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Multi-criteria decision analysis (MCDA) method for assessing the sustainability of end-of-life alternatives for waste plastics: A case study of Norway

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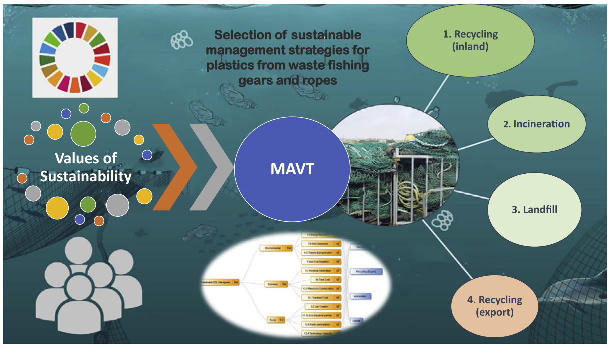
HIGHLIGHTS

- Modified MAVT is used to ensure sustainable end-life management of fishing gears.
- MAVT procedure offers a structured and transparent decision making framework.
- SDGs proven effective in engaging stakeholders and communicating sustainability.
- Results highlight the need for ensuring sustainability in circular strategies.
- Results identify barriers and opportunities to realize circular business models.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic, and its pollution of marine ecosystems, has emerged as a global concern. Among the several other sources, plastics from *abandoned*, *lost*, *or discarded fishing gears* (ALDFG), and ropes are considered the most dangerous for marine wildlife. In EU states, the management ALDFG is prioritized through a dedicated action plan owing to the hazardous nature of ALDFG and the increase in commercial fishing activity in EU waters. The action plan demands to close the loop of plastics from fishing to ensure sustainable resource management using strategies of the circular economy (CE). Commercial fishing is a crucial sector in Norway, generating 4000 tons of waste plastic annually from fishing gears and ropes. While recycling, landfilling, and incineration are the standard end-of-life management options, the recycling industry in the region is immature. The lack of recycling capacity and inadequate infrastructure results in exporting most of the recyclable fraction out of Norway for further processing. Although within the framework of CE, the transboundary export of waste for recycling misses the opportunity to create value out of waste within the region. Therefore, in the pursuit of CE strategies, it is essential to ensure regional sustainability.

In this study, we assess the environmental, economic, and social impacts of landfilling, incinerating, and recycling of waste fishing gears in Norway. To represent the current state, we include two existing recycling scenarios for the assessment, namely, recycling (inland) and recycling (export). Based on qualitative and quantitative data from relevant stakeholders, we adapted multi-criteria decision analysis (MCDA) to rank the end-of-life (EOL) alternatives through their ability to sustainably manage 4000 tons of waste plastics from fishing gears in Norway.

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The ranking and insights from stakeholder interaction were used to ascertain potential barriers in realizing principles of CE and to further recognize opportunities for establishing circular business models in the region.

1. Introduction

Plastic pollution has become a global concern as plastic debris has reached all the oceans of the world, adversely affecting marine biodiversity, human livelihoods, and the economy (Thevenon et al., 2014). The transboundary nature of plastic pollution and the need for focused international collaboration was acknowledged at the Rio + 20 United Nations Conference on Sustainable Development in June 2012. While plastic provides essential applications in many industrial sectors, its growing use in short-lived applications, which are not designed for reuse or cost-effective recycling, means that related production and consumption patterns have become increasingly inefficient and linear (Union, 2019). Contrary to the linear economic model, circular economy (CE) has recently gained traction in policy, business, and academia to advocate a transition from a linear 'take-make-dispose' model, towards a circular model, in which waste is a resource that is valorized through recycling and reuse (MacArthur, 2013). The appeal of CE is that it promises to reconcile environmental and economic goals by reducing resource use and stimulating economic growth at the same time (Baldassarre et al., 2019).

In the EU, the principles of CE were seen as essential measures to mitigate and ensure the sustainable management of plastic waste. On 16th Jan 2018, the European Commission (EC) adopted the *European strategy for plastics in a circular economy*, which recognizes plastics as a significant source of marine litter (EC, 2018a). In the elaborated action plan, additional action on plastics from fishing gears (FGs) was stressed, owing to the hazardous nature of abandoned, lost, or discarded fishing gears (ALDFG) and an increase in commercial fishing activity in EU waters (EC, 2018b).

