life-Cycle Assessment
MCDA	Multiple Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
MIOT	Monetary Input Output Table
MIOCT	Monetary Input Output Coefficient Table
NPV	Net Present Value
PIOT	Physical Input Output Table
PIOT	Physical Input Output Coefficient Table
R&D	Research and Development
UN	United Nations
UNEP	United Nations Environment Program
UT	University of Twente

1. Introduction

1.1. Background

In-No-Plastic (Innovative approaches towards prevention, removal, and reuse of marine plastic litter) is a three-year EU funded project with the goal to develop and demonstrate nano-, micro-, and macro-plastic clean-up technologies in the aquatic ecosystems. A consortium of 17 companies from 10 different countries is assigned with the ambitious task of developing and demonstrating the clean-up technologies. One of those technologies is the so-called Archimedean Drum Screw (ADS), which works as a screen allowing 90% of the water flow to pass through while catching (plastic) debris, (jelly) fish, algae, and seaweed. The consortium member responsible for the developments and demonstrations of the ADS is FishFlow. However, even though FishFlow has rigorously tested and continuously improved the technology, insufficient research has been carried out regarding the possible categorical locations to position the ADS and the subsequent steps when handling the collected waste. As a result, the problem owner – In-No-Plastic consortium and more specifically FishFlow – is concerned that there is a lot of uncertainty on the actual sustainability performance of the clean-up technology. The research outlined in this paper focuses explicitly on helping the problem owner by solving this uncertainty.

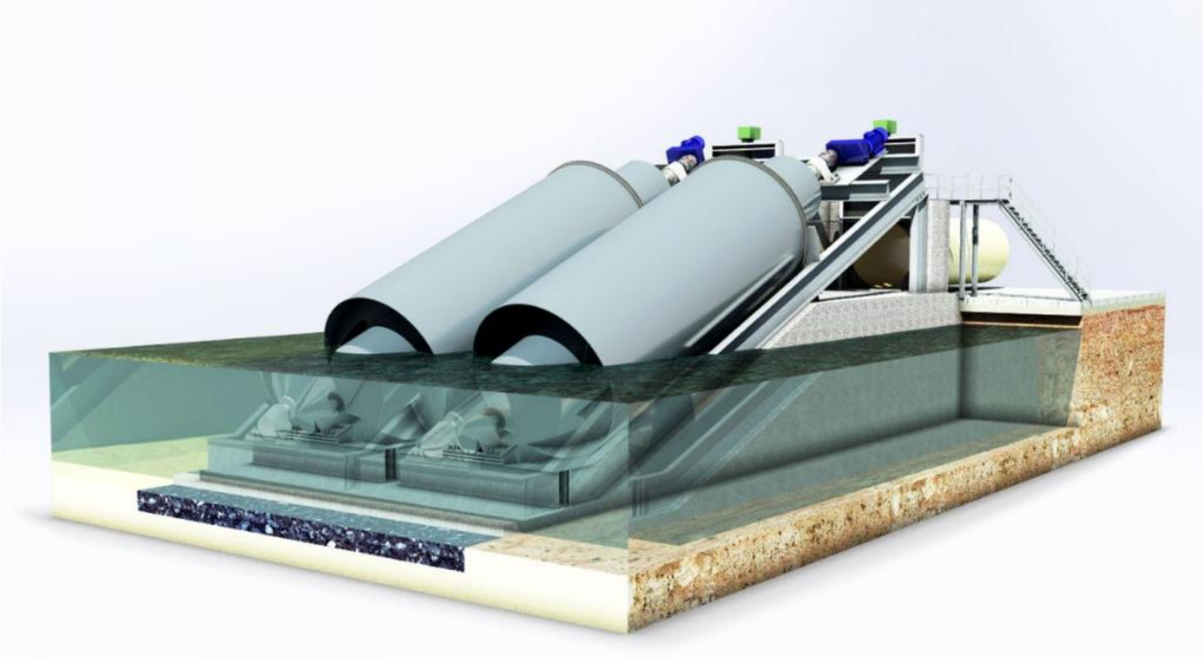

Figure 1. Archimedean Drum Screen

1.2. Stakeholders

In order to provide further clarity to the significance and nature of the academic activities performed as part of this research, a brief elaboration on each relevant stakeholder is provided below.

In-No-Plastic consortium

A consortium of 17 companies from 10 different countries assigned with the task of developing and demonstrating sea water clean-up technologies. It includes 2 research institutions, 2 Government bodies, 4 industry end-users, 2 NGOs, 7 SMEs of which 4 technology and 3 service providers. Due to the distinct and diverse experience of each participating body, close collaboration within the consortium is paramount to reaching the goals of the project. Naturally, this is also the case when it comes to the development of the ADS technology and carrying out the corresponding assessments. This implies that the input of a variety of companies within the consortium is required while performing the research as part of this study.

BlueXPRT

Project management and consulting company from the Netherlands, part of the In-No-Plastic consortium. Responsible for coordinating a variety of activities linked to the dissemination of results and the demonstration and valorization of the clean-up technologies. Moreover, BlueXPRT is in charge of defining the relevant KPI's of the technologies and performing the techno economic assessments of the In-No-Plastic clean up solutions. Mentoring the researcher[1] and serving as a first point of contact.

Fishflow

Engineering and manufacturing expert from the Netherlands, part of the In-No-Plastic consortium. Responsible for designing and manufacturing the ADS technology. Hence, main problem-owner of all issues related to the ADS and primary user of the results from this research.

General public

Another key stakeholder interested in the results from this research, due to the very strong public presence of the project stemming from the effective execution of a communication & dissemination strategy.

University of Twente

The home academic institution of the researcher and the respective supervisors– enabling the research and ensuring that the four basic principles of research – Autonomy, Beneficence, Non-maleficence, Justice – are followed.

1.3. Problem Identification

To bring order to the problem context and to identify the core problem, all problems along with their connections are mapped. The tool used for the mapping is a problem cluster – Figure 2 (Heerkens & Van Winden, 2021). Stemming from the problem cluster, the solvable core problem is the lack of supply chain understanding regarding the collection and handling of biomass and plastic waste coming from the operation of the Archimedean Drum Screen clean-up technology. This is the solvable core problem since it exists, has no direct causes, can be influenced by the researcher and appears to have the greatest impact effect at the lowest cost – meeting all four criteria of Heerkens & Winden (2021). As such, the core problem is also the primary action problem and can be described as the gap between the following norm and reality:

Reality: *Insufficient understanding of the inputs and outputs of the biomass and plastic waste supply chain stemming from the operation of the Archimedean Drum Screen clean-up technology.*

In this context, insufficient understanding means no available data for most inputs and outputs and scarce availability of data at nominal level of measurement (Cooper & Schindler, 2014) for the rest.

Norm: *Sufficient understanding of the inputs and outputs of the biomass and plastic waste supply chain stemming from the operation of the Archimedean Drum Screen clean-up technology.*

In this context, sufficient understanding means availability of data at ratio and (where ratio does not apply) interval level of measurement (Cooper & Schindler, 2014) for all inputs and outputs.

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[1] The "researcher" pertains to the author of this document. It is used throughout this document to adhere to academic standards and avoid the use of 1st person point of view.

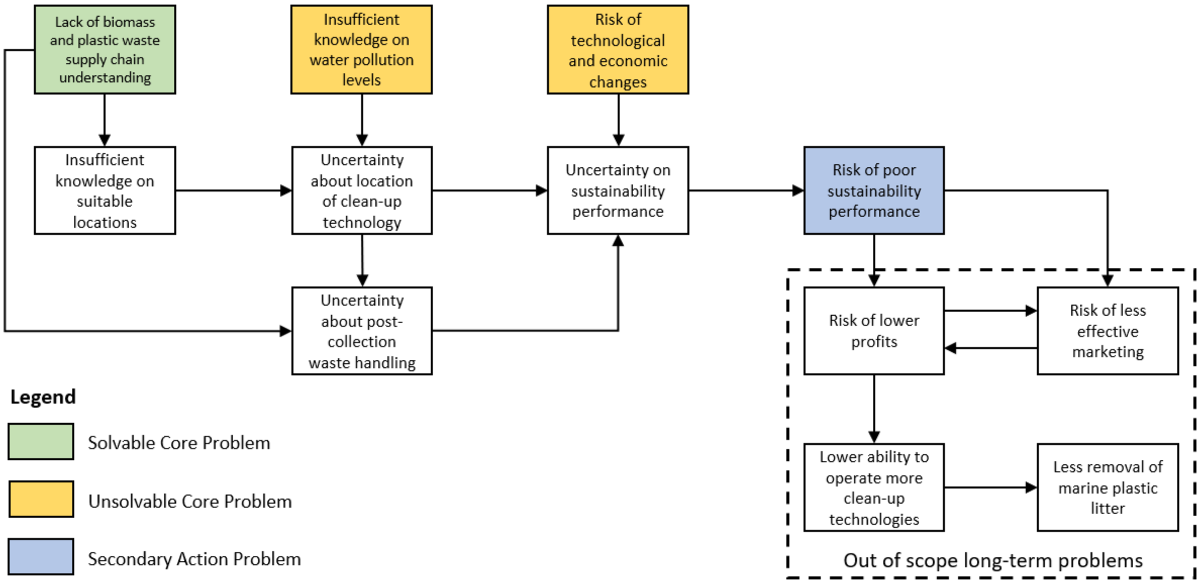

Figure 2. Problem cluster

Even though “Insufficient knowledge on water pollution levels” and “Risk of technological and economic changes” are two additional problems with no direct causes in the problem cluster, they score lower on the criteria of Heerkens & Van Winden (2021) since they fail to meet criterions 3 and 4. More specifically, the first problem is currently being addressed by other partners within In-No-Plastic who are performing various studies and water sampling procedures in different locations across Europe. As such, except for a rudimentary literature review, the problem is practically unsolvable on behalf of the researcher since the contributions would be negligible. Similarly, the second problem represents the possibility that technological innovations (creation of better clean-up technologies, etc.) and/or economic changes (increase in CO_2 emissions per kWh of electric consumption, etc.) may affect the sustainability performance of the ADS. Evidently, this problem is beyond the influence of the researcher as well. As a result, none of the two afore described problems can be regarded as the true core problem. Moreover, the remaining problems fail to qualify as core problems as well by simply not meeting criterion 2 – presence of no direct causes. The problem cluster also includes a secondary action problem (coloured in blue), which is the surface level problem that is manifested to the world, and which stands for the gap between norm and reality that the technology engineers and operators want to close.

Lastly, it is important to note that the lack of (biomass and plastic waste) supply chain understanding will have a detrimental impact on the overall objective of In-No-Plastic in the short as well as long-term. In the short term, it will simply result in improper utilization of the clean-up technology and the subsequent removal of inadequate levels of plastic litter. In the long-term, poor sustainability performance of the clean-up solution will create a set of other problems for FishFlow such as “Risk of lower profits” and “Risk of less effective marketing” with respect to the technology (ADS). This is likely to undermine the main objective of In-No-Plastic by further exacerbating the problem of “Lower ability to operate more clean-up technologies”. However, this set of problems is defined as “Out of scope long-term problems”.

2. Background Literature

As evident from the nature of the core problem, a comprehensive literature review is needed to not only substantiate the gap in research but to also corroborate the conceptual framework and the resulting methodological approach. Thus, the ensuing text is the synthesis of the preliminary literature review carried out to address those two aspects.

Research gaps

Pinpointing the specific gap in research as it pertains to the problem faced by FishFlow is a complex endeavour since a variety of academic fields and viewpoints can be amalgamated. Nevertheless, to bring simplicity and direction to this examination of background literature, the emphasis is on the holistic measure taken to resolve the core problem – the measure of evaluating the sustainability of the ADS technology. This is no arbitrary decision since sustainability measurement is the backbone (Johnsen et al., 2018) for many following activities such as improvement actions (Trianni et al., 2017), reporting (Katiyar et al., 2018), and benchmarking (Ferrari et al., 2019).

To begin with, current analytical and quantitative modelling capabilities fall short of being able to capture all 17 SDGs and their targets when trying to encompass sustainability performance (Zimm et al., 2018). Even highly ambitious and optimistic pathways often used in research, such as SSP1/SSP1-2.6 (Meinshausen et al., 2020), do not meet all SDGs (sustainability gaps) and fail to provide information on some of them (knowledge gaps). Hence, Zimm and colleagues (2018) argue that for research and modelling purposes, the SDG targets can serve as a basis but need to be properly operationalized to reduce complexity and to also account for long-term sustainability concerns.

One more sustainability research gap is the absence of adequate methods for capturing the dynamics of changes and trends and the trajectories of important features of the earth system and social and economic pressures (Dahl, 2012). In other words, since no part of earth exists in isolation it is necessary to capture the interaction between different processes, environmental sectors, and social and economic trends. As such, sustainability analysis must research the most significant driving forces and their causal relationships and identify the indicators relevant to the points in the system where management actions would be most effective.

A particular issue – the existing divide between scholars and practices resulting in inefficient and time-consuming implementation of sustainability assessments – has led to the discovery of another research gap: the omnipresent deficiency of a set of comprehensive indicators for sustainability development assessment (Taisch et al., 2013). Availability of comprehensive indicators can enable assessment tools to consider different aspects of sustainability and consequently reduce the need for executing complementary tools, frameworks, or methods to measure, aggregate and compile the results to get to a unique set of conclusions that can support decision-makers. Another gap investigated by Taisch and colleagues (2013) is that existing tools, methods, and processes of sustainability development assessments are mostly specific ones which focus on special criteria, sector or sustainability aspect. This can be a challenge because it may require time to find out about the most suitable tool that serves the best for the intended purpose of sustainability measurements. Yet, even if the gap exists, it doesn't necessarily indicate a shortcoming on behalf of the academic community since specificity is traditionally also linked with benefits such as more accuracy, less time, etc. Nevertheless, based on the two research gaps, Taisch and his fellow researchers purport two main solutions. Firstly, developing indicators for a comprehensive Rapid Sustainability Assessment Tool. Secondly, introducing and integrating energy efficiency as a key enabler for sustainability assessments.

Last but certainly not least, a valuable addition to research is to determine indicators that could be used to measure sustainability performance at the supply chain level to obtain a more comprehensive view of sustainable manufacturing (Mengistu & Panizzolo, 2022). Hence, it is interesting for future research to expand the methodological approach to the entire supply chain in the stages of supply, production, distribution, use, and post-use. Furthermore, the focus is usually on indicators that have been used by scientific papers (i.e., academic papers), so future research could consider analysing indicators that have been used by organizations engaged in sustainability performance measurement.

Additionally, Mengistu & Panizzolo (2022) claim that research is also not agreeing on why certain indicators are not commonly used for measuring industrial sustainability.

All things considered, there are several research gaps in the current sustainability evaluation practices as it pertains to a supply chain process or a technology. The more significant gaps are the lack of ability to effectively operationalize and capture the SDGs via current quantitative and qualitative techniques, the absence of adequate methods for capturing the complex dynamics between earth, social and economic issues, the evident lack of standardized indicators for sustainability development assessment and more specifically their ineffectiveness to reflect the entire supply chain and not just a single step in it.

Relevant methodologies

As far as relevant methodologies are concerned, despite the wide-ranging literature, overlaps in certain areas are very clear. To start, the Sustainability Assessment of Technologies (SAT) methodology (UNEP, 2012) suggests the integration of Economic, Social and Environmental considerations to ensure resource (economic and environmental) Efficiency and Social Acceptability. The methodology addresses strategic as well as operational levels and employs a progressive assessment procedure, thereby allowing entry points for a diversity of stakeholders and optimizing information requirements. Consequently, by placing importance on information expertise and stakeholder participation it is also in line with the practices of In-No-Plastic. SAT utilizes a set of quantitative procedures that allow more objective assessment, sensitivity analyses and incorporation of scenarios. The methodology also tries to ensure the application of technology “systems” as opposed to individual technologies. Moreover, two of the targeted areas of application of the SAT Methodology are namely recycling and waste management technologies.

Alternatively, the Integrated Innovation and Sustainability Analysis (IISA) methodology (Gasde et al., 2020) puts an even greater emphasis on stakeholder involvement. It is based on the early and systematic involvement of stakeholders, along with a sustainability assessment of the planned innovation to provide feedback loops into technology development. The four main steps of the IISA approach are Stakeholder Analysis, Stakeholder Dialogue, Stakeholder Integration and Sustainability Assessment. Ultimately, the overall goal of the method is to improve the potential impact on sustainability in the three dimensions: economic, environmental, and social through stakeholder involvement.

The Prospective Sustainability Assessment of Technologies (Prosuite) is another novel methodology that can be used as a tool for sustainability assessment of existing and new technologies (Blok et al., 2013). It is conceived as an impartial assessment methodology meant to evaluate whether a technology helps to address important sustainability challenges or merely creates new ones. The Prosuite framework revolves around five major impact categories (as opposed to three): Human Health, Social Well-being, Prosperity, Natural Environment, Exhaustible Resources, and three levels of assessment: Chain, Technology, System. Prosuite recognizes LCA as a well-established (as well as ISO standardized) methodology for assessing the environmental performance of products and services. Hence, in a similar manner to Heijungs and colleagues (2010), it builds upon the principles of explicit definition of the cause-effect chain and scientific and transparent calculation methodology.

In conclusion, the dominant system of decision making in technology selection and evaluation should not focus solely on economic considerations and disassociate social and environmental ones. This fragmented approach in making technology choices has negative implications on efficiency and sustainability of new technologies. To circumvent that a suitable methodology for decision making and sustainability evaluation that encompasses the entire triad of factors must be employed. According to an in-depth literature review the most suitable such methodologies are SAT, IISA and Prosuite.

3. Theoretical Framework

The theoretical framework embraced by this paper is based on the theory provided so far in the IEM program, specifically in "How to solve managerial problems systematically" (Heerkens & Van Winden, 2021) combined with the theory stemming from the SAT methodology (UNEP, 2012). As a result, the research will mostly adhere to the guidelines set by the BMS faculty of the UT with some minor modifications in order to capture the nuances of the research problem at hand. The phases of the managerial problem-solving method (MPSM) are as follows:

1. Defining the problem
2. Formulating the approach
3. Analysing the problem
4. Formulating (alternative) solutions
5. Choosing a solution
6. Implementing the solution
7. Evaluating the solution

In addition, a visual representation of the SAT methodology is shown in Figure 3.

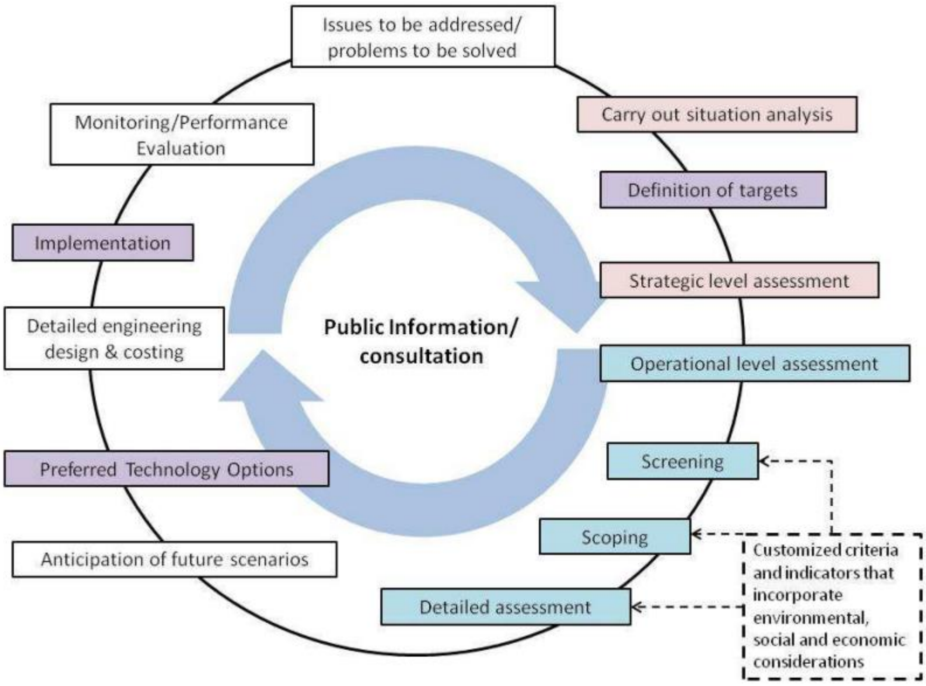

Figure 3. The SAT Methodology. From *Application of the Sustainability Assessment of Technologies Methodology*: *Guidance Manual* (p.11) by UNEP, 2012.

The key concepts stemming from the research problem and the preliminary literature review are "Sustainability", "Waste", "Clean-up Technology" and "Supply Chain". Of course, evident connections between these concepts are present. In particular, inverse relationships between sustainability and waste as well as a direct relationship between sustainability and clean-up technology. Yet, all the relationships are to be investigated in much greater detail later in this study. Based on the preliminary literature review, the central concept to be operationalised – by disaggregating it to variables and indicators - is "Sustainability". This further supports the adoption of the SAT methodology due its specific focus on addressing sustainability as it pertains to the integration of environmental soundness, social/cultural acceptability, and technical and economic feasibility. Ultimately, the combination of MPSM and SAT results in a highly customized framework that is visualized in Figure 4.