FG is defined as "any physical device or part thereof or combination of items that may be placed on or in the water or on the seabed with the intended purpose of capturing or controlling for subsequent capture or harvesting, marine or freshwater organisms whether or not it is used in association with a vessel" (FAO, 2016a). The design and material of FGs vary based on the type and purpose of that gear. Plastic polymers (polypropylene [PP], polyethylene [PE], and Nylon) remain the primary building blocks of any FGs, constituting approximately 60–90% of FG material (Deshpande et al., 2020). Of the total plastic waste entering the oceans, ALDFG is considered a particularly troublesome waste fraction, which can continue to trap marine animals for decades upon release (Laist, 1997; Macfadyen et al., 2009). The amount, distribution, and effects of ALDFG have risen substantially over past decades with the rapid expansion of fishing efforts and fishing grounds, and the transition to synthetic, more durable, and more buoyant materials used for FGs (Derraik, 2002; Gilman, 2015). In addition to the threat to marine ecology, the loss of fish stocks due to ghost fishing and the cost of losing valuable resources from lost or abandoned FGs also constitute significant economic setbacks (Deshpande and Aspen, 2018). Therefore, it is imperative to investigate sustainable strategies to reduce and manage waste generated from ALDFGs.

Although commercial fishing is a primary activity in most EU-EEA member states, Norway alone contributes to around one-third of the total catch, owing to its resource-rich coastline and advanced fishing fleet (Deshpande et al., 2019; Lawson, 2015). In 2016, an estimated 4000 tons of plastic waste was generated from commercial fishing in Norway, out of which 55% was segregated for recycling, 26% landfilled, and 19% incinerated (Deshpande et al., 2020). While the recycling rate exceeds the other two end-of-life (EOL) management alternatives, landfill and incineration, little or no industrial-scale recycling was present in Norway before 2017. The lack of in-house recycling resulted in the export of most of the recyclable fraction to eastern European countries for further processing.

The export of recyclable fractions from developed to developing countries is a common practice in many sectors including ships (Deshpande et al., 2012), electric and electronic waste (Bi et al., 2007), and plastics (Gourmelon, 2015; Brooks et al., 2018). In 2012, 87% of the waste plastic from the EU was reportedly exported to China alone (Gourmelon, 2015). However, considering the actual environmental costs of plastic recycling, in 2017, China imposed a ban on importing plastic waste and other materials. This ban has placed significant pressure on developed countries and may provide a stimulus for exploring regional strategies to manage plastic waste through CE principles (Walker, 2018). Industrial-scale recycling for obsolete plastics from the fishing and aquaculture sector began in Norway in the latter half of 2017. Nonetheless, inadequate infrastructure, lack of political support and innovation, and the absence of eco-industrial partnerships have hindered the development of circular business models (CBM) in the region. In designing strategies for the EOL management of plastic waste, it is essential to ensure that the chosen strategies are sustainable.

Several multi-criteria decision analysis (MCDA) based frameworks have been developed and deployed successfully for the operationalization of sustainability in strategic decision making (Huang et al., 2011; Martín-Gamboa et al., 2017). Typically, MCDA based sustainability assessment methods encompass the triple-bottom-line aspects (Elkington, 1998) but with a primary focus on the secondary environmental impacts, which are not always quantitatively assessed with a life cycle perspective in decision making tools (da S Trentin et al., 2019; Hou et al., 2018). Further, these tools are not completely quantitative in economic and social aspects, which makes the analysis performed using these tools subjective and unreliable.

In this study, we assess the environmental, economic, and social impacts of landfilling, incinerating, and recycling waste plastics from FGs in Norway. To obtain a clear picture, we include two existing recycling scenarios for the assessment, namely, recycling (inland) and recycling (export). Based on quantitative data from site visits and qualitative information from expert stakeholders, we adopted MCDA to rank the EOL alternatives based on their ability to sustainably manage 4000 tons of waste plastics from FGs in Norway. The ranking and insights from stakeholder interaction were also used to identify shortcomings in existing EOL strategies. The stakeholder engagement was further used to identify what are the potential barriers in realizing the principles of CE and to recognize opportunities for establishing CBMs in the region.

2. Description of a case study alternatives

In Norway, EOL FGs and ropes from commercial fisheries are sent to the nearest waste management companies (WMCs) or at the port reception facility (PRF) in the state when they cannot be repaired any further. The ALDFG collected from beach and ocean clean-up efforts also end up in WMCs. In the WMCs, the collected waste is segregated into three fractions, i) for recycling, ii) for incineration, and iii) for landfill (Deshpande and Aspen, 2018). The segregated waste fractions are then collected from the targeted locations by waste collectors or recyclers and transported to the respective treatment sites. Before 2017, most of the recyclable fraction was exported out of Norway for recycling. However, the industrial recycling of EOL FGs began in 2017, and dedicated recycling plants are located in the central part of Norway. Therefore we consider four EOL alternatives for assessment in this study.

2.1. Recycling (inland)

Fig. 1 shows the process flow diagram of sequential processes carried out at the recycling facility in Norway. Waste fractions are transported to the recycling facility by trucks/lorries. These transported fractions are then unloaded at the storage yards, sorted, and further segregated as per the quality and type of the material. The additional segregation step is necessary to perform quality control of the recycling process and to ensure the separation of metal fractions from the waste. The recyclable fraction of the waste is then sent to the mechanical shredding unit. If the shredded fraction is laden with dirt, biomass, or oil, then it is washed. The washed and shredded fraction is then fed into a granulation machine where it undergoes a series of mechanical processing steps to convert shredded waste FG and ropes to high-density polyethylene (HDPE) pellets. These steps include melting, vacuum treatment, filtration, cutting, and cooling of the recycled pellets. Dried pellets are then stored in transportable bags. The entire recycling process has an efficiency (mass) of about 50% to 60%, which varies significantly based on the nature of the waste. The waste fraction generated as a residue of the recycling process is sent to incineration for energy recovery. The industrial recycling of plastics from fishing is still a relatively new sector in Norway, with a current handling capacity of 3000 tons/yr. Although the recycling capacity is less than the annual waste generated from obsolete FGs, it is currently underutilized due to the transboundary export of the recyclable plastic fraction.

2.2. Recycling (export)

The lack of industrial recycling practices results in the transboundary export of most of the recyclable plastic fraction from Norway. Therefore, recycling (export) was considered separately for the assessment of sustainable EOL management alternatives. The mechanical recycling process is the same for both the inland and export recycling alternatives. The only notable difference is in the transport distances for the waste FGs and ropes. For recycling within Norway, the typical transport distances are 150–200 km, while 1400–1600 km transport distances were assumed for recycling out of Norway.

2.3. Incineration

An estimated 19% of the collected EOL FGs are sent directly to incineration every year in Norway. Incineration burns the waste at waste-to-heat incinerators or co-generators within Norway to recover energy in the form of electricity or thermal energy, which is then used for district heating. The waste FGs from WMCs are transported to incineration facilities in which they undergo mechanical sorting and shredding before being fed into the incinerator. In 2017, 84,000 tons of plastic were incinerated in Norway (Anders et al., 2017). Fig. 2 demonstrates the typical processes involved in the Norwegian incineration facilities.

2.4. Landfill

Landfilling is the final waste management alternative used to deposit both general and inert waste fractions in Norway. Typically, 1.6 m^3 of landfill volume is consumed per ton of waste plastic (Granlund, 2016). In 2017, 4000 tons of plastic was landfilled in Norway (Granlund, 2016). Although the technology to recover energy through landfill gases is available, significant variations in the landfill gases and methane content make it difficult to use as a stable energy source in Norway (Granlund, 2016). Hence, it is assumed that no resources, material, or energy, are conserved from landfilling the 4000 tons of waste FGs in Norway (Fig. 3).