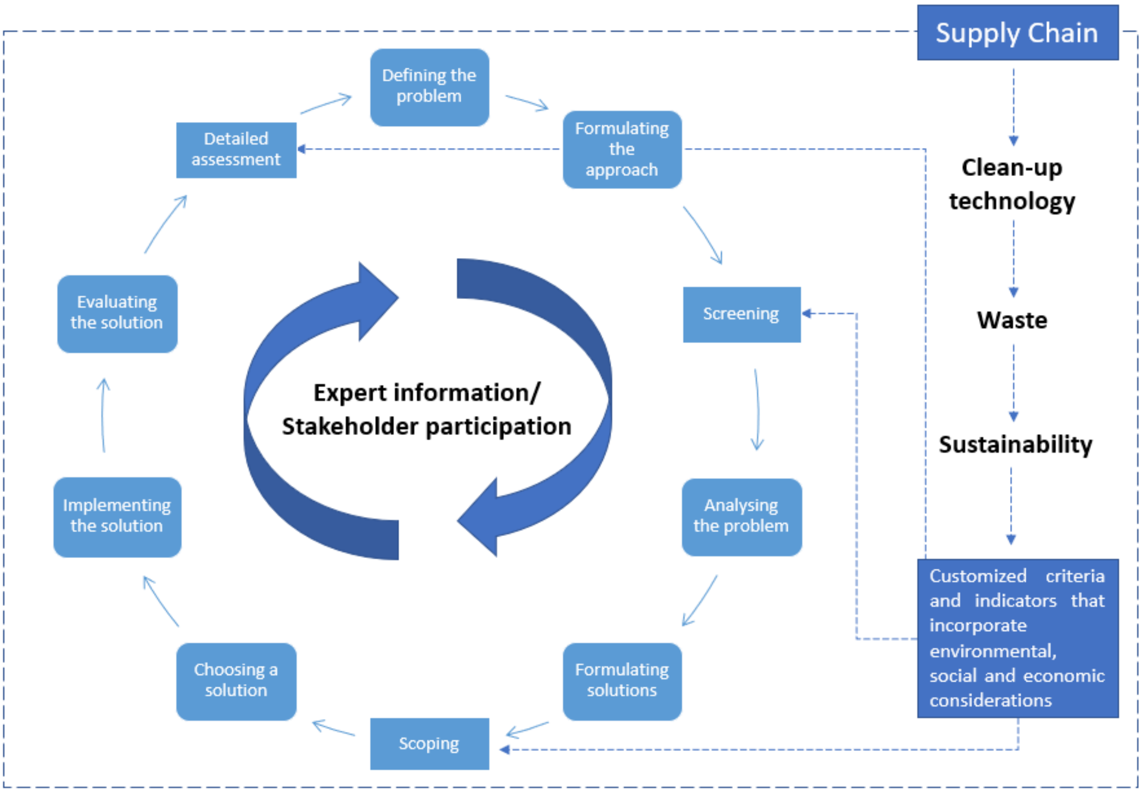

Figure 4. Customized theoretical framework

4. Methodology

4.1. Research Aims

The research goal (Heerkens & Van Winden, 2021) as part of the highest level of abstraction research cycle is:

"Evaluate the sustainability performance of the Archimedean Drum Screen biomass and plastic waste clean-up technology by performing a supply chain analysis"

Subsequently, the problem statement (Heerkens & Van Winden, 2021) is defined as:

"How to perform a supply chain analysis for gaining insight into the sustainability performance of the Archimedean Drum Screen biomass and plastic waste clean-up technology"

This research goal, and the associated problem statement, stem from the gap in literature identified in the literature review together with the problems faced by FishFlow. The problem statement yields several research questions that make it more accessible by splitting it up into relatively easy to address subparts. A list of those research questions is provided in Table 1.

Q1	How to model a waste handling and collection supply chain in aquatic ecosystems?
Q2	How do the operations of the Archimedean Drum Screw (ADS) technology impact the waste handling and collection supply chain?

Q3	How to measure sustainability across a supply chain resulting from the introduction of a novel technology?

Table 1. Research questions

4.2. Research Design

Research design is defined as the overall strategy utilized to carry out research that defines a succinct and logical plan to tackle established research question(s) through the collection, analysis, and interpretation of data. Put more simply, it is a plan to answer a set of question(s) (McCombes, 2021). As such, choosing a specific research design is inextricably linked to the overarching dissertation research goal as well as the different types of research assumptions. These comprise assumptions about human knowledge (epistemological assumptions), about the realities encountered in the research (ontological assumptions) and the extent and ways personal values influence the research process (axiological assumptions).

To effectively visualize the different levels of the research design, a research 'onion' diagram is used (Figure 1). The diagram depicts the issues underlying the choice of data collection techniques and analysis procedures (Saunders et al., 2009). To provide more elaboration on the research design of this study, the various layers are covered in the ensuing chapters.

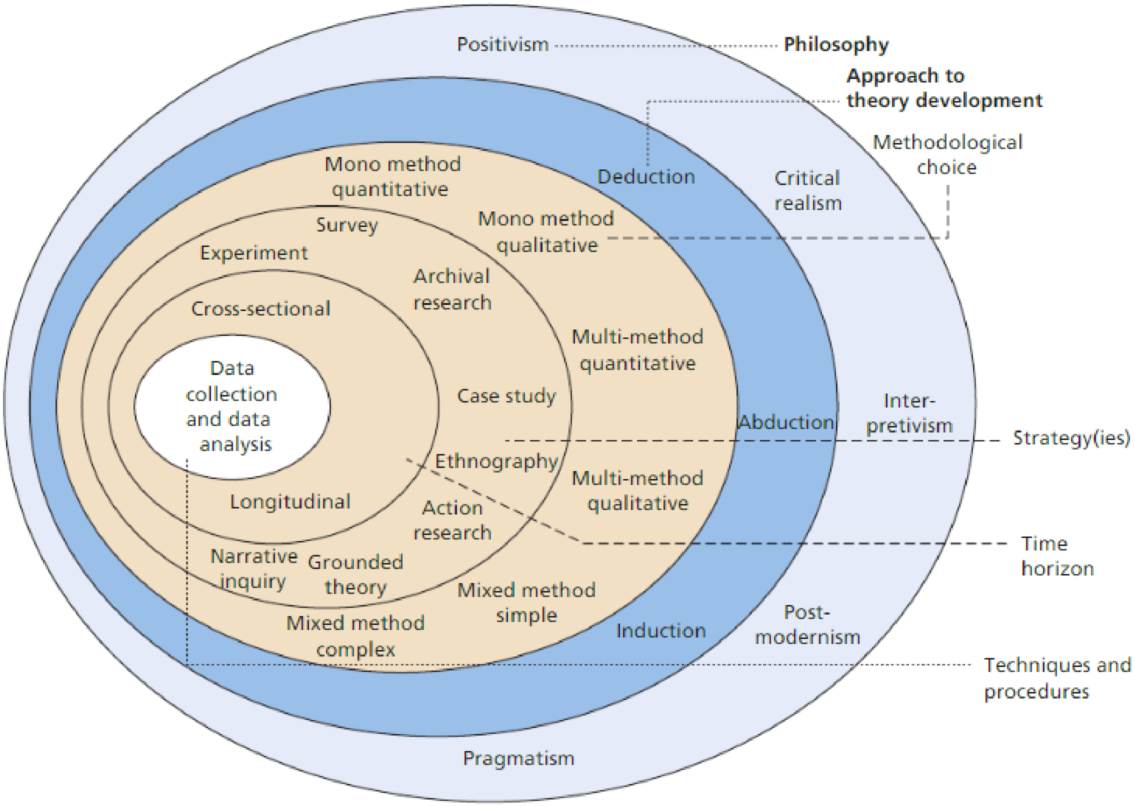

Figure 5. The research 'onion'. From *Research Methods for Business Students* (p.124) by Saunders et al., 2009.

4.2.1. Research Philosophy

The identification of research philosophy is the first matter to be clarified in the research design chapter since it serves as a basis for all subsequent methodological steps. This is the case because the research philosophy is associated with the nature of truth and knowledge and tackles the ways in which data about a phenomenon is collected, analysed, and used. In essence, by formulating a relevant belief system and a set of assumptions, the research philosophy deals with the source, nature, and development of knowledge (Bajpai, 2011).

Due to the nature of the research questions and the great amount of variety in collecting and analysing the data within this study, a mixed research philosophy approach is embraced. First and foremost, critical realism serves as a basis for this research by recognizing that research is inherently value-laden, and that the researcher must try to be as objective as possible. As such, the intention is to strive to be aware of the ways in which the socio-cultural background and the involvement of multiple different stakeholders might influence the research and to seek minimisation of such biases. Yet, according to critical realism, despite the presence of subjectivity reality remains the most important philosophical consideration with a structured and layered ontology being crucial (Fleetwood, 2005).

With reality being the most important consideration, the research philosophy of positivism also finds its place into this study. This is the case because regardless of the social dimensions of this study, at its core, it aims to investigate a specific technology and the associated supply chain. Therefore, a range of clearly observable and measurable data is present, demanding for a set of highly structured and quantitative methods of analysis. An analysis bound to universalism (the assumption of one true reality) and the adoption of a purely scientific method where I, as the researcher, must try to obtain an objective stance.

However, though suitable for analysing the already compiled, almost purely quantitative data, positivism falls short when it comes to the handling of qualitative information. More importantly, it also falls short when it comes to the collection of non-generic, highly unstructured data from multiple sources with varying levels of interest in the research. Hence, the assumption behind this study is that "access to reality (universal or socially constructed) is through social constructions such as language, consciousness, shared meanings, and instruments" (Myers, 2013). As such, interpretivism has a pivotal role to play in this study. In addition, by recognizing that multiple meanings and interpretations can exist and by acknowledging the importance of new perceptions and worldviews, interpretivist principles also enable for greater, in-depth understanding of the main variable analysed in this study – sustainability.

To summarise, facets of several research philosophies prove to find its vital place in this study. At its core, the study assumes the principles of critical realism, but it also recognizes the value brought by interpretivism when collecting data and positivism when analysing it. Hence, because of the intricate nature of the research problem, the focus of this study will be on assigning meaning to data, but multiple methods will be employed in order to reflect different aspects of the research issue addressed by this paper.

4.2.2. Research Approach

As far as the research approach is concerned, the aim is to employ a deductive approach. A deductive approach is defined as "developing a hypothesis (or hypotheses) based on existing theory, and then designing a research strategy to test the hypothesis". (Wilson, 2014). Unlike induction, which begins with observation and seeks to find a pattern, deduction begins with an expected pattern "that is tested against observations" (Babbie, 2010). Therefore, the move is from a broad generalization to a specific observation.

In general, the reason for adopting the deductive approach is that it allows for exploring a known phenomenon and testing if it is valid in given circumstances. This approach is very fitting to the research goal of this study – the sustainability evaluation of the ADS technology - since it also offers the possibility to explain causal relationships between concepts and variables. Moreover, the deductive approach is suitable for cases where a lack of time to complete the study, risk averseness and an abundance of literature sources are all present – which very much applies to the analysis of such clean-up technology.

Ultimately, the deductive research approach as part of this study consists of the following stages:

1. Explore existing theory (and create a problem statement)
2. Formulate a falsifiable hypothesis based on existing theory
3. Collect data to test the hypothesis
4. Analyze the data
5. Decide whether to reject the null hypothesis or not

The actions as part of stage 1 have been covered in the preliminary literature review and research aims sections. With regards to stage 2, based on the existing theory and the problem statement the following null hypothesis is formulated:

"All Archimedean Drum Screen technologies produced by FishFlow are sustainable in accordance with the triple bottom line."

By examining the sustainability of the ADS technology, this hypothesis will be subject to rigorous testing and a decision to reject it or not will be made by the end of this study. In a deductive manner, the goal is to make an inference by going from a general premise to a specific conclusion. Stages 3-5 of the research approach are covered in the solution phase of this study.

4.2.3. Research Type

Given that determining a single research type will not cover the full spectrum of this study, a three-dimensional research type is incorporated.

Firstly, based on the general category, a mixed methods approach is adopted where qualitative research is used to explore the situation, develop hypothesis, and capture nuanced topical information and quantitative methods are used to analyze the gathered information and test the hypothesis. The qualitative research part involves collecting and analyzing non-numerical data (text and audio) to understand concepts, opinions, or experiences. It is used to gather in-depth insights into the problem and potentially generate new ideas for research. As a method it focuses on obtaining data through open-ended and conversational communication, such as interviews. However, the analysis part of this research is mostly quantitative as even though no databases or strictly numerical datasets are investigated, the examination of technical documentation, the literature review and even the interviews are to produce largely numerical data, which must be analyzed in order to test the hypothesis. By analyzing the data quantitatively, the goal is to find patterns and describe the sustainability performance of the ADS.

Secondly, based on the type of data this is secondary research. This is the case because the data used to carry out this study has already been curated through primary research in the past. In other words, traditional secondary data sources such as books, trade journals, industry publications and records are readily used. Moreover, even when conducting interviews or reviewing technical documentation, the data remains secondary since the researcher hasn't carried out the primary data gathering. Of course, all research entails gathering and analyzing secondary data during the literature review stage of the research process but what characterizes this research is that even at the later stages, data is always gathered either through literature review or interviews - no direct data gathering is taking place.

Thirdly, based on the nature of the research, a mix of a descriptive research design and an explanatory research design is implemented. The descriptive research design part aims to obtain information to systematically describe the relevant problem context. More specifically, it encompasses answering the what, when, where, and how questions regarding the research problem, rather than the why. No control or change in any of the variables is facilitated, instead, the focus is on observation and measurement. It consists of gathering, analyzing, and presenting collected data. On the other hand, the explanatory research design part enables further exploration of theories and the why of the defined research question. As a method it is established to explore phenomena that have not before been researched or adequately explained, as is exactly the case with an innovative technology like the Archimedean Drum Screen and its corresponding supply chain.

4.2.4. Research Strategy

The research strategy provides the overall direction of the research including the process by which it is conducted. Thus, based on the nature of the research problem a case study strategy is applied. Reason being that the case study allows in-depth, multi-faceted explorations of complex issues in their real-life settings (Crowe et al., 2011) as is the case with the analysis of the ADS. In other words, a case study is defined as an " In-depth study undertaken of one particular 'case', which could be a site, individual or policy" (Green & Thorogood, 2009). More specifically, an instrumental case study (Stake, 1995) which uses a particular case (specific ADS technology) to gain a broader appreciation of an entire phenomenon (the entire set of ADS technologies) is applied.

As implied by the definition, crucial condition for a successful case study is that the researcher should have access to whatever constitutes the chosen unit of analysis for the study. What separates this case study from a traditional case study is that it relies on secondary data, therefore direct access to the unit of analysis (ADS technology) is unfeasible. Nevertheless, indirect access via the technology developers and evaluators is achieved. Hence, the selected information providers need to be hospitable to the inquiry (Stake, 1995) if they are to be informative and answer the research question(s). Therefore, great effort has been placed on ensuring that the selected providers of secondary data are willing to cooperate for the sake of completing the research. Moreover, to further aid in the implementation of a case study from secondary sources, the conceptual framework developed specifically for such cases by Reddy and Agrawal (2012) is followed – see Appendix A.

4.2.5. Time Horizon

Data will be collected at several points in time over the same sample of people – the experts as it pertains to the development of the ADS technology and its corresponding techno-economical and life-cycle assessments. To be more specific, the research design involves repeated observations of the same variables and the data gathering process takes place from 20th of August until 20th of November 2022. As such, the change is at the individual level – the situation as it pertains to the ADS technology - and not at the collective level. In other words, information about the same technology and from the same people will be compiled over a fixed time horizon instead of information from different sets of people or pertaining to different technologies. The purpose of this structure is to ensure that the inevitable changes in available information linked to that specific technology will be reflected in the study. Hence, the study is longitudinal by nature. However, unlike a social study, the subjects are not people but the ADS technology itself. The technology will be studied over time through the evolving knowledge of the people responsible for developing and evaluating it.

4.2.6. Sampling Strategy

As with any study, the chosen sample is critical to the overall research process. Therefore, specific rules for the sample selection process are laid out. First of all, the sampling strategy follows these steps: 1) conceive a general idea of where and with what population to start; 2) Select the target population, 3) Select the accessible population, 4) State the eligibility criteria, 5) Continue sampling until saturation is achieved.

Important to note is that the strategy does not aim at limiting the amount of sampling bias since the findings as a result of this research pertain to a technology and will not be generalized over a population (of which the data collection sample is representative). Nevertheless, due the nature of the research question, data is collected from highly knowledgeable experts - five people in total - that are either familiar with the workings of the technology or with any of the associated assessments (life cycle and techno-economic). In other words, a non-probability (non-randomized) sampling method is utilized. Though this type of sampling is less likely than probability sampling to produce representative samples it ensures that the two main requirements of the sampling (convenience & purposefulness) are met. Of course, practicalities such as the availability of appropriate experts, and resource constraints also play a role in that choice of sampling strategy.

4.2.7. Data Collection Method/s

The data collection methods applied in the project are literature review and informal in-depth interviews with the appropriate professionals, technology developers and relevant problem owners. Based on this mixed methods approach and as outlined in chapter 4.2.3. Research Type section 2, elements of quantitative and qualitative research are combined in order to answer the overall research question. The goal is to gain a more complete picture than the one a standalone quantitative or qualitative study can provide. From a quantitative point of view, numerical and measurable data stemming from the literature review of articles and relevant technical documentation will be analyzed. In contrast, qualitative data will be curated during both the interviews and the literature review.

For the most part, answering the questions in Table 1 can be achieved by simple data collection techniques (Cooper & Schindler, 2014). Literature review and in-depth interviews with experienced supply chain managers and LCA experts will be conducted for the sake of answering question Q1. Next to that, Q2 is tackled by examining technical documentation. However, due to the highly specific nature of Q2 the primary tool for information gathering will be formal and informal interviews with domain-specific experts and the developers of the ADS technology. Lastly, the essence of Q3 implies that a comprehensive study of what has been done so far (and has been documented in academia) must be conducted. Therefore, Q3 is also addressed by performing a systematic literature review. Throughout the entire data gathering process the goal is to achieve the highest level of measurement – ratio and interval (Cooper & Schindler, 2014), since one can always collapse interval/ratio data into nominal or ordinal groupings but expanding the other way around is impossible (McHugh, 2003)

4.2.8. Data Analysis Methods

When it comes to data analysis, a triangular approach is taken as the use of multiple sources of data has been advocated as a way of increasing the internal validity of a study (Delmont & Mason, 1997).

From a qualitative standpoint, content and discourse analysis are employed to effectively assess the relevant literature information and interview transcripts. Content analysis is used to evaluate patterns and identify the frequency with which pertinent ideas are shared. This will bring order to the collected data and greatly aid the subsequent steps as part of the solution process. In addition, discourse analysis is particularly suitable for studying written or spoken language in relation to its social context, which is crucial for making sense of the data when dealing with multiple stakeholders and a nuanced issue such as the sustainability of a technology. It should be noted that the nature of the research and the small sample sizes are expected to reduce the time needed for utilizing both methods. Moreover, since the purpose of the qualitative analysis is to merely prepare the data, give a direction and not draw any conclusions yet, fastidious implementation refinement of the methods is not required.

From a quantitative standpoint, the cleaned out and structured data stemming from the qualitative analysis is fed into the supply chain model which stands at the core of this research project. The model aids in defining, analyzing, and communicating the concepts related to the core research problem and makes additional interpretation leaps by utilizing the information. Subsequently, the data returned from the model is further analyzed to make additional conclusions, assess relationships between variables and test the hypothesis with the use of descriptive statistics. This is possible since the data coming out of the model is at the highest levels of measurement (ratio & interval) and is susceptible to algebraic manipulation. Regarding software, the data is analyzed exclusively via Excel and a strategic decision is made to not utilize (even supplementary) an LCA toolset (such as gabi) to avoid confliction of models.

4.3. Research Limitations

4.3.1. Methodological Limitations

Self-reported data

Self-reported data is limited by the fact that it rarely can be independently verified. In other words, what people say during the data collection process cannot be verified and must be taken at face value. Self-reported data can contain several potential sources of bias that are noted as follows: (1) selective memory: remembering or not remembering experiences or events that occurred at some point in the past; (2) telescoping: recalling events that occurred at one time as if they occurred at another time; (3) attribution: the act of attributing positive events and outcomes to one's own agency, but attributing negative events and outcomes to external forces; and (4) exaggeration: the act of representing outcomes or embellishing events as more significant than is actually suggested from other data. Since the interview participants are experts that are either involved in the design and engineering of the ADS technology or the respective life cycle & techno economic assessments their responses are likely to be biased to protect reputation, defend past decisions, etc. This issue is alleviated by reviewing and adjusting the interview questions which might elicit a clearly favourable answer on their behalf.

Lack of data

An evident lack of data as it pertains to the impact of the ADS technology is present. This results in the limitation of the scope of the analysis and becomes a significant obstacle in finding trends and meaningful relationships between variables. This lack of data stems from the innovative nature of the ADS technology and the fact that limited amount of real-life testing has been carried out. Moreover, even during the already performed initial testing, very small amounts of information were collected on behalf of the organization responsible for it. This limitation is addressed by adjusting the research scope and ensuring that any new data is promptly fed into the analysis.

4.3.2. Researcher Limitations

Limited access to data

Since the research involves receiving information from a limited number of (non-local) professionals and specific organizations, limited access to these respondents is present. Due to this limited access, the research design, including the time horizon and sampling strategy, is carefully structured so that no delays in carrying out the research occur. This limitation is further mitigated by optimizing the information gathering process and aiming to extract as much information as possible during each contact with the data providers.

Lack of time

The time available to investigate the research problem and to measure change or stability over time is constrained by the expected duration of the preparation and solution phases of this assignment (20 weeks in total) as set by the UT. This limitation is particularly relevant since with testing currently taking place, more information about the ADS technology becomes available with every next week. Nevertheless, the research problem is chosen so that completing the literature review, applying the methodology, and gathering and interpreting the results does not require an excessive amount of time and is not entirely a function of the ADS testing activities. Moreover, mitigation of this issue is also achieved by synchronizing crucial technology testing activities with the time horizon of this study.

5. Solution

5.1. Solution Context

To ease the reader in understanding the nature of the solution – and the corresponding value it brings to the problem owner – additional clarification about the relevant solution context and basic terminology is provided below. More specifically, essential information on the overall workings of the ADS technology, the broader system within which the clean-up technology is meant to operate, and the assumed perspective for modelling that system.

Archimedean Drum Screen

The Archimedean drum screen (Figure 6) is a variant design of the infamous Archimedes' screw - a slowly rotating screw that transports water. To provide a uniform outflow there is a screw surface installed on the inner cylinder of the screen. The outer drum is made of a stainless-steel mesh which functions to capture debris and litter and lets the filtered water sift through. For optimum functioning of the system there needs to be a flow of water inside the system. Hence, the system itself is modularly designed so a connection, for example, to an axial pump to create flow is possible. Ultimately, the technology works as a screen allowing 90% of the water flow to pass through while catching (plastic) debris and floating vegetation. What makes the screen unique is that it is completely fish friendly, so the collection of waste doesn't come at the cost of the local fish species, which exit the screen through a special outlet.