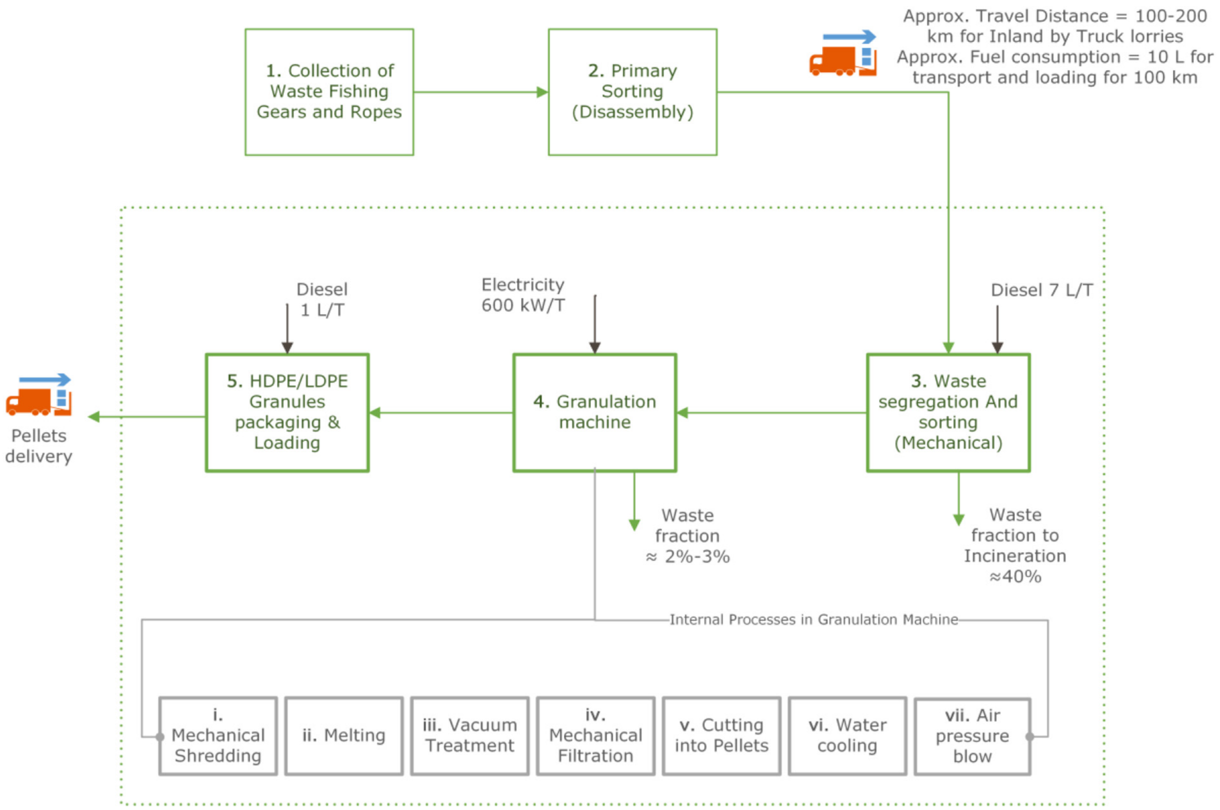

Fig. 1. Typical process flow diagram for mechanical recycling of EOL plastic FG and ropes in Norway.

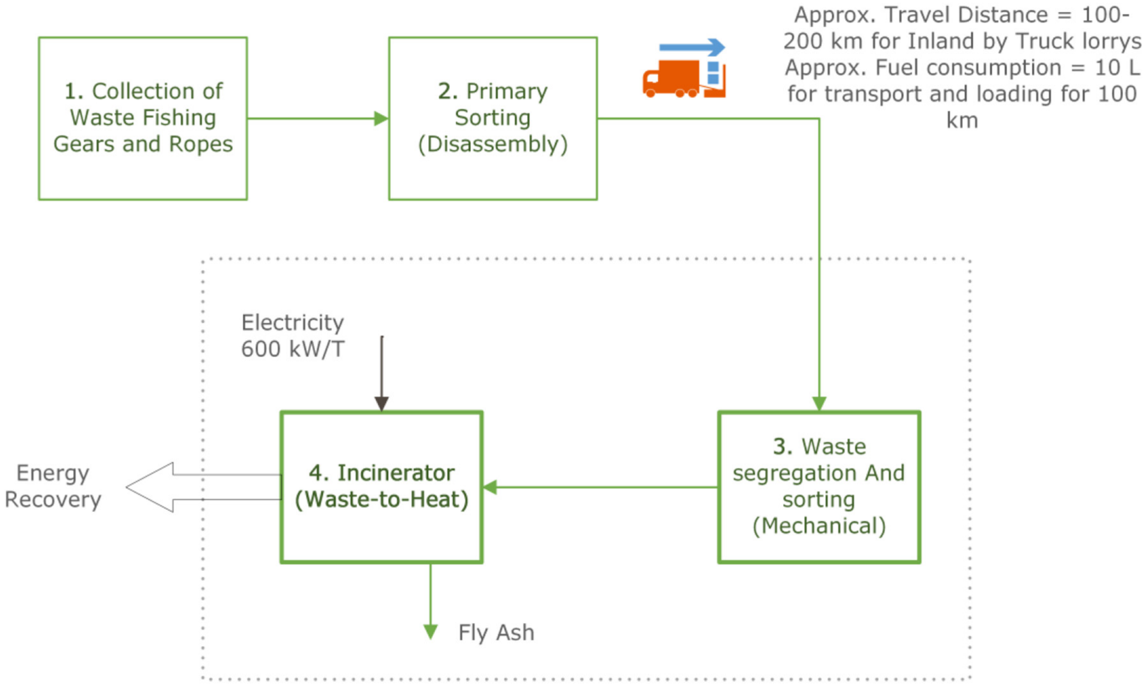

Fig. 2. Typical process flow diagram of waste to energy Incineration in Norway.

3. Methodology

3.1. Sustainability assessment

There exist several approaches, guidelines, as well as case studies focusing on the inclusion of sustainability assessments in management problems. Most of these approaches include comparative assessments of the environmental, social, and economic impacts of selected management alternatives for overall sustainability. The assessment frameworks vary with respect to the type of assessment (qualitative, semi-quantitative, or quantitative), criteria and indicators considered, and the overall aim of the assessment. Most of these tools focus on environmental footprint analysis and sometimes incorporate economic and social impacts with a semi-quantitative approach for overall sustainability assessment (da S Trentin et al., 2019).

Existing sustainability theories suggest that sustainability assessment should be both universal and context dependent (Hou et al., 2018). Therefore, in this study, sustainable management is defined as *the ability of EOL management alternatives to manage 4000 tons of waste FGs annually through maximizing environmental, economic, and social benefits, while minimizing the negative effects*. The Sustainable development goals (SDGs) and targets are considered useful in assessing the three dimensions of sustainability, environmental, economic and social, proposed by Elkington (1998). The SDGs primarily address some of the systemic barriers to sustainable development (SD) and contain better coverage of and balance between the three dimensions of SD and their institutional/governance aspects, which are usually neglected in traditional sustainability assessments (Costanza et al., 2016). Sustainability evaluation of waste management alternatives is an inherently multi-attribute problem. It is characterized by many different dimensions pursuing heterogeneous and often conflicting objectives (Ferretti et al., 2014). MCDA is a vital component of sustainability assessment tools as it allows for assessing the uncertainty associated with the data used and also identifies the relevance and/or importance of each criterion used in sustainability assessments. Therefore, the choice of the MCDA approach and its relevance to the current context is elaborated here.

3.2. Multi-criteria decision analysis

The literature suggests several approaches to deal with multi-attribute problems, each characterized by specific mathematical properties with various implications. Among the many MCDA methods, Multi-Attribute Value Theory (MAVT) was selected for assessing the most sustainable EOL alternative to manage waste plastics from FGs in Norway due to its suitability for the participatory process (Van Herwijnen, 2010) and its flexibility. Applications of MAVT range from technology assessment (Tsang et al., 2014), risk management (Sorvari and Seppälä, 2010) to sustainable site selection (Ferretti and Comino,

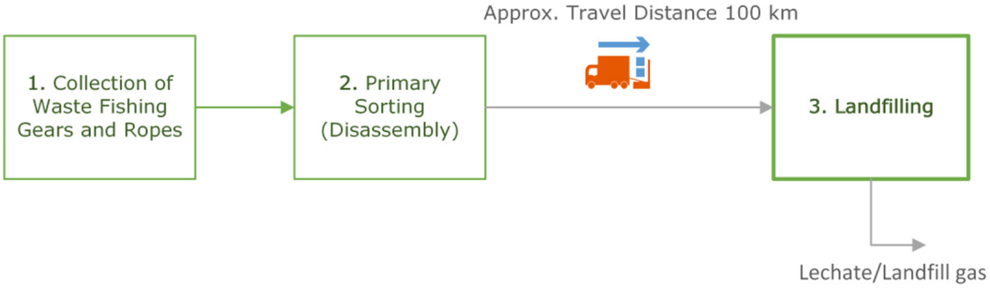

Fig. 3. Typical process flow diagram for landfilling of waste FGs and ropes in Norway.

2015). Typically it involves ranking different management alternatives using the opinions of relevant stakeholder groups, aimed at finding the “best” solution (Stefanopoulos et al., 2014; Belton and Stewart, 2002). MAVT is known for handling both quantitative and qualitative data. In the absence of quantitative information, expert judgements can be used to estimate the impacts on a qualitative scale (Ferretti et al., 2014).

MAVT is also known for its simplicity, transparency, and robustness in eliciting stakeholder preferences (Osterwalder et al., 2014). Here the MAVT method of (Pesce et al., 2018) was adopted, with modifications to fit the local situation and relevance. Fig. 4 demonstrates the stepwise approach used to address the problem at hand. Initiated in Jan 2019, the study lasted for 6 months and included stakeholder interviews, data collection from site visits, analysis, and presentation of results.