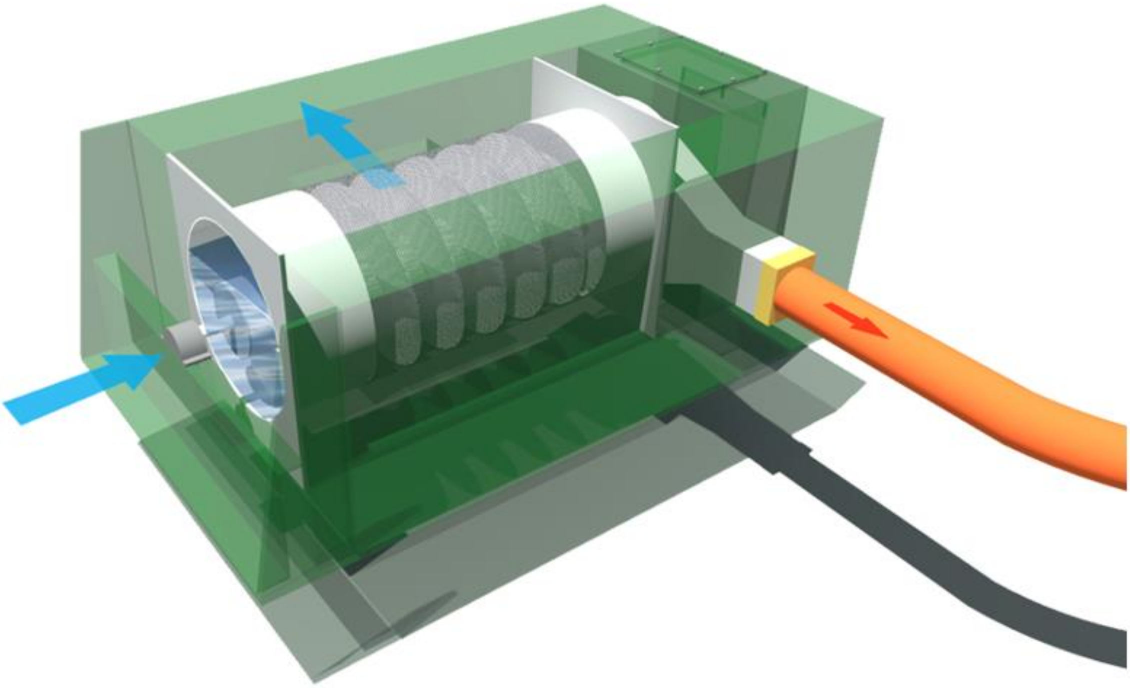

Figure 6. Archimedean Drum Screen design

Supply Chain

Since the ADS is only a single node in a much larger system of waste collection & waste management, it is of pivotal importance to gain an understanding and describe the processes resulting from the introduction of the ADS. To do so in a holistic and standardised way, the concept of "supply chain" is introduced to this paper.

The notion of “supply chain” is well established in the literature and has traditionally been referred to as “the alignment of firms that bring products or services to market” (Lambert et al., 1998). In simpler terms, La Londe and Masters (1994) propose that a supply chain is “a set of firms that pass materials forward”. More recently, Bridgefield Group (2006) defines Supply Chain as “a connected set of resources and processes that starts with the raw materials sourcing and expands through the delivery of finished goods to the end consumer”, whereas Pienaar and Vogt (2016) define it as a “general description of the process integration … to transform raw materials into finished goods and to transport them to the end-user”. The above definitions pinpoint the core determinants of a supply chain by signifying the need for a source and a destination within which goods flow. More specifically, they recognize that supply chains ought to start with resources (raw materials), combine several value adding activities and finish with the transfer of finished goods to consumers.

Evidently, in a biomass and plastic waste supply chain, the role of the ADS is to serve the raw material suppliers – the source. The subsequent value adding activities are to be performed by entirely different processes. Hence, due to the combinatorial supply chain complexity because of all the possible value adding activities and/or process inputs, a number of different supply chain scenarios must be identified. Those scenarios all have the ADS in common but differ in the ways of handling the output stemming from the clean-up technology.

Input Output Modelling

To effectively approximate the holistic sustainability impact of the ADS, the performance of the corresponding supply chain must be predicted. According to Epstein (2008) the best way of achieving such an approximation is by modelling it. Regarding the most appropriate type of model, Polenske and McMichael (2002) argue that as long as a supply chain is defined as a set of tightly interconnected production processes, converting raw materials into final products it can be described as an input-output system. Moreover, from a physical point of view, a supply chain is in principal an input–output system that encompasses the product flows existing among production processes (Storper & Harrison, 1991). Thus, the presentation of an input-output system makes it possible to understand the existing relationships among the production units by disaggregating the level of analysis and looking at the material and energy flows between production units. Additionally, input–output models have the ability to reflect supply chain linkages in industrial networks (Tan et al., 2019). Based on all of that, after devising a set of possible ADS supply chain scenarios, a corresponding set of input-output models representing the supply chains must be generated. This will aid in quantifying the scenarios and is a crucial step in evaluating the holistic sustainability performance of the ADS.

5.2. Solution Design

Solving a non-trivial research problem as the one posited in section 4.1. of this paper requires the implementation of an appropriate set of tools structured in the right way. Hence, to effectively address the problem statement, a five-stage solution process is adopted – Figure 7. The process is part of the broader problem-solving approach – Appendix B – defined prior to implementing the solution. Every phase of this solution strategy is crucial for achieving the overall research objective and has been carefully crafted in accordance with the theoretical framework. Visualizing the solution design also aims to bring more clarity into the solution development procedure, which is covered in the ensuing chapters.

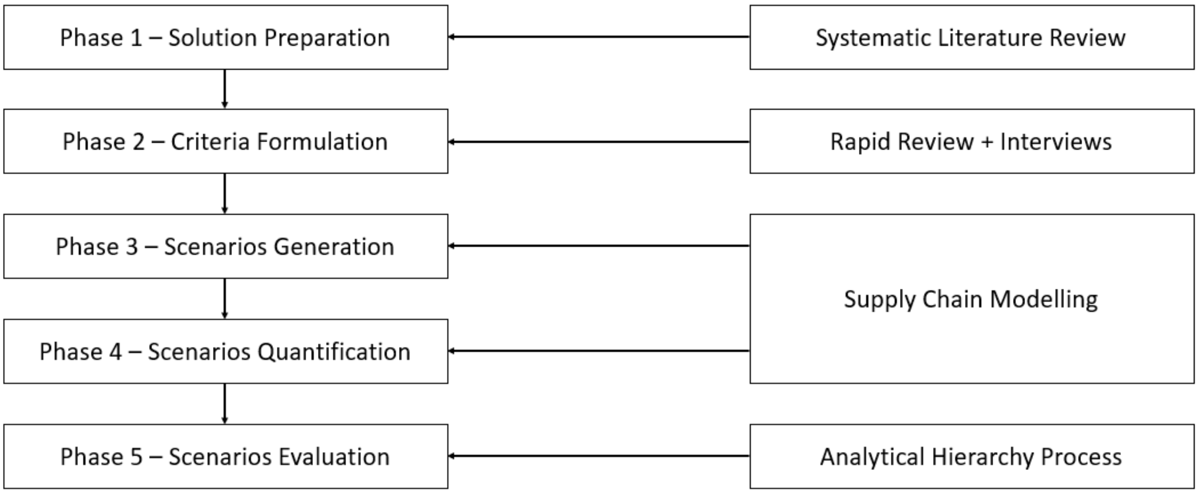

Figure 7. Solution design

5.2.1. Solution Preparation

Solution preparation is the first step of the solution execution phase, and it serves the purpose of addressing the research questions of this study – Table 1. Hence, to aid the solution development process, a systematic literature review is carried out. Though the review aims primarily at answering Q3: *"How to measure sustainability across a supply chain resulting from the introduction of a novel technology?"*, major insights into answering the other research questions are also gained. This review is based on the theory provided so far in the IEM program, specifically in module 11, combined with the methodology outlined in "How to do a systematic literature review" (Papadopoulos & Rheeder, 2000). As a result, the review adheres to the guidelines set by the UT with some very small variations always supported by literature. The resultant systematic literature review synthesis is presented below. Further details about the review (Inclusion & exclusion criteria, Search terms, Search strategy, etc.) are provided in Appendix C.

Systematic Literature Review Synthesis

To begin with, owing to the comprehensive nature of the term sustainability, effective measurement (across a supply chain or not) is not feasible unless a specific perspective is adopted first. However, one of the big challenges in researching sustainability is the lack of consistent definitions in the literature (Moore et al., 2017) as 'sustainability' remains an open concept with myriad interpretations and context-specific understandings. Hence, getting a grasp on how to address issues of sustainability is one of the most significant translational research problems of our time (Proctor et al., 2015).

Of course, a ubiquitous definition of sustainability is the one supplied by the United Nations Brundtland Report (1987): "Meeting the needs of the present without compromising the ability of future generations to meet their own needs". But as such, the definition lacks the intricacies necessary for proper operationalization and evaluation. Nowadays, sustainability performance is usually evaluated from multiple aspects within the triple bottom line framework. (Wang et al., 2020) (Neri et al., 2021) Likewise, as it pertains to supply chains, sustainability deals with environmental, social, and economic factors (Badiezadeh et al., 2018). Or in other words, in the context of supply chains sustainability balances profit, competitive advantages, and environmental considerations (Kalantary & Farzipoor Saen, 2022). Yet, some researchers do not approach sustainability from a holistic point of view but rather utilize an agent-based perspective by emphasizing that companies are the critical contributors to the social, environmental, and economic well-being of communities (Varsei et al., 2014). Others refer to it as the management of material and information flows as well as cooperation among companies along the supply chain while taking economic, environmental, and social goals into account (Erol et al., 2011).

As apparent from the above definitions, an emerging common thread is the reliance on the environmental, social, and economic dimensions (Mori and Christodolou, 2012), also referred to as pillars (Moldan et al., 2012), perspectives (Arushanyan et al.,2017), components (Zijp et al.,2015), etc. However, even this particularly prevalent tripartite overall description of sustainability is not without its criticism. Thompson (2017) notes “much of the discourse around sustainability is organized around the three-circle rubric without much disciplined thought about how it does and does not translate into a more comprehensive understanding of sustainability”. And even though much contemporary sustainability literature revolves around the United Nations’ more diverse set of sustainable development goals (SDGs), the three pillars themselves were still explicitly embedded in their formulation (UN, 2012). Regardless of these considerations, the triple bottom line perspective is universally recognized by industry practitioners evidenced by the widespread exploration of trade-offs among economic, environmental, and social performance of supply chains, which, in turn, could assist in creating a viable business case for sustainability (Varsei et al., 2014). Moreover, the perspective also remains omnipresent in research (Purvis et al., 2019), and will therefore be embraced by this paper.

When it comes to sustainability measurement, interest has grown exponentially over the recent years, and the topic is becoming established in different areas of research, including (amongst others): industrial engineering and supply chain management (Mura et al., 2018). Mura and colleagues (2018) also add that from a research viewpoint, the most frequently used theories in sustainability measurement studies can be grouped into two categories: (1) socio-political theories such as legitimacy theory and institutional theory and (2) managerial theories such as agency theory and Simon's levers of control, which focus on the organization's governance and strategy. These theories serve as the backbone for the ensuing sustainability measurement techniques.

The literature is unequivocal on the point that sustainability performance ought to be assessed by both qualitative and quantitative criteria (Govindan et al., 2013) Subsequently, the inclusion of both qualitative and quantitative data analysis techniques, by developing a novel practical method, to measure sustainability performance of supply chains with incomplete information, has been investigated by research (Qorri et al., 2022). The results show that the solution is a combination of Content Analysis, Experts Evaluations, fuzzy Entropy and fuzzy TOPSIS. In addition, the solution also considers all three sustainability dimensions across the entire supply chain, from raw material providers to consumers to reverse logistics providers. This also stems from the understanding that broad integrated approach to examine interactions among environmental, economic, and social dimensions is often better than applying deep, but disconnected expertise in each one (Varsei et al., 2014), particularly in the environmental dimension. In another paper by Qorri et al. (2018) a novel conceptual framework and a guideline for evaluating sustainability of supply chains are suggested. Moreover, Life-Cycle Assessment is also brought up as a widespread and particularly crucial tool for assessing sustainability across supply chains.

Another notable sustainability measurement technique is the combination of an input-output modelling approach and a data envelopment analysis (DEA) procedure. The measurement technique can account for the multidimensional characteristic of supply chains in a global context (Wang et al., 2020). In a similar manner to Wang, Kalantary and Farzipoor Saen (2022) propose a dynamic data envelopment analysis model of the inverse type to assess the sustainability of supply chains. A unique aspect of their approach is that the sustainability is assessed via a Learning by Doing (LBD) criterion that is being projected on learning curve models. Other studies present the development and application of an additive network DEA model suitable for sustainability estimation of multi-stage processes (including supply chains, production systems, etc.) (Kahi et al., 2017) Another advocate for the DEA approach is Badiezadeh et al., (2018) who focuses on evaluating the performance of supply chains in the presence of Big Data – something not achievable given the current context.

Evidently, the literature indicates that measuring SC sustainability performance is a multi-criteria decision making (MCDM) problem and it identifies 15 MCDM techniques from which two main clusters are recognized - Analytic Hierarchical Process and Weighted Arithmetic Mean (Diaz-Balteiro et al., 2017). Crucially, due to the multidimensional nature of supply chain performance assessment, multi-criteria decision making, and multi-objective mathematical programming approaches have been extensively documented in literature (Brandenburg et al., 2014). Yet, other methods still exist. For example, another widely adopted strategy for the measurement of sustainability across supply chains is implementing an analytical framework. This framework is based on the principles of elimination, substitution, redesign, and efficiency improvement to the respective design of supply chains (Schaltegger & Burritt, 2014).

However, even though the application of MCDM techniques for measuring SC sustainability performance is increasing, according to Qorri and colleagues (2022) to increase the accuracy of the assessment, such methods should be combined with fuzzy logic since it is a suitable approach for integrating uncertainty, intangibility, and vagueness. Strong cases for the application of fuzzy logic in sustainability measurement are the papers by Erol et al., (2011) and Govindan et al., (2013). Both papers advocate for the application of MCDM methods together with fuzzy logic to deal with vagueness in decision-making problems when it comes to improving sustainability. More specifically, the use of fuzzy entropy and fuzzy multi-attribute utility is documented by Erol et al. (2011), whereas TOPSIS and AHP are investigated by Govindan et al. (2013).

As far as sustainability indicators are concerned, the literature supports mapping between the three sustainability dimensions and the respective set of indicators. More specifically, a comprehensive study carried out by Saeed & Kersten (2017) and based on content analysis led to 70 unique and coherent Sustainability Performance Indicators (SPIs). Out of which 49% indicators were identified as environmental SPIs, 37% as social SPIs and 14% as economic ones. A later study by Saeed & Kersten (2020) yielded a unique and coherent list of 68 SPIs. Of these indicators, 47% originated from the environmental sustainability dimension, 31% from the social sustainability dimension, and 22% from the economic sustainability dimension.

On the other hand, Neri and colleagues (2021) propose a novel set of 33 KPIs, based on a Balance Score Card - Supply Chain Operations Reference integrated framework. The proposed set: i) assures a balanced coverage of the sustainability pillars and related intersections; ii) addresses different decision-making levels, financial bases, and components of performance; iii) simultaneously tackles the sustainability performance of an entire supply chain. The final set is also empirically validated and organized according to six perspectives: Financial, Internal Process, Learning and Growth, Customer, Environmental and Social. More recently, Kalantary and Farzipoor Saen (2022) also discuss a range of sustainability KPI’s: pollution control, number of obtained ISO standards, rights of employees, financial capability, etc. and underline the difficulty in combining different aspects of sustainability especially during measurement.

In conclusion, embracing the triple bottom line perspective is a must when approaching problems related to supply chain sustainability measurement. Two theories are leading the way in sustainability measurement research: 1) socio-political and 2) managerial, and the investigated literature is unambiguous on the point that sustainability performance ought to be assessed by both qualitative and quantitative criteria. Moreover, in line with Qorri et al., (2018), this review shows that various measurement approaches are used to assess sustainability in different supply chains. The application of multi-criteria decision-making methods is increasing, and several promising measurement frameworks have been developed. The most used sustainability measurement techniques include Analytical Hierarchy Process, Fuzzy set approach, TOPSIS and Data envelopment analysis, with Life Cycle Assessment used as a basis for the quantifications. For increase in accuracy and precision, combining some of the latter techniques is also possible – with the combination of fuzzy logic and traditional MCDM methods (such as AHP) being prevalent. Last but certainly not least, the literature is rich in different KPI's suitable for tracking sustainability performance and advocates for establishing a strong link between KPI's and sustainability dimensions.

5.2.2. Criteria Formulation

To effectively shape the impact of an innovation on sustainability, the early phases of the innovation process are crucial. This is especially true for complex collaborative R&D projects with multiple partners – as is the case with In-No-Plastic. According to the literature review summarized in the previous section, meeting this ever-increasing need for simple methods that enable partners in such projects to carry out sustainability-oriented assessments is best achieved by embracing the triple bottom line perspective. Hence, in congruence with the literature review, the criteria applied in this study consists of a selection of sustainability performance indicators (in varying importance) used for evaluating the different supply chain scenarios stemming from solution phases 3 & 4. Notably, the criteria and corresponding weights are formulated prior to conceiving the supply chain scenarios to avoid bias.

First, based on the analysed literature and the information gathered through the interviews, an uncategorised list of KPIs is curated (93 KPI's in total). Subsequently, the preliminary list of KPI's is reduced to only those that are applicable[2]. The applicable KPIs are divided per perspective (environmental, societal, economic) and per category (12 categories in total) – Table 2. Six KPI categories are assigned to the environmental dimension, whereas three KPI categories are assigned to the social and economic dimension.

	CATEGORIES	KEY PERFORMANCE INDICATORS
ENVIRONMENTAL	Energy Efficiency	Total annual energy consumption
		Total annual renewable energy consumption
	Material Efficiency	Total annual material consumption
		Total annual renewable material consumption
		Total annual recycled material
	Water management	Total annual volume of utilized water
		Industrial water-use efficiency
	Waste management	Total amount of waste generated
		Total amount of waste collected
		Percentage of reused waste
	Emissions	Total annual amount of direct GHG (CO$_2$, CH$_4$, N$_{20}$, HFCs, PFCs, SF$_6$, NF$_3$) emissions (Scope -1)
	Land use	Total size of operational sites/facilities
SOCIAL	Human rights	Percentage of employees entitled to life insurance, healthcare, pension, and parental leave
		Total annual salary per employee
	Human resource	Total annual number of employees
		Total annual number of new employees
		Total annual number of new female employees
		Total annual turnover per employee
	Local community impact	Total number of new jobs from the region
		Openness to local stakeholders' involvement in decision making
		Total number of local lost jobs

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[2] An applicable indicator should reflect supply chains' environmental, social, or economic performance.

ECONOMIC	Stability and profitability	Total revenue
		Operating profit
		Free cash flow
	Income distribution	Total annual amount of wages and benefits given to employees
		Total annual amount of taxes paid to the government
	Market competitiveness	Ratio of entry-level wage to minimum wage
		Expected annual growth
		Margin on sold products

Table 2. Applicable KPIs

Lastly, to ensure that the KPI's can be successfully utilized during the supply chain performance evaluations, they are subject to a final round of filtering. The characteristics that must be met by each KPI are listed in Table 3.

#	CHARACTERISTIC	DESCRIPTION
1	Measurable	An indicator should be possible to measure
2	Clear	An indicator should be unambiguous, simple, and understandable to a wide range of audiences.
3	Balanced	An indicator should reflect both positive and negative performance
4	Comparable	An indicator should have a target level, a baseline or be able to support in analysing relative performance to other supply chains
5	Distinct	An indicator should be unique in meaning and doesn't carry information that overlaps with other indicators

Table 3. Characteristics of KPIs

Applying the matrix on the applicable KPI's results in Table 4. To ease the analysis and ensure no dubiousness (and meeting characteristic #5), a single specific KPI is mapped to each sub-category. Certain KPI's are adjusted in unit size to provide a better reflection of the solution (for example, total annual number of employees converted to total annual number of person hours and total annual amount of taxes paid to the government converted to total annual profit). Important yet constant in value KPI's such as "total amount of waste collected" and "total annual volume of utilized water" are not included in the final list, since their quantifications will remain the same throughout the scenarios and as such wouldn't contribute to the comparison process. Such KPI's matter in absolute terms but not in relative terms.

CATEGORIES		KEY PERFORMANCE INDICATORS
ENVIRONMENTAL	Energy Efficiency	Total annual energy consumption
	Material Efficiency	Total annual recycled material
	Water management	Industrial water-use efficiency
	Waste management	Percentage of reused (non-incinerated) waste
	Emissions	Total annual amount of direct CO_2 emissions
	Land use	Total size of operational sites/facilities
SOCIAL	Human rights	Total number of new employees entitled to life insurance, healthcare, pension, and parental leave
	Human resource	Total annual number of person hours
	Local community impact	Openness to local stakeholders' involvement in decision making

ECONOMIC	Stability and profitability	Total revenue
	Income distribution	Total annual profit
	Market competitiveness	Margin on sold products

Table 4. Final KPI's

5.2.3. Scenarios Generation

Since the holistic sustainability performance of the ADS is largely dependent on the subsequent managing of the waste, assessing only a single waste management scenario might unjustifiably deem the technology unsustainable. Therefore, the purpose of the Scenarios Generation effort is to ensure that multiple and distinctive waste handling cases are explored. Hence, with the help of the customized theoretical framework and the information gathered from the interviews and the literature review, three meticulously thought-out scenarios are generated. Each scenario is characterised by a different set of clearly defined system boundaries and describes the utilization of the primary system input – seawater – in a different way. Due to capacity considerations, some processes are pooled together, and negligible process inputs/outputs are omitted. As a result, certain value-adding activities encompass multiple sub-steps, and only their main material and energy inputs/outputs are included in this analysis. Moreover, a commonality between all scenarios is the presumed Power Plant and ADS industrial symbiosis. This categorical location (positioning the ADS next to power plants) has been established as the most viable option for integrating the ADS into already existing processes based on discussions with In-No-Plastic partners and a brief market analysis. As a result, the problem is effectively transformed into a post-collection waste handling one.

5.2.3.1. Scenarios

Scenario 1. Waste separation case

The waste separation scenario is characterized by the systematic sorting of the waste stemming from the ADS. More specifically, after the initial partition into biomass and plastic waste, a second filter is applied to separate between low and high value plastics. In the end, the three waste streams are handled differently: the biomass is liquified, the low-value plastic is incinerated, and the high-value plastic is recycled.