3.3. Selection of system boundary and alternatives

The selection of system boundaries and alternatives for comparison through MAVT is a crucial step for ensuring robust analysis. The typical system lifecycle of FGs and ropes from the Norwegian commercial fishing was defined by (Deshpande and Aspen, 2018). Accordingly, the geographical territory of Norway was used as a system boundary for the MAVT analysis. Consequently, all the monetary and material flows out of the system boundary are not accounted for in the assessment. In MAVT, the chosen alternatives are evaluated and ranked based on their performance against the assessment criteria. Thus, balanced and extensive criteria selection is the next step of the assessment.

3.4. Selection and ranking of assessment criteria

The criteria selected for assessment should reduce the uncertainty, increase the understanding of the selected system, and measure the performance of the alternatives against a defined goal (Convertino et al., 2013). Here, the initial criteria selection was based on a literature survey and refined through interviews with relevant stakeholders. Deshpande and Aspen (2018) demonstrated how relevant SDGs and targets could be used to identify the criteria for assessing sustainability in managing FG resources in Norway. In this study, primary criteria selection was inspired by the relevant SDGs and targets.

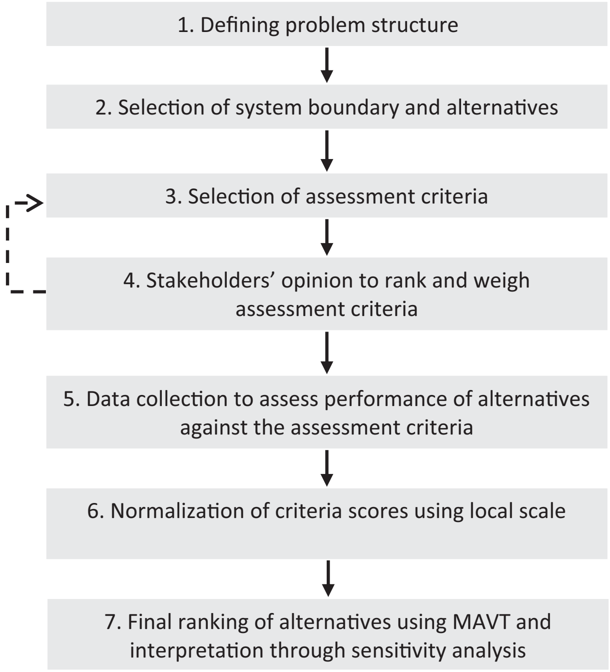

Fig. 4. A proposed stepwise method for assessing and ranking EOL management alternatives.
(Modified from Collier et al., 2014).

Incorporating the knowledge of experts for selecting and ranking assessment criteria is a common practice in MCDA studies (Tsai, 2018; Tsai et al., 2018). Accordingly, a simple questionnaire was formulated and distributed among the list of attendees in the scientific workshop organized in Tromsø, Norway, on 21st January 2019. The workshop was part of a research project on marine plastic pollution in the Arctic region, making the stakeholders especially relevant for our context. The survey was distributed after a brief introduction to plastic pollution due to FGs and typical EOL alternatives of fishery-related waste in Norway. In total, 31 responses from the experts in the field were recorded and further analyzed. The supplementary information (SI) presents the sample questionnaire and statistical analysis of stakeholders' response.

3.5. Synthesizing weights from stakeholder responses

The questionnaire responses were coalesced and summarized to show the distribution of priorities encountered in the working group, as shown by Collier et al. (2014). Points allocated to criteria and subcriteria were converted into weights based on the following equation.

$$\mathrm{W_i} = \frac{\mathrm{S_i}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{S_i}}$$

where W_i is the weight of criterion i; S_i is the score in points assigned to criterion i, and n is the number of criteria being weighted within that particular group of criteria or sub-criteria.

Finally, the best of four sub-criteria and their weights were designated to represent the three main sets of criteria, namely environmental, economic, and social. Both qualitative and quantitative criteria were selected to ensure the holistic assessment of sustainability. Table 1 shows the list of assessment criteria, relevant SDGs, targets, and overall criteria goals, stating whether the ideal alternative should maximize or minimize the performance of that criterion.

3.6. Performance assessment of alternatives

In this study, both qualitative and quantitative assessment criteria were used. The criteria under the environmental and economy category are quantitative, while four criteria for the social category demanded qualitative analysis. The data collection methods and calculation protocol used for the performance assessment of the four alternatives are elaborated here. The collected data and calculation methods are detailed in SI.

3.6.1. Environmental criteria

Four criteria were selected to evaluate the environmental performance of EOL alternatives: i) E1. Depletion of fossil fuels, ii) E2. Greenhouse gas (GHG) emissions, iii) E3. Marine eutrophication and iv) E4. Energy recovery.

The performance of the four alternatives for criteria E1–E3 was calculated through the raw data obtained from regional recyclers and the central statistics bureau (SSB) of Norway. The primary data was collected through site visits to recycling, landfill, and incineration facilities within Norway between February and May 2019 and extrapolated to annual figures. Semi-structured interviews and annual reports were used to collect the energy and material flows of the processes involved in each alternative. The data was then fed into SimaPro 7.2 (PRé Consultants, 2008), and the ecoinvent database 3 (www.ecoinvent.org) was used for screening life cycle assessment (LCA). As explained earlier, the recycling (inland) process generates recycled plastic polymers, and energy is recovered from incinerating the reject. Therefore, the real environmental impacts of recycling (inland) include emissions from the recycling and incineration process but should also consider the

Table 1
Selected assessment criteria for comparing EOL alternatives.

TBL	Assessment criteria	Description	Relevant SDGs	Goal	Unit	Calculation method
Environmental	E1. Depletion of fossil fuels	Consumption of fossil fuels while implementing the management options.	14	Minimize	kg oil eq	Screening life cycle assessment (LCA)
	E2. Greenhouse gas (GHG) emissions	Carbon emissions in implementing the management options.	13	Minimize	ton CO_2-eq./year	Screening LCA
	E3. Marine eutrophication	Pollution potential of waste management alternative.	14.7	Minimize	kg P eq	Screening LCA
	E4. Energy recovery	Energy recovered (thermal/electricity) while implementing the EOL scenario.	13	Maximize	GWh	Data from recyclers and incineration units
Economic	C1. Resource conservation	Resources conserved in the form of materials or energy by adapting the EOL alternative.	12.5	Maximize	Tons of recycled plastic polymer	Data from recyclers, SSB Norway and (Deshpande et al., 2020)
	C2. Revenue generation	Revenues generated (NOK) from conserved material or energy from EOL alternatives.	9.2	Maximize	mNOK	Data from recyclers, SSB Norway and (Deshpande et al., 2020)
	C3. Total cost	The costs incurred by recyclers/waste managers in managing 4000 tons of waste FGs and ropes, excluding transport costs.	9b	Minimize	mNOK	Data from recyclers, SSB Norway
	C4. Transport cost	Costs of transporting waste to the management facility.	9.1	Minimize	mNOK	Data from recyclers, SSB Norway and (Søiland, 2018)
Social	S1. Job creation	Direct employment opportunities created by a management alternative.	9.2	Maximize	Number	Recyclers and stakeholder interview
	S2. Eco-industrial partnerships	Possibilities of creating eco-industrial partnerships (product-to-product) recycling.	17.16	Maximize		Recyclers and stakeholder interview
	S3. Awareness and public participation	Management alternative promoting public awareness and participation.	12.8	Maximize		Stakeholder interview
	S4. Technology capacity	The current capacity of management alternative to handle 4000 tons of waste.	12.4	Maximize	%	Recyclers and literature review

emissions avoided from the production of energy and recycled polymers. In recycling (export), emissions from the recycling process were neglected to respect the system boundary. In Norway, waste plastic from FGs and ropes are typically mixed with other plastic waste and then subjected to landfill or incineration. Therefore, to obtain the life cycle inventory data for incineration and landfilling, the ecoinvent database was used for Norway and Europe. The lifecycle inventory analysis was then followed by normalization using ReCiPe Midpoint (H) V1.13/ Europe method. The raw data was then used to estimate the energy recovery per year for the selected alternatives.

3.6.2. Economic criteria

Four criteria were shortlisted to assess the economic impacts of EOL alternatives: i) C1. Resource conservation, ii) C2. Revenue generation, iii) C3. Total cost and iv) C4. Transport cost.