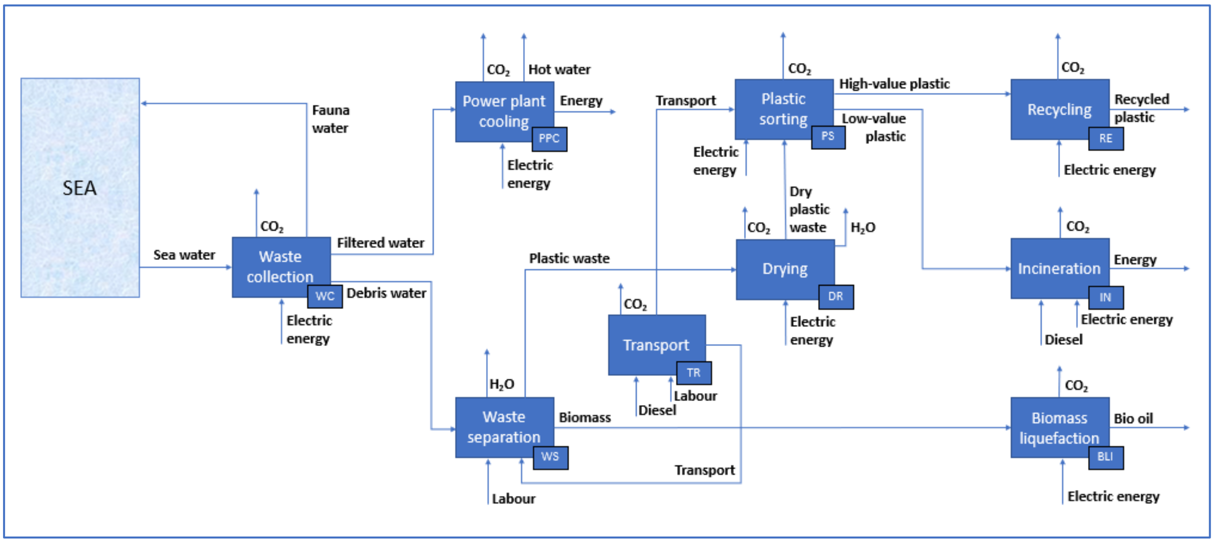

Figure 8. Waste separation case

Scenario 2. Waste pelletizing case

The waste pelletizing scenario is characterised by its innovative yet very effective approach to handling the ADS outputs. By eliminating the additional waste separation steps, this scenario assumes that the biomass and plastic wastes collected by ADS are processed together. More specifically, the combined waste stream is dried, shredded and converted into bio-pellets.

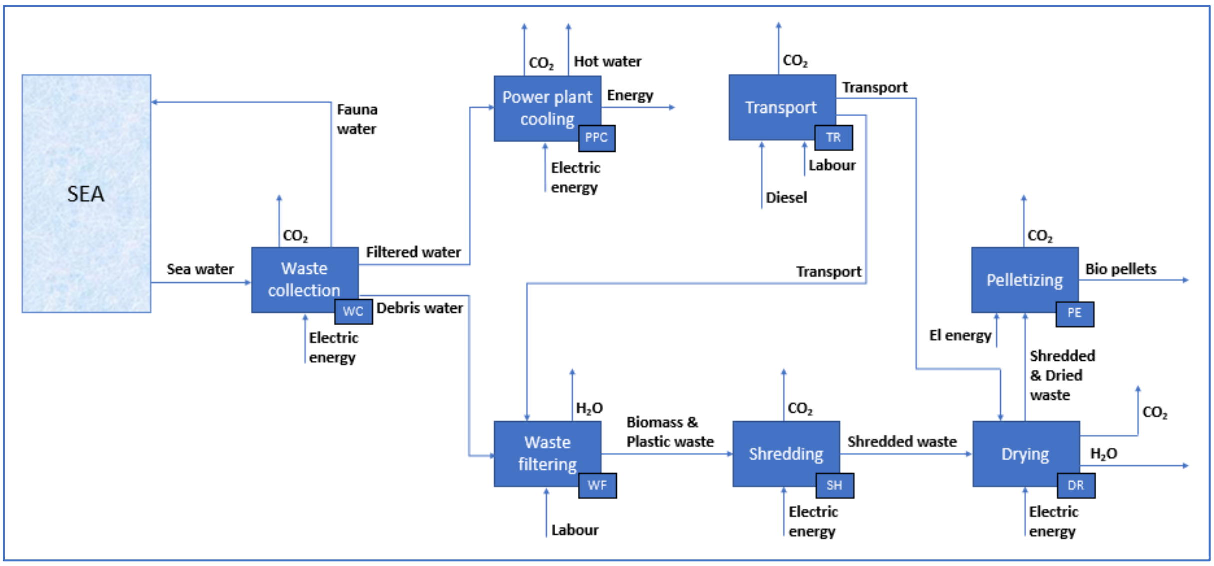

Figure 9. Waste pelletizing case

Scenario 3. Waste liquefaction case

The waste liquefaction case is characterised by its lack of sophistication and corresponding efficiency. Much like the waste pelletizing case, no waste separation takes place. What's more, to avoid further energy waste, the drying step is omitted. As a result, the combined waste stream – biomass and plastic – is directly liquefied and converted into bio-oils.

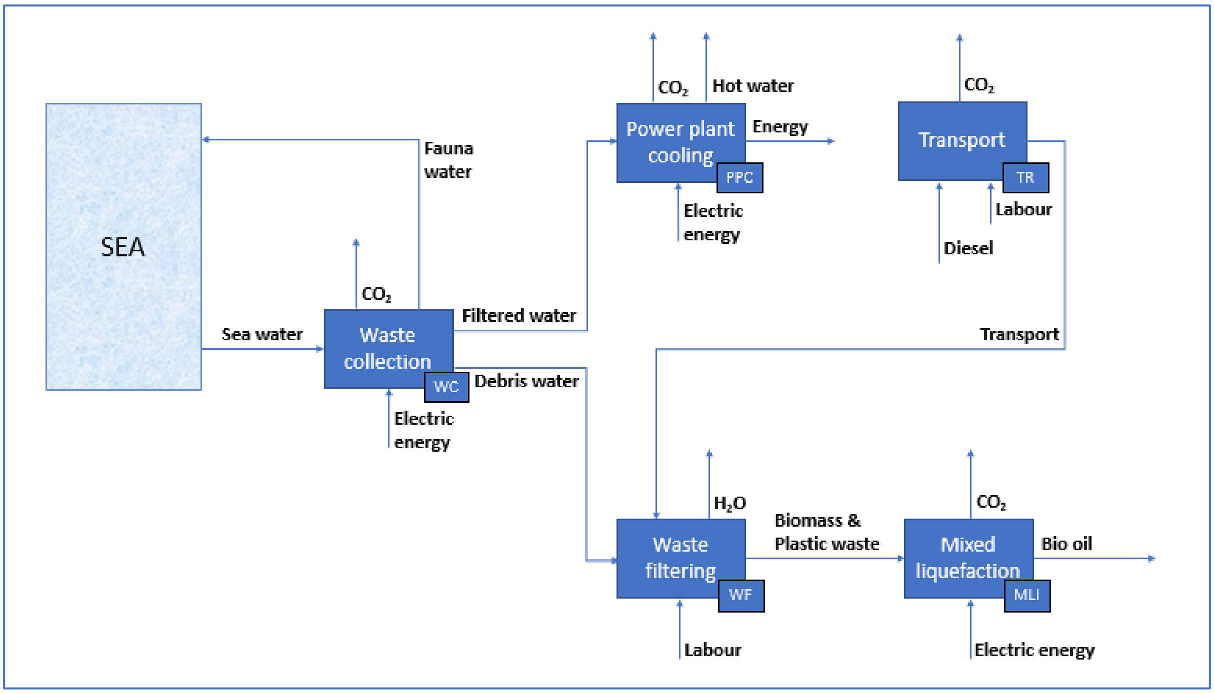

Figure 10. Waste liquefaction case

5.2.3.2. Processes

Further information on the value-adding activities that are used as building blocks for constructing the scenarios is provided below.

Waste Collection (WC)

Evidently, each of the supply chains starts with the waste collection step – representing the operations of the ADS technology. The primary input of this process is seawater[3], complemented by electric energy. The only labour associated with this step is the one for setting up the technology, so no continuous labour input is required. The associated outputs are filtered water (90% of input seawater), debris water (9% of input seawater) and fauna water (1% of input seawater). The debris water is the one containing the biomass and plastic waste and the fauna water contains the marine animals.

Power Plant Cooling (PPC)

A pivotal step in the supply chain is the immediate use of the filtered water resulting from the operations of the ADS. Based on a brief market analysis, discussion with potential customers, and information provided by FishFlow, a suitable application is selected – power plant cooling. As a result, every scenario starts with the same combination of waste collection and power plant cooling. The choice of use case is supported by evidence that invasions of marine animals (primarily jellyfish) have proved adept at shutting down power plants (Associated Press, 2013). Hence, a strong business case can be built around the ADS – serving as a supplier of filtered water that can prevent such problems while being 100% fish friendly. Accordingly, the economic benefits to the power plant operators are related to the savings from preventing power plant shutdowns and from not having to finance a dedicated cooling system cleaning procedure. It is also crucial to note that the (usually gravitational) water pumps of the power plants are strong enough to accommodate the addition of the ADS to the water extraction process without requiring the addition of an axial pump to increase the water flow. Still, due to the presence of an extra filter (ADS), a slight increase in the energy consumption of the main water pumps is anticipated and reflected in the analysis. An important consideration is that a single ADS is not sufficient for filtering all water required by a (typical) power plant for cooling. Hence, the ensuing analysis assumes the implementation of 15 ADS technologies.

Waste Separation (WS)

The waste separation activity is the first step of the waste handling procedure whenever the biomass and the plastic must be segregated. Yet, due to the intricate nature of the separation, automation of this process is not feasible. To be more precise, separation by any specific material property is not easily achievable since neither the biomass nor the plastic particles in the water are typified by a specific size, colour, etc. that makes automated differentiation between the two easy. Therefore, the combined waste is collected via nets (<4mm diameter holes), allowing for the water to flow through. Subsequently, the nets are removed from the water and the waste streams are separated via manual labour of trained staff.

Drying (DR)

Drying plays an important role in both the waste separation and the waste pelletizing scenarios. In general, drying is used to minimize or eliminate complications that may be caused by too much moisture – which is certainly an issue for biomass and plastics recovered from water. Notably, the drying process is one of the more energy intensive ones across the entire supply chain covered within the analysis but remains crucial for value-generation.

In the waste separation case, drying of plastics is achieved in a two-step manner. The first step is the use of a simple centrifugal drying machine. Due to its unique design, the dewatering machine has comparatively low energy consumption and can take in material with high water content and reduce it

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[3] Seawater - water from sea or an ocean. As defined in: Sea water (sciencedaily.com)

to low levels (~20%). Next, to further the drying process, a thermal dryer is used in getting the moisture levels to below 3% - so that the plastics can be effectively recycled or incinerated.

When it comes to the pelletizing case, the drying of combined biomass and plastics is achieved via a screw press squeezer. The moisture content is reduced to approximately 3%, which is a suitable level for the ensuing step - densifying. To complete the drying process, the screw press squeezer heats the combined waste stream and densifies it into small granules that can be used directly in pelletizers.

Plastic sorting (PS)

Plastic waste is usually sorted through a sequence of sorting steps (Ragaert et al., 2017) and comprises sorting on size and on type of material. Because of the nature of the waste collection process the typical float sink separation step (Civancik-Uslu et al., 2021) can be omitted, since only floating debris are collected in the first place. To further simplify the process, only two different types of plastic are distinguished - high value plastics and low value plastics. High-value plastic stand for easily recyclable fractions rich in films – PET, HDPE & PP, whereas low-value plastic includes those fractions that are difficult and expensive to recycle – PVC, LDPE, PS, etc ("Which plastic can be recycled?", 2021). Because of the nature of the waste collection process there is no need for float sink separation, since only floating debris are collected in the first place. The technique used for the sorting is an automated near infrared spectroscopy sensor (NIR). The sensor identifies the type of plastic and employs jets of air to separate the different types of plastic in different directions.

Transport (TR)

An irreplaceable and not to be neglected process, transport serves as the link between the different value-adding activities. Despite being a significant source of air pollution, it remains a pivotal part of every modern material related supply chain – including the three scenarios described above. The method of transport to be applied to the scenarios is roadway, with traditional semi-trailer trucks (trailer dimensions[4]: 12m, 4m, 2.55m) as the choice of vehicle. Obviously, the associated inputs are labour and diesel. The choice of diesel fuel for the scenario evaluations stems from the prevalence of diesel run trucks in Europe - approximately 95.8% of newly registered trucks[5]. The outputs considered in the assessments are transport (as an input to other processes) and CO_2.

Recycling (RE)

The recycling activity is the final stage of plastic waste handling and consists of multiple different sub-processes. In principle, the main steps within recycling are washing, drying, shredding, milling and extrusion (Civancik-Uslu et al., 2021), which ultimately results in plastic pellets. In this analysis, the energy intensive and complex drying stage is regarded as separate from the recycling and has a dedicated activity which is described above. Also, since the plastic supplied as input to the value chain has been in water, a less intensive washing process is required. Therefore, the washing step is omitted. Yet, effective shredding, milling and extrusion still must take place to achieve sufficient market level quality plastic granulate. Hence, the sorted high-value plastics is shredded – resulting in particles of grain sizes of approximately 300mm to 100mm (IUT, 2019). Subsequently, milling ensures that the particles are reduced to a size of approximately 20mm. Finally, the plastic pellets are formed via a single screw extrusion process, which is the state-of-the-art method for extrusion of secondary raw materials (IUT, 2019).

Incineration (IN)

Incineration is the process of burning hazardous materials at temperatures high enough to destroy contaminants (EPA, 2012) As such, it is suitable for handling the low-value plastic (PVC, LDPE, PS, etc.) stemming from the plastic sorting process. Admittedly, the primary reason for the use of incineration is that it is the current state-of-the-art due to cost efficiency. This is the case since

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[4] https://www.itf-oecd.org/sites/default/files/docs/dimensions-2019.pdf

[5] https://www.acea.auto/figure/trucks-eu-fuel-type/

handling the low-value plastic in an environmentally friendly, yet economically viable way is difficult. Moreover, although incinerators require a lot of fuel for their operation, the heat generated can be used to generate electric power in a “waste-to-energy” manner. In terms of requirements, a traditional moving grate incinerator (waste moving through the combustion chamber), is sufficient.

Liquefaction (LI)

Hydrothermal liquefaction is a thermochemical depolymerisation process in an enclosed reactor to convert wet biomass (that can also be mixed with other waste) into biocrude oil (Zhang & Chen, 2018). The conversion takes place at moderate temperature (typically 200–400°C) and high pressure (typically 10–25 MPa). When it comes to the waste separation scenario, biomass liquefaction is an energy intensive, costly process but enables the whole of biomass to be processed to a single entity without any need of dewatering, thus minimizing other postprocessing problems (Chiaramonti et al., 2015). This greatly reduces the overall costs and enables the supply of bio-oils at competitive prices.

The latter benefits are amplified even more in the mixed (waste) liquefaction case. More specifically, conversion of mixed plastics to fuel oil via liquefaction has been well demonstrated in the scientific literature (Benavides, 2017), as has hydrothermal conversion of biomass (Behrendt et al., 2008), as well as unseparated municipal waste (plastic & biomass) (Seshasayee & Savage, 2019). Therefore, since both biomass and plastic waste are carbon-based, no separation step is required, and the entirety of waste can be converted into bio-oils via hydrothermal liquefaction. Liquefaction is also selected over conventional pyrolysis because the process equipment is simple and relatively inexpensive compared to conventional pyrolysis.

Pelletizing (PE)

Waste pelletizing offers an interesting and flexible alternative to waste energy recovery - as the last step of the value chain - since pellets are easy to transport and can be sent to a variety of industrial applications. The process condenses the waste and solidifies it to produce fuel pellets, also referred to as refuse derived fuel (RDF). The calorific value of RDF pellets can be around 4000 kcal/ kg depending upon the percentage of organic matter in the waste. Crucially, the presence of plastics within the waste can boost the heat content value since the plastics serve as natural binder materials. This is also likely to lessen the need for costly post-industrial plastic additives and decrease the cost of the pellets. Demand for RDF is continuously increasing with market growing at an annual CAGR in the range of 3.5% to 5.5% (depending on the biomass type) with important applications in cement kilns, power plants and industrial steam/heat boilers.

5.2.4. Scenarios Quantification

To effectively quantify the scenarios, the solution design dictates their representation as input-output models. Hence, each supply chain architecture is described as a physical input output table and a monetary input output table (Raa, 2006). Overview of the physical input output tables is provided in Appendix D. The information used for quantifying the inputs of the physical input output tables is supplied in accordance with the data collection methods and can be classified into three types – gathered from literature review, supplied internally within In-No-Plastic and derived from the already gathered information. The sources used for justifying the inputs of the physical input output tables are summarised in Table 5. The “In-No-Plastic” tag denotes information supplied internally by partners inside In-No-Plastic. The primary tool for the data gathering within the project is in-formal interviews with the appropriate professionals and relevant problem owners. However, sporadically, data has also been gathered via emails and extraction from technical documentation. The “Derived” tag denotes information obtained by performing calculations with the already existing parameters/inputs within In-No-Plastic and/or the external sources of information. The remainder of the tags indicate the name of the author/s of the relevant publications.

	Electric energy	**Labour**	**Water**	**Plastics**	**Biomass**
WC	In-No-Plastic	-	In-No-Plastic	In-No-Plastic (Debris water data)	
PPC	In-No-Plastic + Frontier [6]	-	In-No-Plastic	-	-
WS	-	In-No-Plastic	In-No-Plastic	Derived	Derived
TR	-	Derived + EC[7]	-	-	-
DR	Amstar[8]	-	Ensinger[9]	Jean-Paul[10]	Derived
PS	Pellencst[11]	-	-	Erni-Cassola et al.[12] + McKinsey[13]	-
RE	Larrain et al.[14]	(IUT, 2019)	-	Larrain et al.	-
IN	Hyeong-Woo et al.[15]	-	-	-	-
BLI	Yang[16]	-	-	-	Derived
WF	-	In-No-Plastic	In-No-Plastic	Derived	Derived
SH	Larrain et al.	-	-	Derived	
PE	Larrain et al.	-	-	Derived	
MLI	Yang	-	-	Derived	

	Transport	**Diesel**	**CO_2**	**Energy**	**Bio oil**
WC	-	-	BP Statistical Review of World Energy[17] Ember European Electricity Review[18] CO2emissie-factoren.nl[19] BASF[20]	-	-
PPC	-	-		In-No-Plastic	-
WS	In-No-Plastic	ICCT[21]		-	-
TR	-			-	-
DR	-	-		-	-
PS	In-No-Plastic	-		-	-
RE	-	-		-	-
IN	-	Hyeong-Woo et al.		Hyeong-Woo et al.	-
BLI	-	-		-	Shakya et al.[22]
WF	In-No-Plastic	ICCT		-	-
SH	In-No-Plastic	-		-	-
PE	-	-		-	-
MLI	-	-		-	Shakya et al., Mukandan et al.[23]

Table 5. Physical-input output table sources

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[6] PROFITABILITY AND DISPATCH OF MPP3 POWER PLANT AFTER COAL PH (frontier-economics.com)

[7] Road transport workers - Your Europe (europa.eu)

[8] Plastic Recycling Machines - Plastic Pelletizers, Shredders & Granulators

[9] Dimensionally stable plastics | Ensinger (ensingerplastics.com)

[10] Managing Plastic Waste—Sorting, Recycling, Disposal, and Product Redesign (utwente.nl)

[11] MistralCONNECT-2021-WEB-UK_1.1.pdf (pellencst.com)

[12] Distribution of plastic polymer types in the marine environment; A meta-analysis - ScienceDirect

[13] stemming the tide full report.ashx (mckinsey.com)

[14] Techno-economic assessment of mechanical recycling of challenging.pdf

[15] (PDF) Life cycle impact assessment of the environmental infrastructures in operation phase: Case of an industrial waste incineration plant (researchgate.net)

[16] A Comparison of Energy Consumption in Hydrothermal Liquefaction and Pyrolysis of Microalgae | Request PDF (researchgate.net)

[17] Statistical Review of World Energy | Energy economics | Home (bp.com)

[18] European Electricity Review 2022 | Ember (ember-climate.org)

[19] Lijst emissiefactoren | CO2 emissiefactoren

[20] Life cycle assessment (LCA) for ChemCycling™ (basf.com)

[21] Fuel consumption testing of tractor-trailers in the European Union and the United States - International Council on Clean Transportation (theicct.org)

[22] Effect of temperature and Na2CO3 catalyst on hydrothermal liquefaction of algae - ScienceDirect

[23] hydrothermal co-liquefaction of biomass and plastic wastes into biofuel: Study on catalyst property, product distribution and synergistic effects - ScienceDirect

The sources used for the construction of the monetary input-output tables (Appendix E) are presented in the excel sheets provided as a supplement to this paper. Important to note is that the monetary input-output tables don't incorporate equipment amortization costs since the majority of the plastic processing equipment, with the exception of the ADS, spends only a negligible amount of work time in this supply chain. Therefore, it is unreasonable to assume that the occurring amortization is due to the participation in this system.

The resulting quantifications per each scenario per KPI are presented below. Two general quantification cases are distinguished. Firstly, a base case covering the entirety of the three supply chain scenarios (collection & post-collection handling of waste). Secondly, a limited case omitting the Waste Collection and Power Plant Cooling processes and covering exclusively the post-collection handling of waste for each of the three supply chain scenarios. The reason for the distinction is that Waste Collection and Power Plant Cooling are (by far) the most energy intensive and carbon emitting processes of every scenario, yet their inputs/outputs remain constant throughout all scenarios and therefore can convolute the analysis and overcomplicate the comparison of the different waste handling approaches. Therefore, the holistic quantification, reflecting conventional input-output analysis standards, is presented in Table 6, whereas Table 7 can be used to easily compare the post-collection handling of waste phases of each scenario.

Key Performance Indicator	***Unit***	***Scenario 1***	***Scenario 2***	***Scenario 3***
Energy consumption	kWh	1 118 529	1 089 702	1 120 600
Recycled plastic	ton	4.2	0	0
Industrial water-use efficiency	m3/ton	39 141 593	26 058 153	33 623 423
Reused (non-incinerated) waste	%	40.00%	100.00%	100.00%
Total CO_2 emissions	kg	383 255	361 924	371 520
Size of operational facilities	m2	600	350	300
Percentage of employees entitled to benefits[24]	%	4.82%	100.00%	100.00%
Number of person hours	person hours	2 616	169	153
Stakeholder involvement	relative	High	Moderate	Low
Total revenue	euro	640 402	720 710	680 182
Total profit	euro	350 317	373 451	360 656
Expected annual growth	% (CAGR)	4.80%	5.50%	4.20%

Table 6. Base quantification (values are per annum)

Key Performance Indicator	***Unit***	***Scenario 1***	***Scenario 2***	***Scenario 3***
Energy consumption	kWh	67 329	38 502	69 400
Recycled plastic	ton	4.2	0	0
Industrial water-use efficiency	m3/ton	3 558 327	2 368 923	3 056 675
Reused (non-incinerated) waste	%	40.00%	100.00%	100.00%
Total CO_2 emissions	kg	37 410	16 079	25 676
Size of operational facilities	m2	500	250	200
Percentage of employees entitled to benefits	%	4.82%	100.00%	100.00%
Number of person hours	person hours	2 616	169	153
Stakeholder involvement	relative	High	Moderate	Low
Total revenue	euro	256 636	336 944	296 416
Total profit	euro	-25 068	-1 934	-14 729
Expected annual growth	% (CAGR)	4.80%	5.50%	4.20%

Table 7. Post-collection quantification (values are per annum)

5.2.5. Scenarios Evaluation

As outlined in the solution design, the final step of the solution is the evaluation of the different scenarios. Based on the knowledge gained as part of UT's IEM bachelor program and based on the systematic literature review within chapter 5.2.1. Solution Preparation the most suitable MCDA technique for performing the evaluation is Analytical Hierarchy Process (AHP). Of course, the

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[24] Life insurance, healthcare, pension, and parental leave. As a percentage of total employees.

evaluation builds upon the previous solution stages, particularly, the Scenarios Quantification. The complete AHP is presented in the excel sheets provided as a supplement to this paper. Still, to gain a sound overview of the decision-making procedure, the most quintessential AHP deliverables are supplied below and Table 8 provides a summary of the overall AHP steps and corresponding results. For even more detail, Appendix G provides screenshots of the entire AHP process.

No	*Step*	*Deliverable*
1	Develop a pairwise comparison matrix for each decision alternative for each criterion	Preference matrix within criteria - Table 9
2	Compute the normalized matrix for each comparison matrix	
3	Develop preference matrix within criteria	
4	Develop a pairwise comparison matrix for the criteria	Preference vector for criteria - Table 10
5	Compute the normalized matrix for the criteria comparison matrix	
6	Develop preference vector for criteria	
7	Compute an overall score for each decision alternative	Ranking of alternatives according to overall scores - Table 11
8	Rank the alternatives	
9	Perform consistency check	Consistency ratios for each comparison matrix - Table 12

Table 8. Summary of AHP steps

	Energy consumption	*Recycled plastic*	*Water-use efficiency*	*Reused waste*	*Total CO_2 emissions*	*Operational facilities size*
Scenario 1	0.092	0.818	0.137	0.067	0.065	0.098
Scenario 2	0.755	0.091	0.623	0.467	0.735	0.334
Scenario 3	0.154	0.091	0.239	0.467	0.199	0.568

	Employees with benefits	*Number of person hours*	*Stakeholder involvement*	*Total revenue*	*Total profit*	*Expected annual growth*
Scenario 1	0.059	0.062	0.701	0.164	0.120	0.234
Scenario 2	0.471	0.354	0.213	0.539	0.608	0.688
Scenario 3	0.568	0.471	0.584	0.085	0.297	0.272

Table 9. Preference vector within criteria

Key Performance Indicator	*Weight*	*As %*	*Rank*
Energy consumption	0.051	5.1	7
Recycled plastic	0.178	17.8	2
Industrial water-use efficiency	0.012	1.2	12
Reused (non-incinerated) waste	0.143	14.3	3
Total CO_2 emissions	0.244	24.4	1
Size of operational facilities	0.016	1.6	11
Percentage of employees entitled to benefits	0.069	6.9	6
Number of person hours	0.029	2.9	9
Stakeholder involvement	0.039	3.9	8
Total revenue	0.022	2.2	10
Total profit	0.110	11.0	4
Expected annual growth	0.086	8.6	5

Table 10. Preference vector for criteria

	Overall score	*As %*	*Overall rank*
Scenario 1	0.2493	24.93	2
Scenario 2	0.5032	50.32	1
Scenario 3	0.2475	24.75	3

Table 11. Scores and rankings of alternatives

Comparison matrix	*Consistency Ratio*
Energy consumption	0.0163
Recycled plastic	0.0000
Industrial water-use efficiency	0.0092
Reused (non-incinerated) waste	0.0000
Total CO_2 emissions	0.0362
Size of operational facilities	0.0123
Percentage of employees entitled to benefits	0.0000
Number of person hours	0.0175
Stakeholder involvement	0.0163
Total revenue	0.0046
Total profit	0.0371
Expected annual growth	0.0387
Overall criteria	0.0796

Table 12. Consistency ratios per comparison matrix

6. Results

To effectively compare the sustainability performance of the different supply chain architectures, a linear non-weighted scenario comparison is provided (Table 13 and Figure 11). This assessment is entirely based on the solution outcomes and serves as the final result of this research. It aims to juxtapose the performance of each scenario for every criterion according to a linear scale of 0-10, with higher scores indicating better performance. To compare in line with the triple bottom line perspective, Table 14 and Table 15 showcase the non-weighted and weighted sustainability performance per scenario per sustainability dimension.

Key Performance Indicator	*Scenario 1*	*Scenario 2*	*Scenario 3*
Energy consumption	5	7	5
Recycled plastic	10	0	0
Industrial water-use efficiency	5	8	6
Reused (non-incinerated) waste	3	10	10
Total CO_2 emissions	3	7	5
Size of operational facilities	6	8	9
Percentage of employees entitled to benefits	2	10	10
Number of person hours	8	3	2
Stakeholder involvement	8	6	4
Total revenue	5	7	6
Total profit	6	8	7
Expected annual growth	7	10	5

Table 13. Linear non-weighted scenario comparison figures (Scores 0-10)

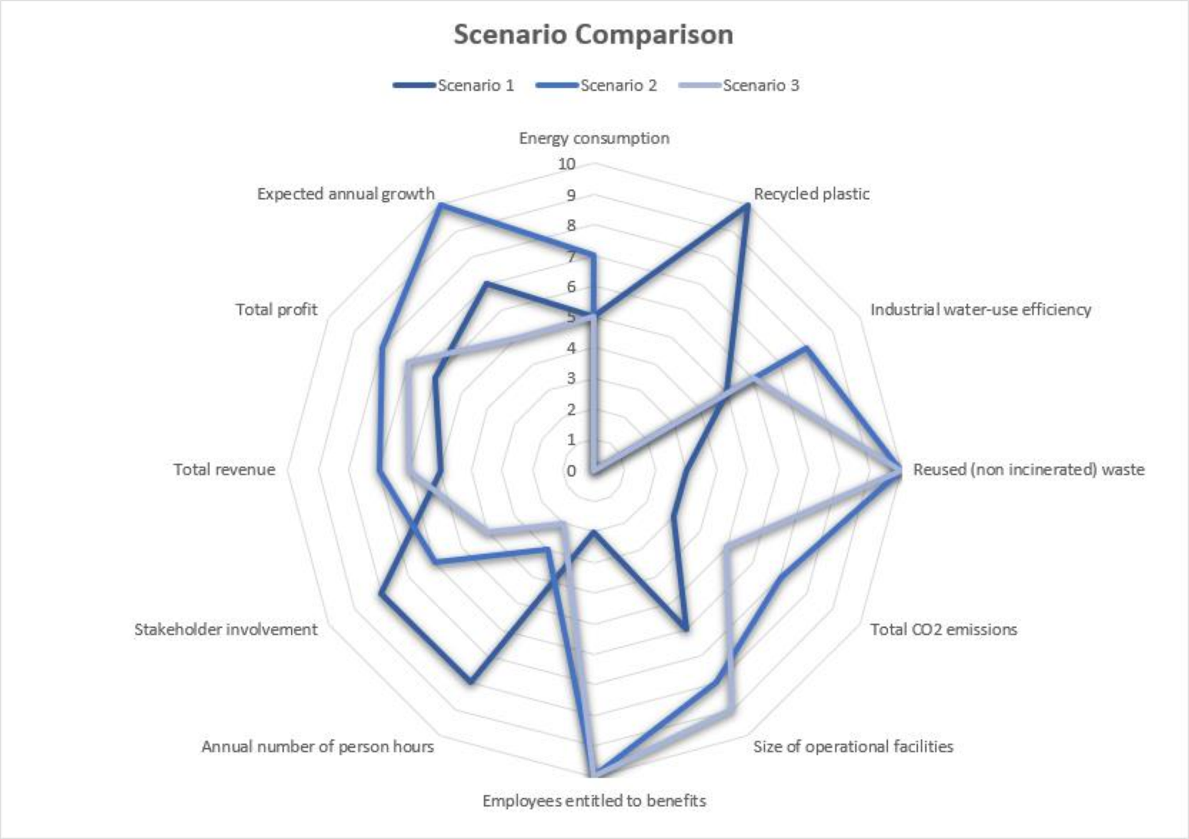

Figure 11. Linear non-weighted scenario comparison chart

Key Performance Category	***Scenario 1***	***Scenario 2***	***Scenario 3***	*Total Average*
Environmental	5.33	6.67	5.83	**5.94**
Social	6.00	6.33	5.33	**5.89**
Economic	6.00	8.33	6.00	**6.78**
Total Average	**5.33**	**7.11**	**5.72**	

Table 14. Categorical (triple bottom line perspective) non-weighted scenario comparison

Key Performance Category	***Scenario 1***	***Scenario 2***	***Scenario 3***	*Total Average*
Environmental	5.20	5.77	4.85	**5.27**
Social	4.98	7.38	6.60	**6.32**
Economic	6.29	8.69	6.11	**7.03**
Total Weighted Average	**5.40**	**6.62**	**5.36**	

Table 15. Categorical (triple bottom line perspective) weighted scenario comparison

7. Discussion

7.1. Analysis

The outcomes of this research have provided insight into the holistic sustainability performance of the ADS by revealing the different levels of achieved success across 12 key performance categories organised around the triple bottom line perspective. Therefore, the overarching research goal of this study: *"Evaluate the sustainability performance of the Archimedean Drum Screen biomass and plastic waste clean-up technology by performing a supply chain analysis"* has been met. The results of the performed input/output modelling supply chain analysis show that the ADS is not a categorically sustainable technology, that technological improvements can greatly change that, and that the post-collection waste handling stage doesn't play a major role in the realised level of sustainability performance. Below, a brief elaboration on the results per sustainability dimension and a brief elaboration on the ranking of the scenarios.

First and foremost, with a combined weight of approximately 75% (Table 10) the environmental dimension is the greatest determinant of the holistic sustainability performance of the ADS technology. Unequivocally, the results show that all scenarios are lacking on the environmental front (Table 14 and Table 15). The main reasons for this are the particularly high energy consumption of the ADS (and ensuing processes), the associated CO_2 emissions, the low water-use efficiency, and the comparatively slight volumes of fully recycled plastics (Table 6). All these factors translate to unreasonably high ratios of CO_2 emissions/energy consumption to quantity of collected/reused/recycled waste, which clearly indicates more environmental damage than benefit. Nevertheless, reused waste and size of operational facilities are two areas, where the supply chains perform particularly well and demonstrate the potential of the ADS technology. Yet, the weights of the latter two criteria are too small to greatly impact the overall dimension performance.

As far as the social dimension is concerned, the three scenarios exhibit modest to moderately high performance (Table 15). Scenario 1 is characterised by high local stakeholder involvement and relatively large number of person hours associated with low percentage of entitlement to benefits (Table 6). On the other hand, Scenarios 2 & 3 claim lower stakeholder involvement and lesser demand for labour. However, 100% of employees involved in the labour as part of scenarios 2 & 3 are entitled to benefits. This major discrepancy in benefit entitlement combined with the higher weight of that indicator (Table 10) is what positions scenarios 2 & 3 ahead of scenario 1 in the social dimension category. However, since the weight of the social dimension is only 15% (Table 10), the contribution to the overall weighted scores (Table 11 and Table 15) is marginal.

Lastly, a very unexpected finding of this study is that all scenarios perform exceptionally well on the economic front with annual profits ranging from 350 000 euro to 373 000 euro and expected annual growth ranging from 4.2% to 5.5% (Table 6). However, it should be noted that the analysis doesn’t account for the initial asset costs – amounting to approximately 300 000 euro per ADS technology (investment costs in other technologies are negligible). Therefore, to achieve an above average net present value for the installation of 15 ADS (cost of ~ 1.5 MLN euro), approximately 5 years of operation are needed (not accounting for inflation, depreciation, growth rate, etc.) Moreover, not all supply chain profits end up with the ADS owner and operator, which further extends the payback period on the technology. Regardless, considering that the operational lifetime of the ADS is approximated at 50-70 years, a positive return on investment is well within the operational limits and should not present a challenge.

By and large, the results indicate that the post-collection handling of the waste plays a relatively minor role in the achieved level of sustainability (comparing Table 6 and Table 7), especially on the environmental front. This implies that if high environmental sustainability is to be achieved, major ADS technological improvements (with regards to energy efficiency) must take place. The purpose of these improvements is to lower the immense energy consumption and corresponding carbon emissions (as supported by the data) linked to the waste collection step. As such, the improvements are also expected to bolster the economic sustainability performance. Therefore, the technological improvements are expected to bring exponential benefits to the sustainability performance of the ADS across the entire triple bottom line.

When it comes to overall scenario ranking, AHP determines the waste pelletizing case (scenario 2) as the most sustainable one (Table 11), followed by waste separation (scenario 1) and then waste liquefaction (scenario 3). Since the consistency ratios of all comparisons are below 0.10 (Table 12), hence satisfactory, all comparisons within AHP are (boundedly) valid. This ranking is also consistent with the overall weighted scenario comparison presented in the results (Table 15). Interestingly, even though the non-weighted scenario comparison still asserts scenario 2 as the most sustainable, it reveals that scenario 3 performs better than scenario 1 (Table 14). This change in ranking infers that scenario 1 scores higher across the more important key performance categories and lower across the less important ones. Notably, the overall scores of all scenarios drop significantly from the non-weighted to the weighted scenario comparison, which implies that all scenarios achieve structurally higher scores in less important key performance categories (Table 14 and Table 15).

Based on the outcomes of this research, the hypothesis:

"All Archimedean Drum Screen technologies produced by FishFlow are sustainable in accordance with the triple bottom line."

is proven to be false. Nevertheless, this is not to say that the introduction of the ADS (and corresponding supply chain) doesn't bring environmental, social, or economic benefits. On the contrary, clear benefits have been observed across all three dimensions (Table 6) and the potential for holistic sustainability on behalf of the ADS – via certain improvements in the energy efficiency of the technology – is clear. This is especially the case for the waste pelletizing case which performs structurally better than the rest of the cases across all dimensions (Table 15).

Moreover, as a supplementary result of this study, a range of additional recommendations that might improve the holistic sustainability performance of the ADS technology are generated. Though the feasibility of implementation of these enhancements hasn't been measured they remain a valuable result of this research and are listed below:

- Addition of renewable energy sources (solar panels and/or wave energy converters) to the ADS technology
- Collaboration with EU companies in paying their plastic tax by supplying them with the collected plastic
- Integration with other blue economy initiatives centred around the sustainable development approach to coastal resources
- Request for EU funding on the basis of the innovativeness of the solution and the potential environmental benefit

7.2. Solution Limitations

This section provides an overview of the solution specific principal limitations, for the overarching research limitations refer to chapter 4.3. Research Limitations.

In general, the solution is limited by the theoretical framework upon which it is built. Since the framework is conceptual and, though based on existing models, created exclusively for the sake of this research, additional and broader validation is required to ensure the academic soundness of the framework.

A major limitation of the solution is the lack of geographical variety of scenarios. Currently, all scenarios are based on numbers assuming the operation of the ADS and handling of the resulting waste in the Netherlands. This is a weakness of this study since the geographical area can largely influence the evaluation and greatly affect the performance across all sustainability dimensions. In particular, the regional differences in energy prices, level of water pollution, CO_2 emissions per kWh of consumed energy, etc. will unequivocally affect the quantifications of the scenarios. This limitation exists due to time constraints on behalf of the researcher.

Additional major limitation is the lack of exploration of different ADS technology integration strategies. The current analysis embraces the industrial power plant/ADS symbiosis throughout all scenarios. However, symbiosis with other industrial (or not) processes which are not covered in this study due to data insufficiency, might result in drastically different sustainability performance and deem the otherwise unsustainable ADS technology as very much so, or the other way around.

Another limitation of this analysis is the supply chain scope. Though the start of the supply chain is self-evident – the waste collection stage, the end of the supply chain is not. In theory, the larger the range of the analysed supply chain levels is, the more accurate the results are. Yet, to make the assessment feasible (from resource and time point of view) clear system boundaries are drawn. The analysis starts with the collection of the waste and ends with the production of the first marketable goods – recycled plastics, energy, bio-oils, and bio pellets. The subsequent steps of the life of the sellable goods are outside the scope of this study.

A limitation of all three scenarios is that certain processes are pooled together and described as one process to simplify the analysis and to reflect capacity considerations. As a result, value-adding activities encompass multiple sub-steps, and only their main material and energy inputs/outputs are included. For example, the process of Drying encompasses multiple distinctive stages but is referred to as one process and negligible process inputs/outputs are omitted.

Lastly, a limitation of the solution results pertains to the inability of indicators to completely meet all Table 3 requirements. More specifically, characteristic #5 – distinctiveness of indicators – is difficult to ensure across the criteria. The difficulty stems from the intricate relationships between the indicators in a supply chain setting. For instance, energy consumption is heavily correlated with CO_2 emissions. Yet, they both play an important role in the analysis as separate carriers of meaning as well. Similarly with other indicators such as total revenue, total profit, etc. Regardless, the limitation is present since avoiding it would mean greatly reducing the criteria scope.

7.3. Further Research

To overcome the two major solution limitations of this study, further research should be carried out to examine the sustainability performance of the ADS (and associated supply chains) in different regions/countries and the possibility of ADS technological symbiosis with processes other than power plant cooling. On the first point, researching locations with exceptionally high or low price of electricity and levels of water pollution is of particular importance. This will help in verifying the robustness of the supply chain because it will test how well it responds to favourable and unfavourable conditions. If greatly favourable conditions deem the holistic supply chain unsustainable, the need for vast technological improvements will be identified. If greatly unfavourable conditions result in adequate sustainability performance, it will indicate good resilience and proper supply chain architecture. As it pertains to the technological symbiosis, possible couplings with sewage treatment plants, agricultural wastewater treatment plants and leachate treatment plants ought to be studied.

To effectively measure the impact that fluctuations in the values of key factors can have on the holistic sustainability performance of the ADS technology, a sensitivity analysis should be performed. This is of imperious significance because it will provide an insight into the performance of the technology during periods of socio-political and/or economic uncertainty. Key factors to be considered for inclusion in the analysis are energy prices, carbon credit prices and fuel prices. Reason being that minor fluctuations in the latter attributes might greatly impact (in a positive or a negative direction) the overall sustainability performance.

Last but certainly not least, for increase in accuracy and precision during the scenario evaluations different (more advanced) techniques should be examined and potentially applied to the decision-making procedure. In particular, the suitability of combining fuzzy logic with MCDM methods such as AHP, synthetic evaluation and Yager’s weighted goals method should be studied in more detail.

The utility of such techniques lies in the possibility to integrate human subjectivity, uncertainty, intangibility, and vagueness into the assessments (Karmaker & Saha, 2015).

8. Conclusion

By evaluating the ADS together with a set of three possible corresponding supply chains, this study established that further technological improvements are needed to ensure high holistic sustainability performance and that the post-collection handling of the waste plays only a minor role in the achieved level of sustainability. More specifically, the results of this study show that none of the three supply chain scenarios related to the handling of waste stemming from the ADS scores structurally high from a holistic sustainability point of view. As a result, the corresponding hypothesis: *"All Archimedean Drum Screen technologies produced by FishFlow are sustainable in accordance with the triple bottom line."* has been rejected. The focal reasons for the insufficiently high levels of sustainability performance are the particularly high energy consumption of the ADS (and ensuing processes), the associated CO_2 emissions, the higher costs of recycling plastics and the inability to achieve truly robust social dimension performance. In any case, the most promising of all supply chain scenarios is waste pelletizing – characterized by comparatively lower CO_2 emissions, complete (100%) waste reuse, above average increase in annual demand of finished products and strong commercial competitiveness on the economic front.

Overall, this study contributes to the academic body of literature by being the first to analyse the innovative ADS technology from a sustainability supply chain point of view with regards to a very niched application (marine waste collection). The significance of this research is the development of a specifically tailored theoretical framework for addressing holistic sustainability related issues and the three quantifications of sustainability performance for each of the conceived supply chain scenarios. The main limitations of this study are the lack of time and data – on the methodological side, and the lack of geographical and technology integration variety within the scenarios – on the solution side. Therefore, if future research is to effectively build upon this study, it ought to conceive a greater number of supply chain architectures spanning across diverse geographical locations and/or assuming different integrations of ADS to existing industrial processes.

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10. Appendix

10.1. A. Data collection conceptual framework

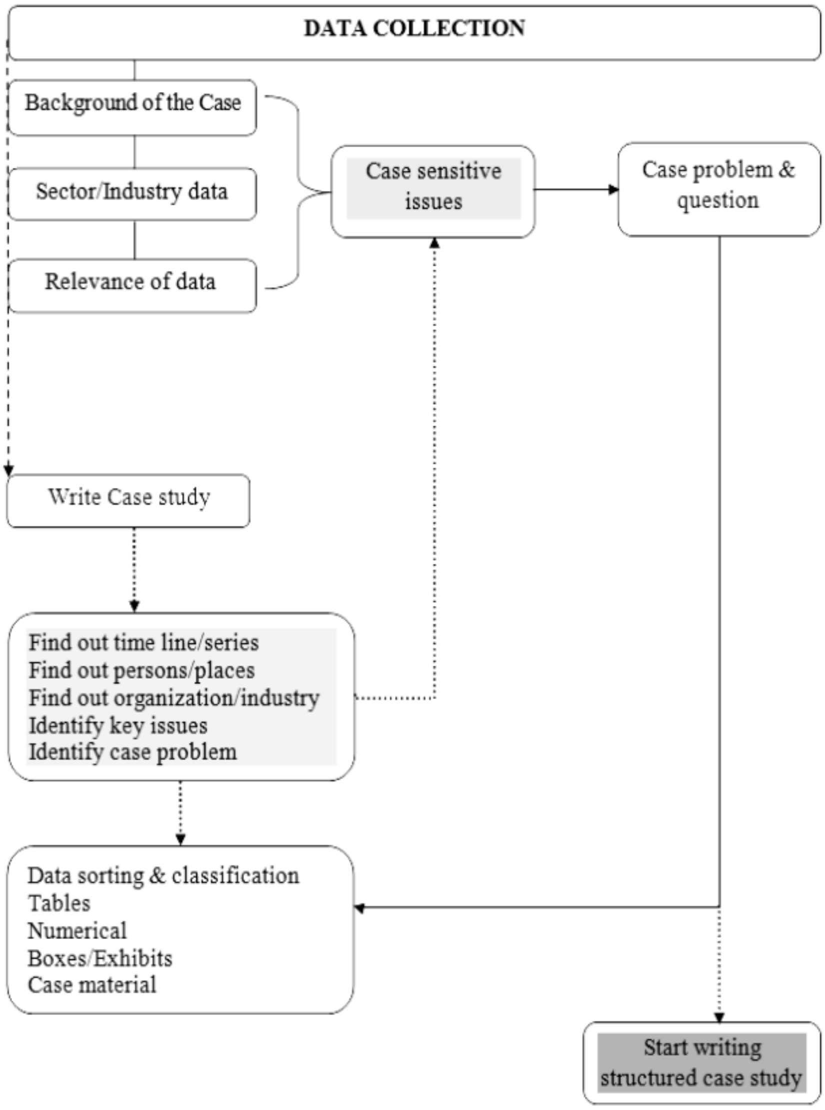


Figure 12. A data collection conceptual framework. From *Designing Case Studies from Secondary Sources – A Conceptual Framework* by Reddy and Agrawal, 2012.

10.2. B. Problem-solving approach

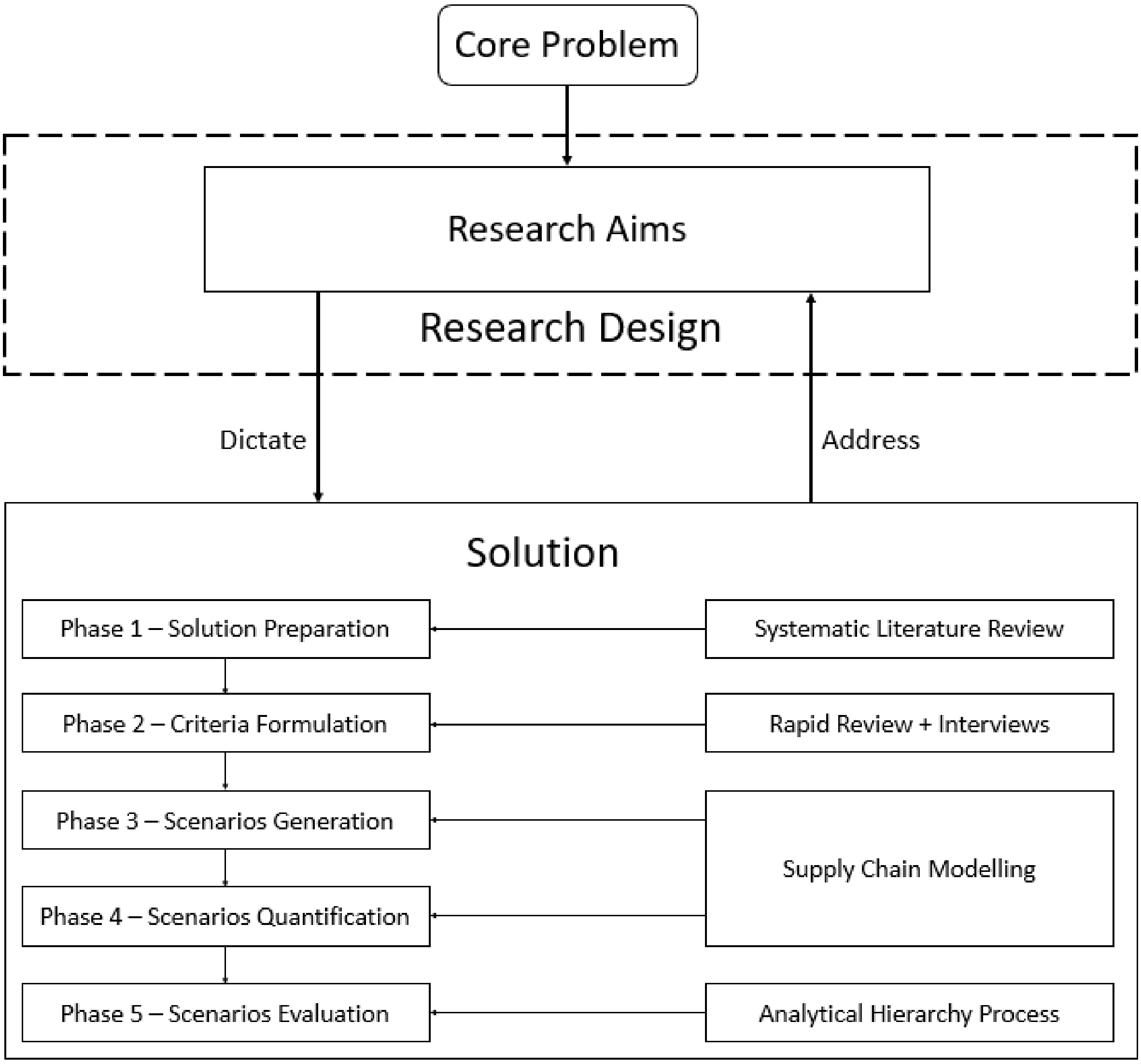


Figure 13. Overall Problem-Solving Approach

10.3. C. Systematic literature review summary

Factor	Inclusion Criteria	Exclusion Criteria
Date	Publications after 1st of January 2010	Publications before 31st of December 2009
Language	Publications in English	Publications not in English
Peer review	Peer-reviewed publications	Not peer-reviewed publications
Reported outcomes	Publications with outcomes reported in an appropriate manner using objective measures	Publications with self-reported outcomes and evaluations
Type of publication	Papers in academic journals, Books, Conference proceedings	Letters, editorials, commentaries, grey literature, ads or other sponsored material, review papers (Although these are screened for some reference)

Table 16. SLR Inclusion/Exclusion criteria

Key Concept	Synonym	Narrower	Broader
Measure	Assess, Evaluate	Quantify, Approximate, Gauge, Estimate	Calculate, Compute, Determine
Sustainability	-	Sustainability Performance, Circularity, Reliability, Equilibrium	Impact, Effect, Awareness, Footprint
Novel	New, Pioneering	Innovative, State-of-the-art, Modern, Futuristic, Advanced	Different, Unusual, Creative
Supply Chain	Value Chain, Production Chain	Distribution Network, Business Process, Logistical Chain, Business Logistics	Trade, Chain, System, Network, Process

Table 17. SLR Search matrix

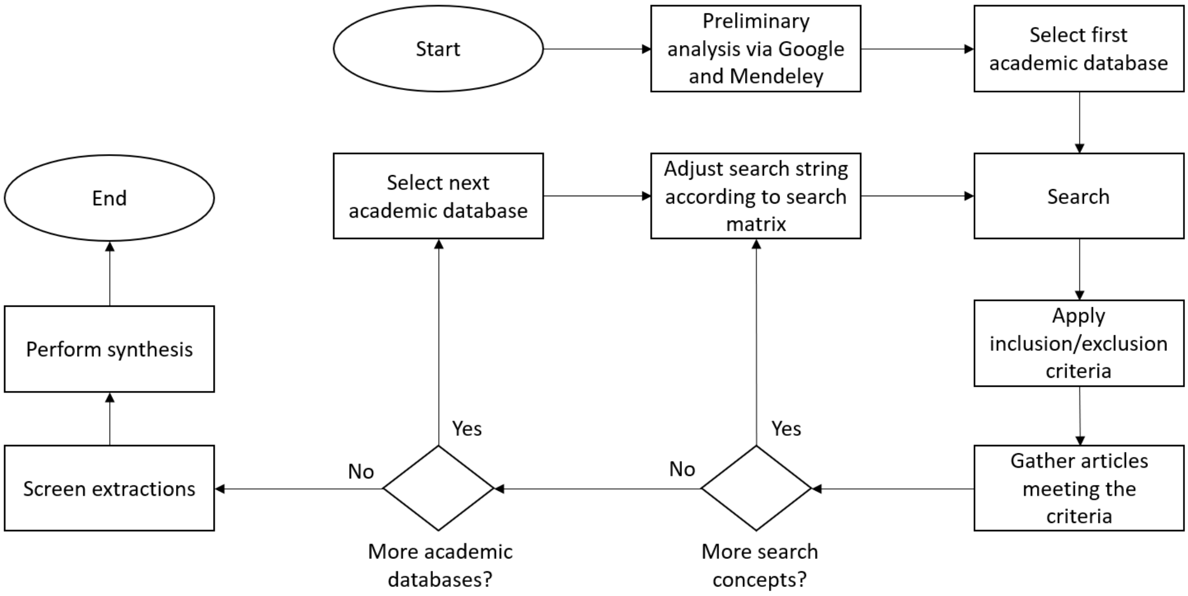


Figure 14. SLR Search strategy flowchart

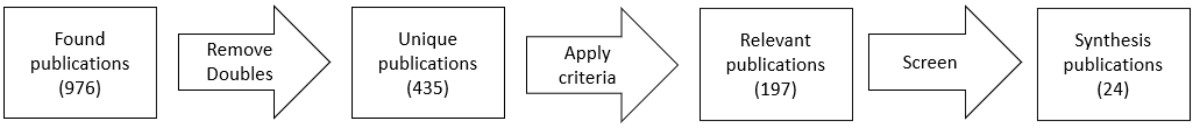


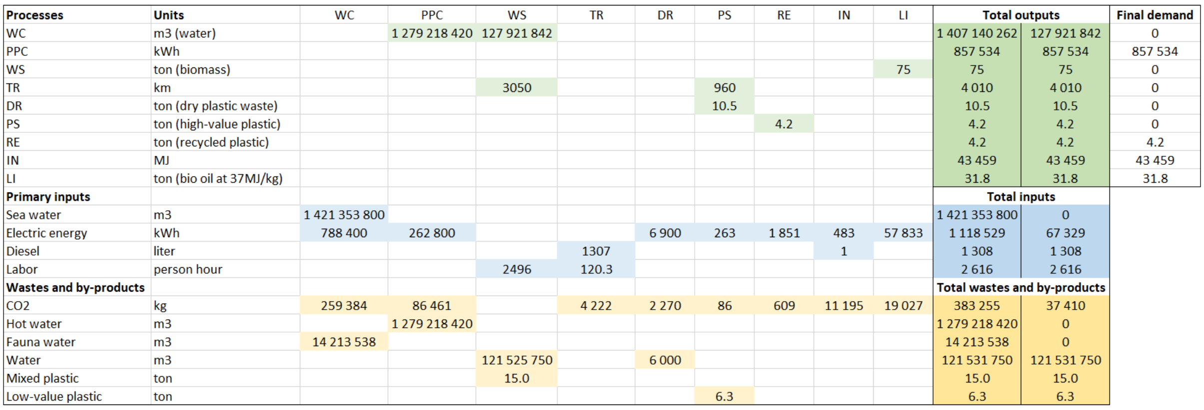
Figure 15. SLR Flow diagram

Concept **Publication**	Sustainability definition/ perspective	Sustainability measurement techniques	Unique approach to novel supply chains	Sustainability indicators
Arushanyan et al., 2017	X			
Badiezadeh et al., 2018	X	X	X	
Brandenburg et al., 2014		X	X	
Diaz-Balteiro et al., 2017		X	X	
Erol et al., 2011	X	X	X	

Govindan et al., 2013		X	X	X
Kahi et al., 2017		X		
Kalantary et al., 2022	X	X	X	X
Moldan et al., 2012	X			X
Moore et al., 2017	X			
Mori & Christodoulou, 2012	X			
Mura et al., 2018		X	X	
Neri et al., 2021		X	X	X
Proctor et al., 2015	X			X
Purvis et al., 2019	X			
Qorri et al., 2018	X	X	X	
Qorri et al., 2022	X	X	X	X
Saeed & Kersten 2017		X		X
Saeed & Kersten 2020		X		X
Schaltegger & Burritt, 2014		X		X
Thompson, 2017	X			
Varsei et al., 2014	X			
Wang et al., 2020	X	X	X	X
Zijp et al., 2015	X			

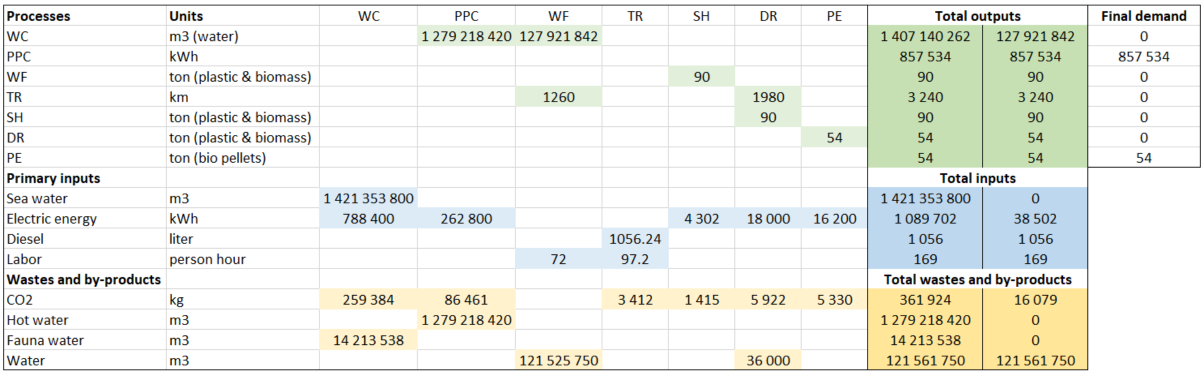
Table 18. SLR Concept matrix

10.5. D. Physical input output tables



Processes	**Units**	WC	PPC	WS	TR	DR	PS	RE	IN	LI	**Total outputs**		**Final demand**
WC	m3 (water)		1 279 218 420	127 921 842							1 407 140 262	127 921 842	0
PPC	kWh										857 534	857 534	857 534
WS	ton (biomass)									75	75	75	0
TR	km			3050			960				4 010	4 010	0
DR	ton (dry plastic waste)						10.5				10.5	10.5	0
PS	ton (high-value plastic)							4.2			4.2	4.2	0
RE	ton (recycled plastic)										4.2	4.2	4.2
IN	MJ										43 459	43 459	43 459
LI	ton (bio oil at 37MJ/kg)										31.8	31.8	31.8
Primary inputs											**Total inputs**		
Sea water	m3	1 421 353 800									1 421 353 800	0	
Electric energy	kWh	788 400	262 800			6 900	263	1 851	483	57 833	1 118 529	67 329	
Diesel	liter				1307				1		1 308	1 308	
Labor	person hour			2496	120.3						2 616	2 616	
Wastes and by-products											**Total wastes and by-products**		
CO2	kg	259 384	86 461		4 222	2 270	86	609	11 195	19 027	383 255	37 410	
Hot water	m3		1 279 218 420								1 279 218 420	0	
Fauna water	m3	14 213 538									14 213 538	0	
Water	m3			121 525 750		6 000					121 531 750	121 531 750	
Mixed plastic	ton			15.0							15.0	15.0	
Low-value plastic	ton						6.3				6.3	6.3	

Table 19. PIOT1 – Waste separation case



Processes	**Units**	WC	PPC	WF	TR	SH	DR	PE	**Total outputs**		**Final demand**
WC	m3 (water)		1 279 218 420	127 921 842					1 407 140 262	127 921 842	0
PPC	kWh								857 534	857 534	857 534
WF	ton (plastic & biomass)					90			90	90	0
TR	km			1260			1980		3 240	3 240	0
SH	ton (plastic & biomass)						90		90	90	0
DR	ton (plastic & biomass)							54	54	54	0
PE	ton (bio pellets)								54	54	54
Primary inputs									**Total inputs**		
Sea water	m3	1 421 353 800							1 421 353 800	0	
Electric energy	kWh	788 400	262 800			4 302	18 000	16 200	1 089 702	38 502	
Diesel	liter				1056.24				1 056	1 056	
Labor	person hour			72	97.2				169	169	
Wastes and by-products									**Total wastes and by-products**		
CO2	kg	259 384	86 461		3 412	1 415	5 922	5 330	361 924	16 079	
Hot water	m3		1 279 218 420						1 279 218 420	0	
Fauna water	m3	14 213 538							14 213 538	0	
Water	m3			121 525 750			36 000		121 561 750	121 561 750	

Table 20. PIOT2 – Waste pelletizing case

Processes	Units	WC	PPC	WF	TR	MLI	Total outputs		Final demand
WC	m3 (water)		1 279 218 420	127 921 842			1 407 140 262	127 921 842	0
PPC	kWh						857 534	857 534	857 534
WF	ton (plastics & biomass)					90	90	90	0
TR	km			2700			2 700.0	2 700	0
MLI	ton (bio oil at 38MJ/kg)						42	42	42
Primary inputs							Total inputs		
Sea water	m3	1 421 353 800					1 421 353 800	0	
Electric energy	kWh	788 400	262 800			69 400	1 120 600	69 400	
Diesel	liter				880.2		880	880	
Labor	person hour			72	81		153	153	
Wastes and by-products							Total wastes and by-products		
CO2	kg	259 384	86 461		2 843	22 833	371 520	25 676	
Hot water	m3		1 279 218 420				1 279 218 420	0	
Fauna water	m3	14 213 538					14 213 538	0	
Water	m3			121 525 750			121 525 750	121 525 750	

Table 21. PIOT3 – Waste liquefaction case

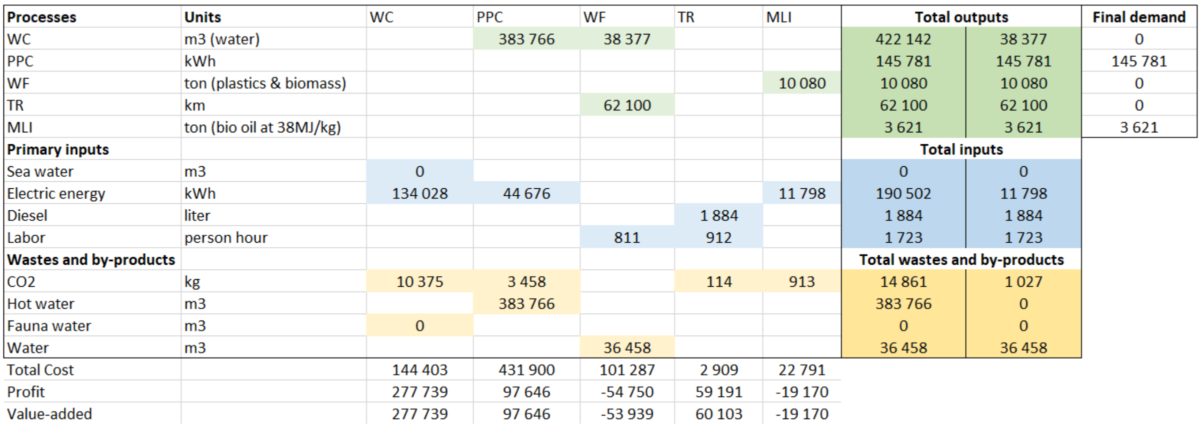
10.6. E. Monetary input output tables

Processes	Units	WC	PPC	WS	TR	DR	PS	RE	IN	LI	Total outputs		Final demand
WC	m3 (water)		383 766	38 377							422 142	38 377	0
PPC	kWh										145 781	145 781	145 781
WS	ton (biomass)									8 400	8 400	8 400	0
TR	km			2 105			662				2 767	2 767	0
DR	ton (dry plastic waste)						772				772	772	0
PS	ton (high-value plastic)							617			617	617	0
RE	ton (recycled plastic)										1 029	1 029	1 029
IN	MJ										1 842	1 842	1 842
LI	ton (bio oil at 37MJ/kg)										19 556	19 556	19 556
Primary inputs											Total inputs		
Sea water	m3	0									0	0	
Electric energy	kWh	134 028	44 676			1 173	45	315	82	9 832	190 150	11 446	
Diesel	liter				2 798				3		2 800	2 800	
Labor	person hour			28 105	2 767						30 872	30 872	
Wastes and by-products											Total wastes and by-products		
CO2	kg	10 375	3 458		169	91	3	24	448	761	15 330	1 496	
Hot water	m3		383 766								383 766	0	
Fauna water	m3	0									0	0	
Water	m3			36 458		2					36 460	36 460	
Mixed plastic	ton			882							882	882	
Low-value plastic	ton						154				154	154	
Total Cost		144 403	431 900	68 586	5 733	1 264	1 482	956	532	18 993			
Profit		277 739	97 646	-22 846	-2 966	-490	-710	73	1 309	563			
Value-added		277 739	97 646	5 259	-200	-490	-710	73	1 309	563			

Table 22. MIOT1 – Waste separation case

Processes	Units	WC	PPC	WF	TR	SH	DR	PE	Total outputs		Final Demand
WC	m3 (filtered water)		383 766	38 377					422 142	38 377	0
PPC	kWh								145 781	145 781	145 781
WF	ton (plastic & biomass)					10 080			10 080	10 080	0
TR	km			28 980			45 540		74 520	74 520	0
SH	ton (plastic & biomass)						11 328		11 328	11 328	0
DR	ton (plastic & biomass)							9 062	9 062	9 062	0
PE	ton (bio pellets)								11 328	11 328	11 328
Primary inputs									Total inputs		
Sea water	m3	0							0	0	
Electric energy	kWh	134 028	44 676			731	3 060	2 754	185 249	6 545	
Diesel	liter				2 260				2 260	2 260	
Labor	person hour			811	1 094				1 905	1 905	
Wastes and by-products									Total wastes and by-products		
CO2	kg	10 375	3 458		136	57	237	213	14 477	643	
Warm filtered water	m3		383 766						383 766	0	
Fauna water	m3	0							0	0	
Filtered water	m3			36 458			11		36 469	36 469	
Total Cost		144 403	431 900	68 167	3 491	10 868	60 165	12 030			
Profit		277 739	97 646	-21 630	71 029	460	-51 092	-702			
Value-added		277 739	97 646	-20 819	72 123	460	-51 092	-702			

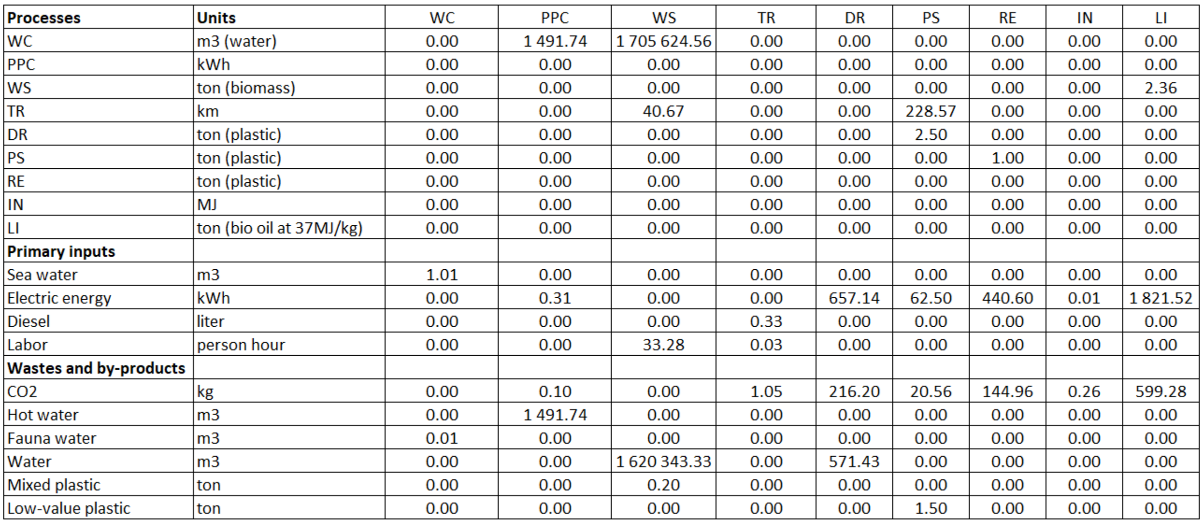
Table 23. MIOT2 – Waste pelletizing case



Processes	Units	WC	PPC	WF	TR	MLI	Total outputs		Final demand
WC	m3 (water)		383 766	38 377			422 142	38 377	0
PPC	kWh						145 781	145 781	145 781
WF	ton (plastics & biomass)					10 080	10 080	10 080	0
TR	km			62 100			62 100	62 100	0
MLI	ton (bio oil at 38MJ/kg)						3 621	3 621	3 621
Primary inputs							**Total inputs**		
Sea water	m3	0					0	0	
Electric energy	kWh	134 028	44 676			11 798	190 502	11 798	
Diesel	liter				1 884		1 884	1 884	
Labor	person hour			811	912		1 723	1 723	
Wastes and by-products							**Total wastes and by-products**		
CO2	kg	10 375	3 458		114	913	14 861	1 027	
Hot water	m3		383 766				383 766	0	
Fauna water	m3	0					0	0	
Water	m3			36 458			36 458	36 458	
Total Cost		144 403	431 900	101 287	2 909	22 791			
Profit		277 739	97 646	-54 750	59 191	-19 170			
Value-added		277 739	97 646	-53 939	60 103	-19 170			

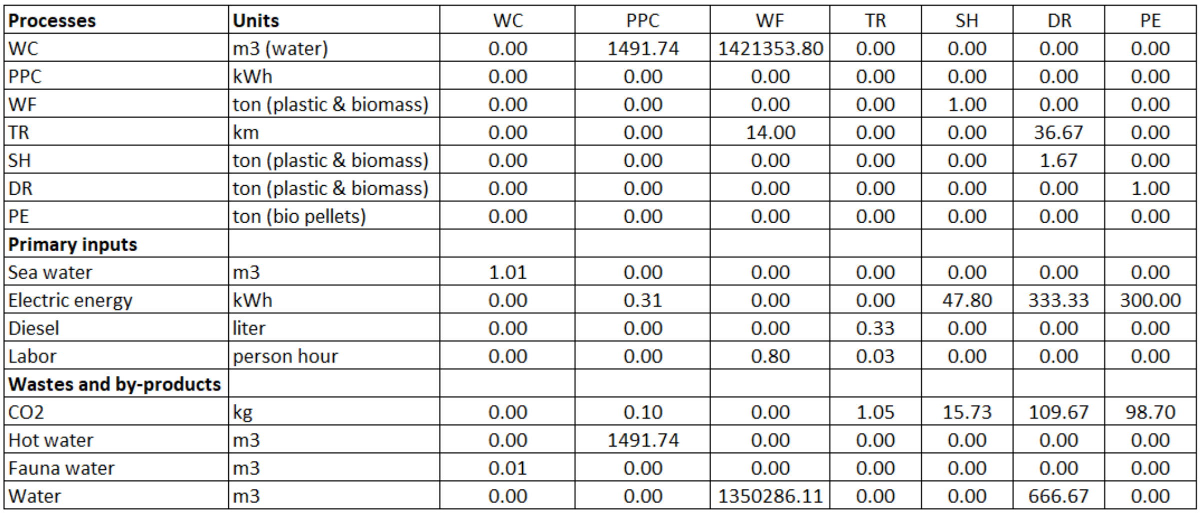
Table 24. MIOT3 – Waste liquefaction case

10.6. F. Coefficient tables



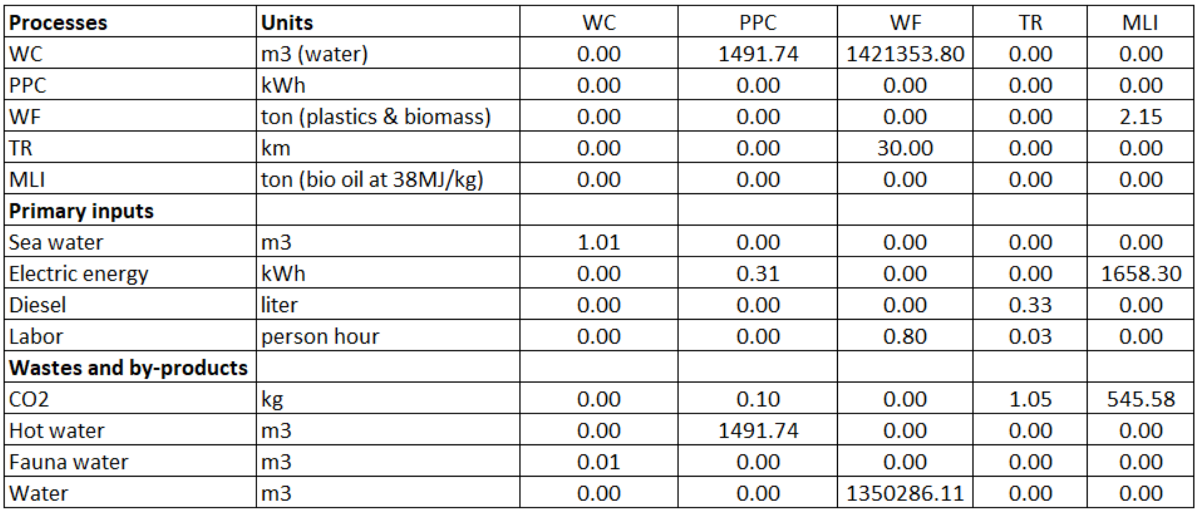
Processes	Units	WC	PPC	WS	TR	DR	PS	RE	IN	LI
WC	m3 (water)	0.00	1 491.74	1 705 624.56	0.00	0.00	0.00	0.00	0.00	0.00
PPC	kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WS	ton (biomass)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.36
TR	km	0.00	0.00	40.67	0.00	0.00	228.57	0.00	0.00	0.00
DR	ton (plastic)	0.00	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00
PS	ton (plastic)	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
RE	ton (plastic)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IN	MJ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LI	ton (bio oil at 37MJ/kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Primary inputs										
Sea water	m3	1.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electric energy	kWh	0.00	0.31	0.00	0.00	657.14	62.50	440.60	0.01	1 821.52
Diesel	liter	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00
Labor	person hour	0.00	0.00	33.28	0.03	0.00	0.00	0.00	0.00	0.00
Wastes and by-products										
CO2	kg	0.00	0.10	0.00	1.05	216.20	20.56	144.96	0.26	599.28
Hot water	m3	0.00	1 491.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauna water	m3	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	m3	0.00	0.00	1 620 343.33	0.00	571.43	0.00	0.00	0.00	0.00
Mixed plastic	ton	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00
Low-value plastic	ton	0.00	0.00	0.00	0.00	0.00	1.50	0.00	0.00	0.00

Table 25. PIOCT1 – Waste separation case



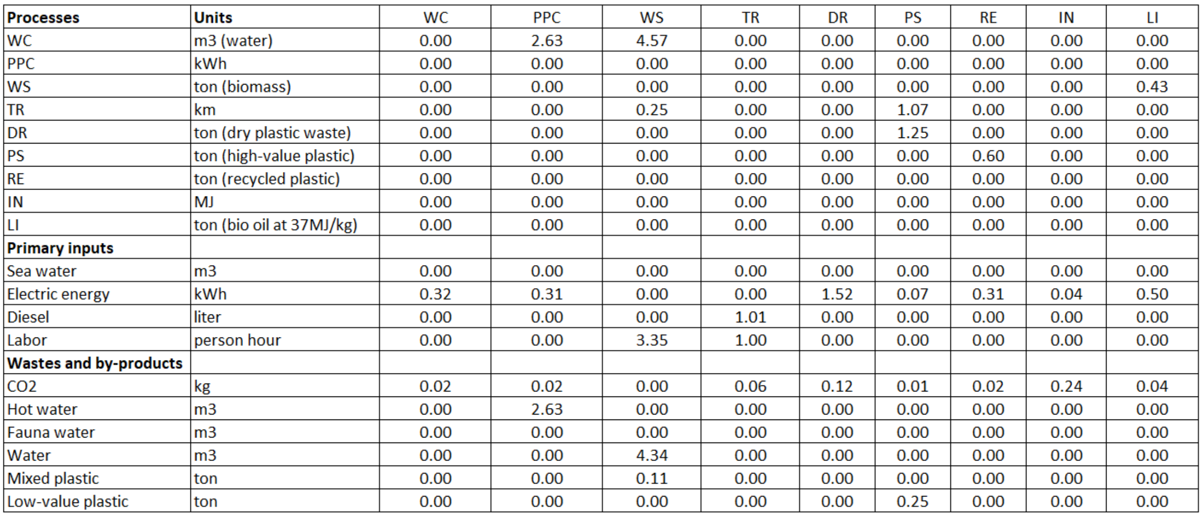
Processes	Units	WC	PPC	WF	TR	SH	DR	PE
WC	m3 (water)	0.00	1491.74	1421353.80	0.00	0.00	0.00	0.00
PPC	kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WF	ton (plastic & biomass)	0.00	0.00	0.00	0.00	1.00	0.00	0.00
TR	km	0.00	0.00	14.00	0.00	0.00	36.67	0.00
SH	ton (plastic & biomass)	0.00	0.00	0.00	0.00	0.00	1.67	0.00
DR	ton (plastic & biomass)	0.00	0.00	0.00	0.00	0.00	0.00	1.00
PE	ton (bio pellets)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Primary inputs								
Sea water	m3	1.01	0.00	0.00	0.00	0.00	0.00	0.00
Electric energy	kWh	0.00	0.31	0.00	0.00	47.80	333.33	300.00
Diesel	liter	0.00	0.00	0.00	0.33	0.00	0.00	0.00
Labor	person hour	0.00	0.00	0.80	0.03	0.00	0.00	0.00
Wastes and by-products								
CO2	kg	0.00	0.10	0.00	1.05	15.73	109.67	98.70
Hot water	m3	0.00	1491.74	0.00	0.00	0.00	0.00	0.00
Fauna water	m3	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Water	m3	0.00	0.00	1350286.11	0.00	0.00	666.67	0.00

Table 26. PIOCT2 – Waste pelletizing case



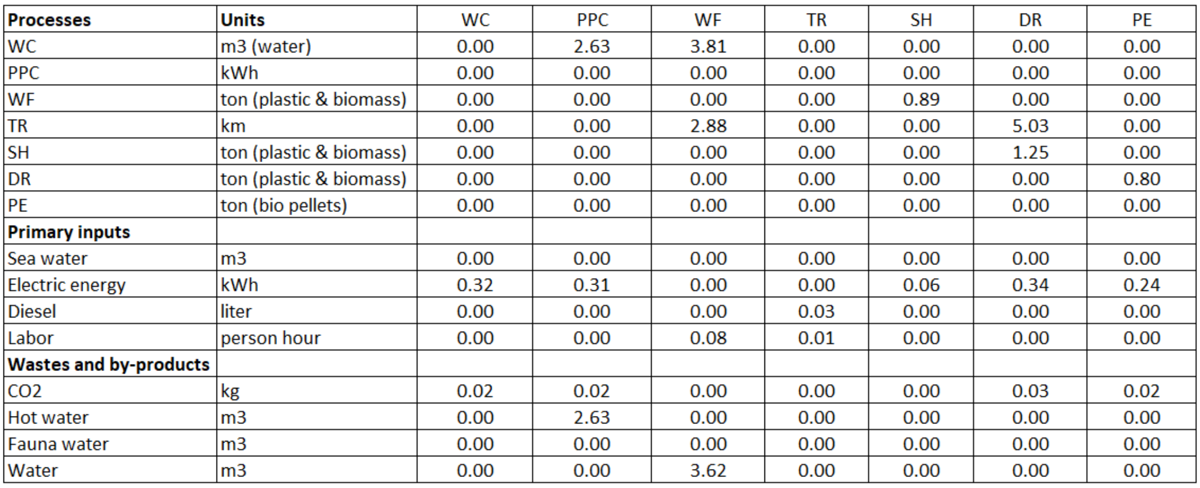
Processes	Units	WC	PPC	WF	TR	MLI
WC	m3 (water)	0.00	1491.74	1421353.80	0.00	0.00
PPC	kWh	0.00	0.00	0.00	0.00	0.00
WF	ton (plastics & biomass)	0.00	0.00	0.00	0.00	2.15
TR	km	0.00	0.00	30.00	0.00	0.00
MLI	ton (bio oil at 38MJ/kg)	0.00	0.00	0.00	0.00	0.00
Primary inputs						
Sea water	m3	1.01	0.00	0.00	0.00	0.00
Electric energy	kWh	0.00	0.31	0.00	0.00	1658.30
Diesel	liter	0.00	0.00	0.00	0.33	0.00
Labor	person hour	0.00	0.00	0.80	0.03	0.00
Wastes and by-products						
CO2	kg	0.00	0.10	0.00	1.05	545.58
Hot water	m3	0.00	1491.74	0.00	0.00	0.00
Fauna water	m3	0.01	0.00	0.00	0.00	0.00
Water	m3	0.00	0.00	1350286.11	0.00	0.00

Table 27. PIOCT3 – Waste liquefaction case



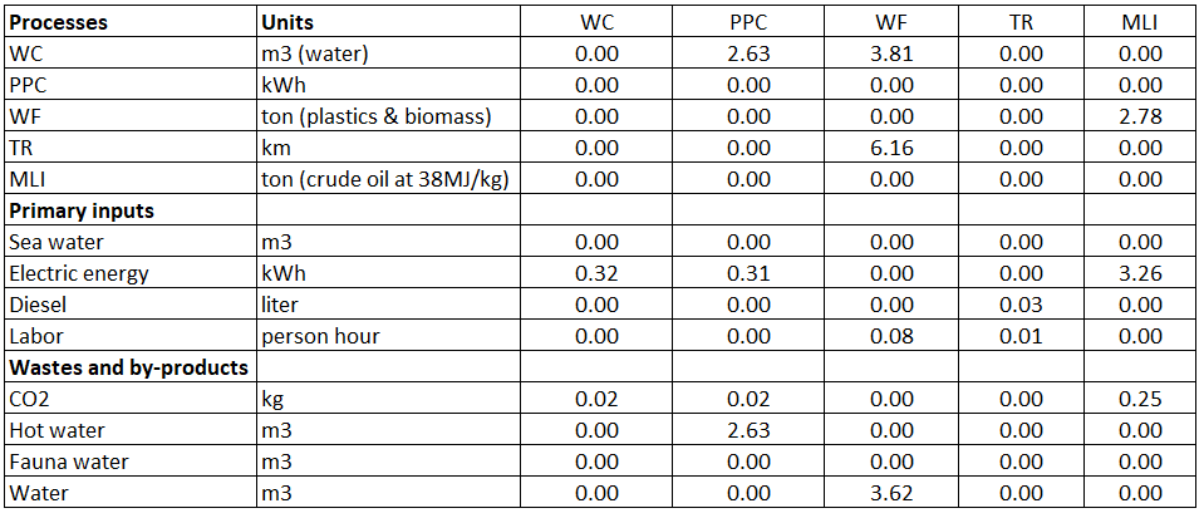
Processes	Units	WC	PPC	WS	TR	DR	PS	RE	IN	LI
WC	m3 (water)	0.00	2.63	4.57	0.00	0.00	0.00	0.00	0.00	0.00
PPC	kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WS	ton (biomass)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43
TR	km	0.00	0.00	0.25	0.00	0.00	1.07	0.00	0.00	0.00
DR	ton (dry plastic waste)	0.00	0.00	0.00	0.00	0.00	1.25	0.00	0.00	0.00
PS	ton (high-value plastic)	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.00
RE	ton (recycled plastic)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IN	MJ	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LI	ton (bio oil at 37MJ/kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Primary inputs										
Sea water	m3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electric energy	kWh	0.32	0.31	0.00	0.00	1.52	0.07	0.31	0.04	0.50
Diesel	liter	0.00	0.00	0.00	1.01	0.00	0.00	0.00	0.00	0.00
Labor	person hour	0.00	0.00	3.35	1.00	0.00	0.00	0.00	0.00	0.00
Wastes and by-products										
CO2	kg	0.02	0.02	0.00	0.06	0.12	0.01	0.02	0.24	0.04
Hot water	m3	0.00	2.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauna water	m3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	m3	0.00	0.00	4.34	0.00	0.00	0.00	0.00	0.00	0.00
Mixed plastic	ton	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00
Low-value plastic	ton	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00

Table 28. MIOCT1 – Waste separation case



Processes	Units	WC	PPC	WF	TR	SH	DR	PE
WC	m3 (water)	0.00	2.63	3.81	0.00	0.00	0.00	0.00
PPC	kWh	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WF	ton (plastic & biomass)	0.00	0.00	0.00	0.00	0.89	0.00	0.00
TR	km	0.00	0.00	2.88	0.00	0.00	5.03	0.00
SH	ton (plastic & biomass)	0.00	0.00	0.00	0.00	0.00	1.25	0.00
DR	ton (plastic & biomass)	0.00	0.00	0.00	0.00	0.00	0.00	0.80
PE	ton (bio pellets)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Primary inputs								
Sea water	m3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electric energy	kWh	0.32	0.31	0.00	0.00	0.06	0.34	0.24
Diesel	liter	0.00	0.00	0.00	0.03	0.00	0.00	0.00
Labor	person hour	0.00	0.00	0.08	0.01	0.00	0.00	0.00
Wastes and by-products								
CO2	kg	0.02	0.02	0.00	0.00	0.00	0.03	0.02
Hot water	m3	0.00	2.63	0.00	0.00	0.00	0.00	0.00
Fauna water	m3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	m3	0.00	0.00	3.62	0.00	0.00	0.00	0.00

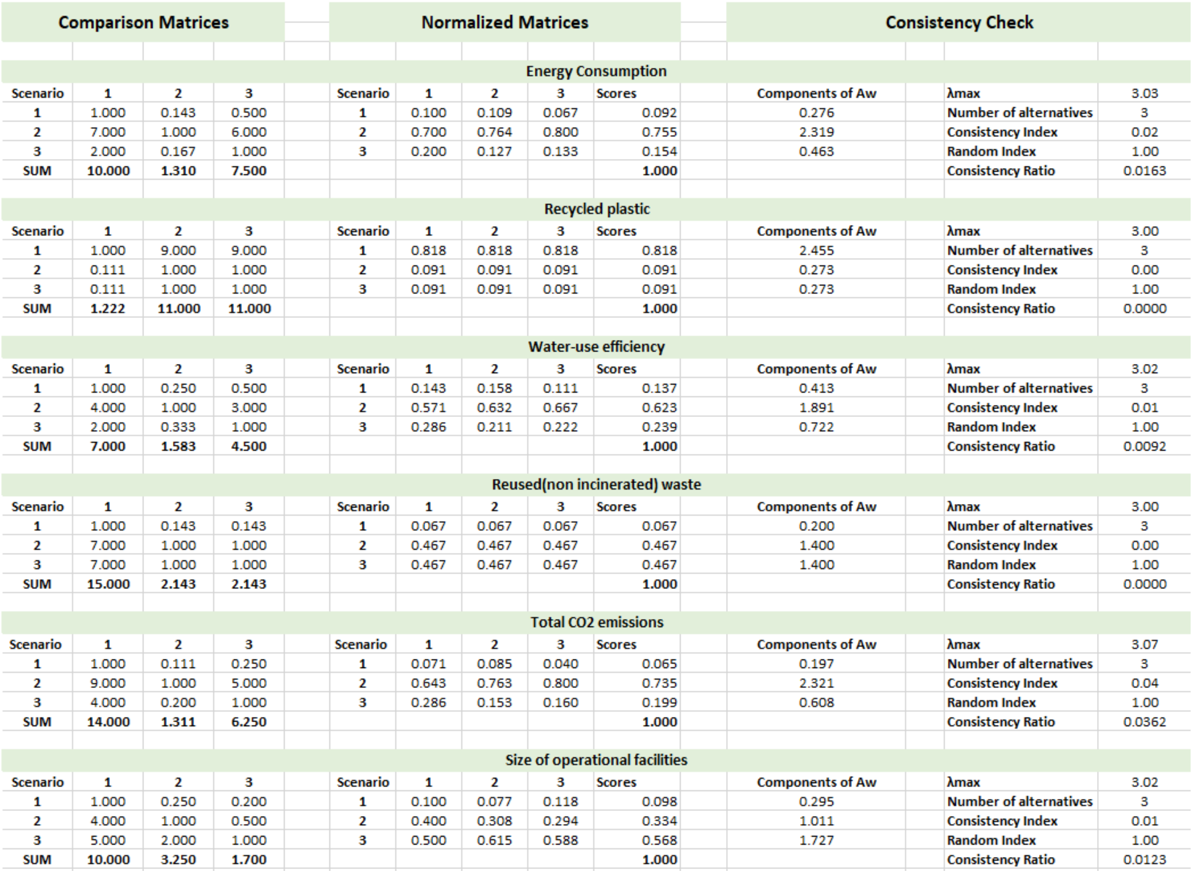
Table 29. MIOCT2 – Waste pelletizing case



Processes	Units	WC	PPC	WF	TR	MLI
WC	m3 (water)	0.00	2.63	3.81	0.00	0.00
PPC	kWh	0.00	0.00	0.00	0.00	0.00
WF	ton (plastics & biomass)	0.00	0.00	0.00	0.00	2.78
TR	km	0.00	0.00	6.16	0.00	0.00
MLI	ton (crude oil at 38MJ/kg)	0.00	0.00	0.00	0.00	0.00
Primary inputs						
Sea water	m3	0.00	0.00	0.00	0.00	0.00
Electric energy	kWh	0.32	0.31	0.00	0.00	3.26
Diesel	liter	0.00	0.00	0.00	0.03	0.00
Labor	person hour	0.00	0.00	0.08	0.01	0.00
Wastes and by-products						
CO2	kg	0.02	0.02	0.00	0.00	0.25
Hot water	m3	0.00	2.63	0.00	0.00	0.00
Fauna water	m3	0.00	0.00	0.00	0.00	0.00
Water	m3	0.00	0.00	3.62	0.00	0.00

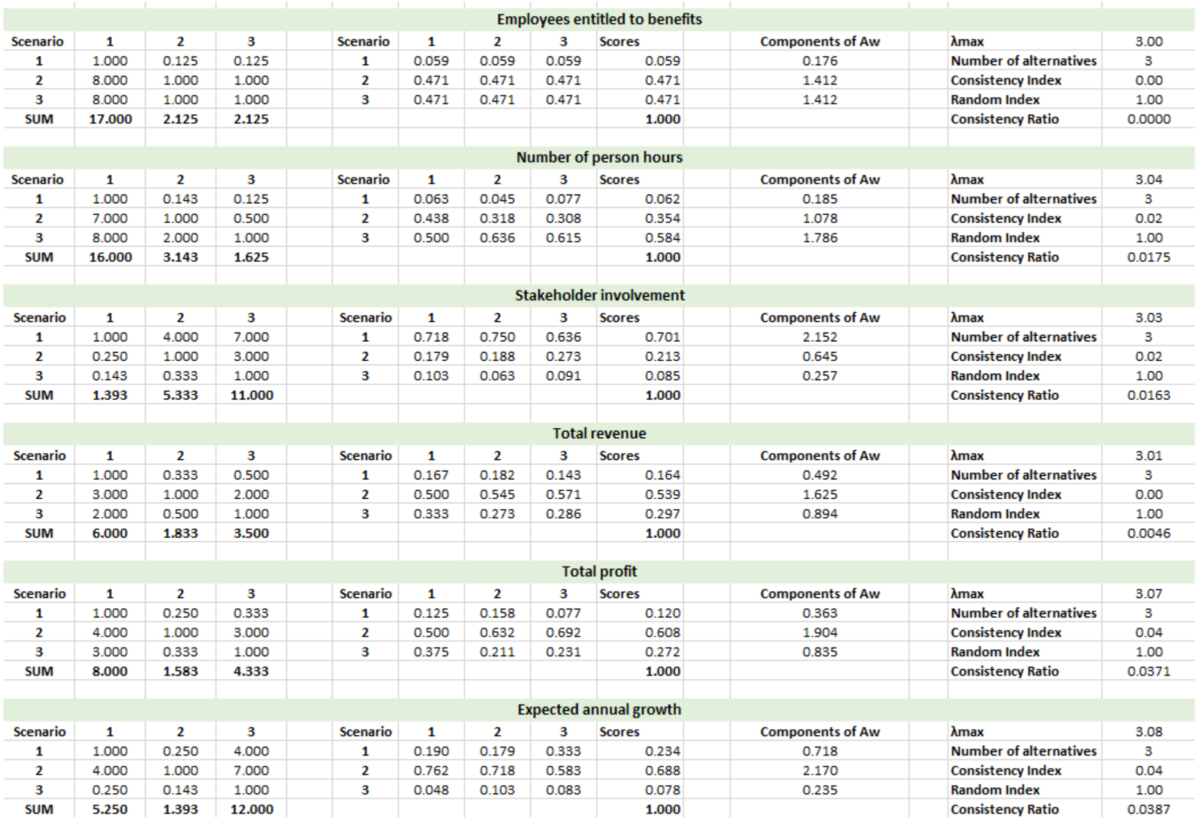
Table 30. MIOCT3 – Waste liquefaction case

10.6. G. AHP Tables



Comparison Matrices				Normalized Matrices					Consistency Check		
Energy Consumption											
Scenario	**1**	**2**	**3**	**Scenario**	**1**	**2**	**3**	**Scores**	**Components of Aw**	**λmax**	3.03
1	1.000	0.143	0.500	**1**	0.100	0.109	0.067	0.092	0.276	**Number of alternatives**	3
2	7.000	1.000	6.000	**2**	0.700	0.764	0.800	0.755	2.319	**Consistency Index**	0.02
3	2.000	0.167	1.000	**3**	0.200	0.127	0.133	0.154	0.463	**Random Index**	1.00
SUM	**10.000**	**1.310**	**7.500**					**1.000**		**Consistency Ratio**	0.0163
Recycled plastic											
Scenario	**1**	**2**	**3**	**Scenario**	**1**	**2**	**3**	**Scores**	**Components of Aw**	**λmax**	3.00
1	1.000	9.000	9.000	**1**	0.818	0.818	0.818	0.818	2.455	**Number of alternatives**	3
2	0.111	1.000	1.000	**2**	0.091	0.091	0.091	0.091	0.273	**Consistency Index**	0.00
3	0.111	1.000	1.000	**3**	0.091	0.091	0.091	0.091	0.273	**Random Index**	1.00
SUM	**1.222**	**11.000**	**11.000**					**1.000**		**Consistency Ratio**	0.0000
Water-use efficiency											
Scenario	**1**	**2**	**3**	**Scenario**	**1**	**2**	**3**	**Scores**	**Components of Aw**	**λmax**	3.02
1	1.000	0.250	0.500	**1**	0.143	0.158	0.111	0.137	0.413	**Number of alternatives**	3
2	4.000	1.000	3.000	**2**	0.571	0.632	0.667	0.623	1.891	**Consistency Index**	0.01
3	2.000	0.333	1.000	**3**	0.286	0.211	0.222	0.239	0.722	**Random Index**	1.00
SUM	**7.000**	**1.583**	**4.500**					**1.000**		**Consistency Ratio**	0.0092
Reused(non incinerated) waste											
Scenario	**1**	**2**	**3**	**Scenario**	**1**	**2**	**3**	**Scores**	**Components of Aw**	**λmax**	3.00
1	1.000	0.143	0.143	**1**	0.067	0.067	0.067	0.067	0.200	**Number of alternatives**	3
2	7.000	1.000	1.000	**2**	0.467	0.467	0.467	0.467	1.400	**Consistency Index**	0.00
3	7.000	1.000	1.000	**3**	0.467	0.467	0.467	0.467	1.400	**Random Index**	1.00
SUM	**15.000**	**2.143**	**2.143**					**1.000**		**Consistency Ratio**	0.0000
Total CO2 emissions											
Scenario	**1**	**2**	**3**	**Scenario**	**1**	**2**	**3**	**Scores**	**Components of Aw**	**λmax**	3.07
1	1.000	0.111	0.250	**1**	0.071	0.085	0.040	0.065	0.197	**Number of alternatives**	3
2	9.000	1.000	5.000	**2**	0.643	0.763	0.800	0.735	2.321	**Consistency Index**	0.04
3	4.000	0.200	1.000	**3**	0.286	0.153	0.160	0.199	0.608	**Random Index**	1.00
SUM	**14.000**	**1.311**	**6.250**					**1.000**		**Consistency Ratio**	0.0362
Size of operational facilities											
Scenario	**1**	**2**	**3**	**Scenario**	**1**	**2**	**3**	**Scores**	**Components of Aw**	**λmax**	3.02
1	1.000	0.250	0.200	**1**	0.100	0.077	0.118	0.098	0.295	**Number of alternatives**	3
2	4.000	1.000	0.500	**2**	0.400	0.308	0.294	0.334	1.011	**Consistency Index**	0.01
3	5.000	2.000	1.000	**3**	0.500	0.615	0.588	0.568	1.727	**Random Index**	1.00
SUM	**10.000**	**3.250**	**1.700**					**1.000**		**Consistency Ratio**	0.0123

Table 31. AHP Comparison of alternatives 1



Employees entitled to benefits

Scenario	1	2	3	Scenario	1	2	3	Scores	Components of Aw	λmax	3.00
1	1.000	0.125	0.125	1	0.059	0.059	0.059	0.059	0.176	Number of alternatives	3
2	8.000	1.000	1.000	2	0.471	0.471	0.471	0.471	1.412	Consistency Index	0.00
3	8.000	1.000	1.000	3	0.471	0.471	0.471	0.471	1.412	Random Index	1.00
SUM	17.000	2.125	2.125					1.000		Consistency Ratio	0.0000

Number of person hours

Scenario	1	2	3	Scenario	1	2	3	Scores	Components of Aw	λmax	3.04
1	1.000	0.143	0.125	1	0.063	0.045	0.077	0.062	0.185	Number of alternatives	3
2	7.000	1.000	0.500	2	0.438	0.318	0.308	0.354	1.078	Consistency Index	0.02
3	8.000	2.000	1.000	3	0.500	0.636	0.615	0.584	1.786	Random Index	1.00
SUM	16.000	3.143	1.625					1.000		Consistency Ratio	0.0175

Stakeholder involvement

Scenario	1	2	3	Scenario	1	2	3	Scores	Components of Aw	λmax	3.03
1	1.000	4.000	7.000	1	0.718	0.750	0.636	0.701	2.152	Number of alternatives	3
2	0.250	1.000	3.000	2	0.179	0.188	0.273	0.213	0.645	Consistency Index	0.02
3	0.143	0.333	1.000	3	0.103	0.063	0.091	0.085	0.257	Random Index	1.00
SUM	1.393	5.333	11.000					1.000		Consistency Ratio	0.0163

Total revenue

Scenario	1	2	3	Scenario	1	2	3	Scores	Components of Aw	λmax	3.01
1	1.000	0.333	0.500	1	0.167	0.182	0.143	0.164	0.492	Number of alternatives	3
2	3.000	1.000	2.000	2	0.500	0.545	0.571	0.539	1.625	Consistency Index	0.00
3	2.000	0.500	1.000	3	0.333	0.273	0.286	0.297	0.894	Random Index	1.00
SUM	6.000	1.833	3.500					1.000		Consistency Ratio	0.0046

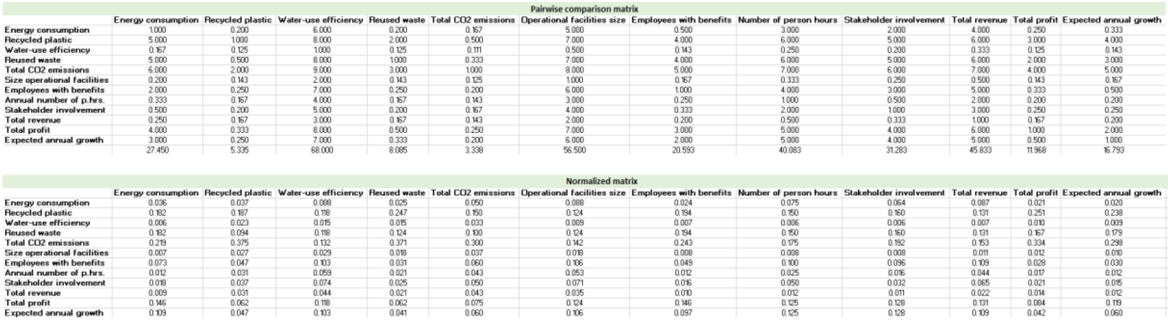
Total profit

Scenario	1	2	3	Scenario	1	2	3	Scores	Components of Aw	λmax	3.07
1	1.000	0.250	0.333	1	0.125	0.158	0.077	0.120	0.363	Number of alternatives	3
2	4.000	1.000	3.000	2	0.500	0.632	0.692	0.608	1.904	Consistency Index	0.04
3	3.000	0.333	1.000	3	0.375	0.211	0.231	0.272	0.835	Random Index	1.00
SUM	8.000	1.583	4.333					1.000		Consistency Ratio	0.0371

Expected annual growth

Scenario	1	2	3	Scenario	1	2	3	Scores	Components of Aw	λmax	3.08
1	1.000	0.250	4.000	1	0.190	0.179	0.333	0.234	0.718	Number of alternatives	3
2	4.000	1.000	7.000	2	0.762	0.718	0.583	0.688	2.170	Consistency Index	0.04
3	0.250	0.143	1.000	3	0.048	0.103	0.083	0.078	0.235	Random Index	1.00
SUM	5.250	1.393	12.000					1.000		Consistency Ratio	0.0387

Table 32. AHP Comparison of alternatives 2



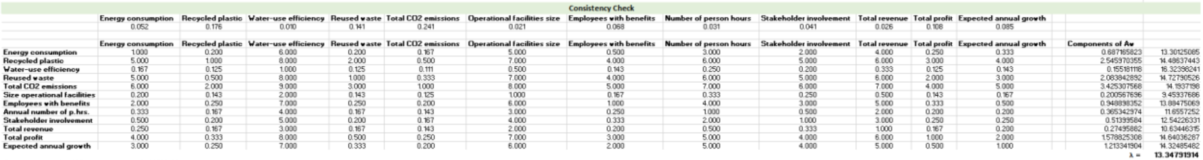
Pairwise comparison matrix

	Energy consumption	Recycled plastic	Water-use efficiency	Reused waste	Total CO2 emissions	Operational facilities size	Employees with benefits	Number of person hours	Stakeholder involvement	Total revenue	Total profit	Expected annual growth
Energy consumption	1.000	0.200	6.000	0.200	0.167	5.000	0.500	3.000	2.000	4.000	0.250	0.333
Recycled plastic	5.000	1.000	8.000	2.000	0.500	7.000	4.000	6.000	5.000	6.000	3.000	4.000
Water-use efficiency	0.167	0.125	1.000	0.125	0.111	0.500	0.143	0.250	0.200	0.333	0.125	0.143
Reused waste	5.000	0.500	8.000	1.000	0.333	7.000	4.000	6.000	5.000	6.000	2.000	3.000
Total CO2 emissions	6.000	2.000	9.000	3.000	1.000	8.000	5.000	7.000	6.000	7.000	4.000	5.000
Size operational facilities	0.200	0.143	2.000	0.143	0.125	1.000	0.167	0.333	0.250	0.500	0.143	0.167
Employees with benefits	2.000	0.250	7.000	0.250	0.200	6.000	1.000	4.000	3.000	5.000	0.333	0.500
Annual number of p.hrs.	0.333	0.167	4.000	0.167	0.143	3.000	0.250	1.000	0.500	2.000	0.200	0.200
Stakeholder involvement	0.500	0.200	5.000	0.200	0.167	4.000	0.333	2.000	1.000	3.000	0.250	0.250
Total revenue	0.250	0.167	3.000	0.167	0.143	2.000	0.200	0.500	0.333	1.000	0.167	0.200
Total profit	4.000	0.333	8.000	0.500	0.250	7.000	3.000	5.000	4.000	6.000	1.000	2.000
Expected annual growth	3.000	0.250	7.000	0.333	0.200	6.000	2.000	5.000	4.000	5.000	0.500	1.000
	27.450	5.335	68.000	8.085	3.338	56.500	20.593	40.083	31.283	45.833	11.968	16.793

Normalized matrix

	Energy consumption	Recycled plastic	Water-use efficiency	Reused waste	Total CO2 emissions	Operational facilities size	Employees with benefits	Number of person hours	Stakeholder involvement	Total revenue	Total profit	Expected annual growth	Scores
Energy consumption	0.036	0.037	0.088	0.025	0.050	0.088	0.024	0.075	0.064	0.087	0.021	0.020	0.051
Recycled plastic	0.182	0.187	0.118	0.247	0.150	0.124	0.194	0.150	0.160	0.131	0.251	0.238	0.178
Water-use efficiency	0.006	0.023	0.015	0.015	0.033	0.009	0.007	0.006	0.006	0.007	0.010	0.009	0.012
Reused waste	0.182	0.094	0.118	0.124	0.100	0.124	0.194	0.150	0.160	0.131	0.167	0.179	0.143
Total CO2 emissions	0.219	0.375	0.132	0.371	0.300	0.142	0.243	0.175	0.192	0.153	0.334	0.298	0.244
Size operational facilities	0.007	0.027	0.029	0.018	0.037	0.018	0.008	0.008	0.008	0.011	0.012	0.010	0.016
Employees with benefits	0.073	0.047	0.103	0.031	0.060	0.106	0.049	0.100	0.096	0.109	0.028	0.030	0.069
Annual number of p.hrs.	0.012	0.031	0.059	0.021	0.043	0.053	0.012	0.025	0.016	0.044	0.017	0.012	0.029
Stakeholder involvement	0.018	0.037	0.074	0.025	0.050	0.071	0.016	0.050	0.032	0.065	0.021	0.015	0.039
Total revenue	0.009	0.031	0.044	0.021	0.043	0.035	0.010	0.012	0.011	0.022	0.014	0.012	0.022
Total profit	0.146	0.062	0.118	0.062	0.075	0.124	0.146	0.125	0.128	0.131	0.084	0.119	0.110
Expected annual growth	0.109	0.047	0.103	0.041	0.060	0.106	0.097	0.125	0.128	0.109	0.042	0.060	0.086

Table 33. AHP Criteria pairwise comparison matrix

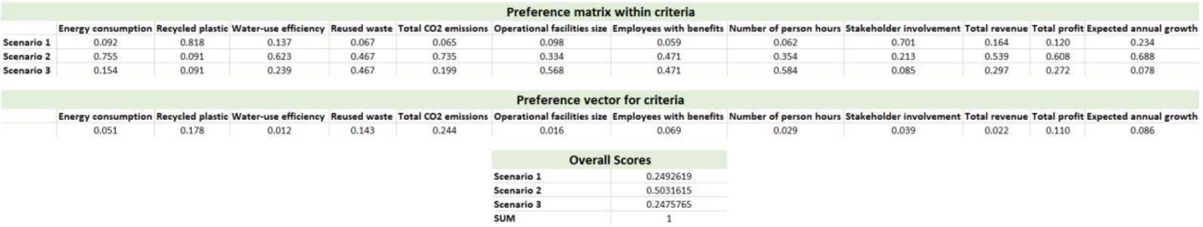


Consistency Check

	Energy consumption	Recycled plastic	Water-use efficiency	Reused waste	Total CO2 emissions	Operational facilities size	Employees with benefits	Number of person hours	Stakeholder involvement	Total revenue	Total profit	Expected annual growth		
	0.052	0.176	0.010	0.141	0.241	0.021	0.068	0.031	0.041	0.026	0.108	0.085		
	Energy consumption	Recycled plastic	Water-use efficiency	Reused waste	Total CO2 emissions	Operational facilities size	Employees with benefits	Number of person hours	Stakeholder involvement	Total revenue	Total profit	Expected annual growth	Components of Aw	
Energy consumption	1.000	0.200	6.000	0.200	0.167	5.000	0.500	3.000	2.000	4.000	0.250	0.333	0.687165823	13.30125085
Recycled plastic	5.000	1.000	8.000	2.000	0.500	7.000	4.000	6.000	5.000	6.000	3.000	4.000	2.545970355	14.48637443
Water-use efficiency	0.167	0.125	1.000	0.125	0.111	0.500	0.143	0.250	0.200	0.333	0.125	0.143	0.155181118	16.32398241
Reused waste	5.000	0.500	8.000	1.000	0.333	7.000	4.000	6.000	5.000	6.000	2.000	3.000	2.083842892	14.72790526
Total CO2 emissions	6.000	2.000	9.000	3.000	1.000	8.000	5.000	7.000	6.000	7.000	4.000	5.000	3.425307568	14.1937198
Size operational facilities	0.200	0.143	2.000	0.143	0.125	1.000	0.167	0.333	0.250	0.500	0.143	0.167	0.200567696	9.45937686
Employees with benefits	2.000	0.250	7.000	0.250	0.200	6.000	1.000	4.000	3.000	5.000	0.333	0.500	0.948898352	13.88475069
Annual number of p.hrs.	0.333	0.167	4.000	0.167	0.143	3.000	0.250	1.000	0.500	2.000	0.200	0.200	0.365342974	11.6557252
Stakeholder involvement	0.500	0.200	5.000	0.200	0.167	4.000	0.333	2.000	1.000	3.000	0.250	0.250	0.51399584	12.54226331
Total revenue	0.250	0.167	3.000	0.167	0.143	2.000	0.200	0.500	0.333	1.000	0.167	0.200	0.27495882	10.63446315
Total profit	4.000	0.333	8.000	0.500	0.250	7.000	3.000	5.000	4.000	6.000	1.000	2.000	1.578825308	14.64036287
Expected annual growth	3.000	0.250	7.000	0.333	0.200	6.000	2.000	5.000	4.000	5.000	0.500	1.000	1.213341904	14.32485482
													λ =	13.34791914

Consistency Index (CI)	0.122538103
Consistency Ratio (CR)	0.079570197

Table 34. AHP Consistency check



Preference matrix within criteria

	Energy consumption	Recycled plastic	Water-use efficiency	Reused waste	Total CO2 emissions	Operational facilities size	Employees with benefits	Number of person hours	Stakeholder involvement	Total revenue	Total profit	Expected annual growth
Scenario 1	0.092	0.818	0.137	0.067	0.065	0.098	0.059	0.062	0.701	0.164	0.120	0.234
Scenario 2	0.755	0.091	0.623	0.467	0.735	0.334	0.471	0.354	0.213	0.539	0.608	0.688
Scenario 3	0.154	0.091	0.239	0.467	0.199	0.568	0.471	0.584	0.085	0.297	0.272	0.078

Preference vector for criteria

Energy consumption	Recycled plastic	Water-use efficiency	Reused waste	Total CO2 emissions	Operational facilities size	Employees with benefits	Number of person hours	Stakeholder involvement	Total revenue	Total profit	Expected annual growth
0.051	0.178	0.012	0.143	0.244	0.016	0.069	0.029	0.039	0.022	0.110	0.086

Overall Scores	
Scenario 1	0.2492619
Scenario 2	0.5031615
Scenario 3	0.2475765
SUM	1

Table 35. AHP Preferences and scores