As with the environmental criteria, all the chosen economic criteria are quantitative. The first criterion is aimed at quantifying the resources conserved within the system through each EOL alternative for handling waste FGs and ropes. The recycled plastic polymers (HDPE, LDPE, or nylon) are termed as resources in this study. The second criterion targets the monetary benefits incurred through EOL alternatives. The revenue generated was estimated through the market value of the recycled polymers and the energy recovered. The total cost criterion aims to quantify the operational costs incurred by each EOL alternative for handling waste within the system. Here, the costs incurred in transporting the waste to the respective management facilities were excluded and calculated in the last criterion. The performance of the alternatives against the economic criteria was calculated using the raw data collected from literature, SSB Norway, road and transport authorities of Norway (Søiland, 2018), and through site visits and interviews with recyclers and waste managers.

3.6.3. Social criteria

The four selected social assessment criteria are i) S1. Job creation, ii) S2. Eco-industrial partnerships, iii) S3. Awareness and public participation, and iv) S4. Technology capacity.

The job creation criteria aimed at ranking the EOL alternatives based on their ability to create new jobs within the system boundary. The second social criterion, eco-industrial partnerships (EIP), was examined as concrete realizations of the industrial symbiosis concept (Chertow, 2007). Industrial symbiosis is defined as a network that engages traditionally separate entities in a collective approach to competitive advantage involving the physical exchange of materials, energy, water, and by-products (Chertow, 2000). The key to industrial symbiosis is collaboration and the synergistic possibilities offered by geographic proximity. Therefore, EIP focuses on the ability of an EOL alternative to promote symbiotic relationships in which companies utilize the waste materials or energy from other companies/sectors.

Similarly, the third social criterion involved assessing the ability of an alternative to raise awareness and public participation within the region. The last social criteria aimed at examining the annual capacity of EOL alternative to handle 4000 tons of waste FGs and ropes. Around 4000 tons of waste FGs and ropes are collected in Norway annually from commercial fishing practices alone; therefore, the capacity and readiness of the four EOL alternatives were assessed through the criteria qualitatively. Unlike environmental and economic criteria, social criteria are typically more qualitative. Therefore, stakeholders' opinions were used to assess the alternatives against the social criteria. Semi-structured interviews and questionnaires with experts in the field of waste management, NGOs, consultants, and academic fields were used to rank the alternatives.

3.7. Final ranking using MAVT

The overall performance of each alternative was measured by a value function, which aggregated the performance of each criterion into a single overall value (Belton and Stewart, 2002). The study adopted a linear additive function that aggregated the different criteria scores and weights to obtain a ranking of the alternatives. The linear function of the model is expressed here (adapted from Belton and Stewart, 2002):

$$V(A) = \sum_{i} W_i V_i (A_i)$$

where $V(A)$ is the overall value function for alternative A, Wi is the weight assigned to criterion i by the stakeholder group, and $Vi(Ai)$ is the performance of alternative *A* on criterion *i* assessed through screening LCA and/or stakeholder judgment.

In MAVT, the goal is defined for each criterion (as presented in Table 1). Apart from greenhouse emissions, fossil fuel depletion, and costs, all other criteria are set to maximize by the preferred alternative. The analysis was performed using DECERNS (Decision Evaluation in ComplEx Risk Network Systems1) software (Yatsalo et al., 2016). Linkov and Moberg (2011) successfully demonstrated the use of DECERNS in mapping and solving multi-criteria problems within the field of environmental and sustainability assessment. Moreover, in order to assess the dependence of the obtained results to changes in stakeholder profiles, a sensitivity analysis of the three main criteria was conducted for each profile. Pesce et al. (2018) advocated the use of sensitivity analysis with MAVT to confirm whether the outcomes are robust to weights. Therefore, each criterion was changed independently, and other weights were automatically adjusted proportionally, holding the weighted total equal to 100.

4. Results

4.1. Quantitative assessment of stakeholder responses

In total, 31 responses were recorded from diverse stakeholders ranging from academics, consultants, NGOs, recyclers, waste managers, and regulatory authorities working in the area of fishery and marine plastic pollution. Fig. 5 shows the distribution of sample points concerning professional expertise. The survey samples were analyzed statistically to calculate the mean, standard deviation and finally, to find out the weights of criteria and sub-criteria for the environment, economy, and social impact categories. Table 2 shows the weights of criteria and sub-criteria based on stakeholders' responses. These weights were used for the MAVT assessment.

Stakeholders' considered the economic dimensions of sustainability to overpower the environmental and social dimensions for the system of EOL management of FGs and ropes in Norway. The economic assessment criteria were weighed 42%, followed by an environmental 34%, and social 23%, underpinning the economy as a critical driver for assessing EOL management alternatives.

Additionally, stakeholder inputs were used to a) shortlist the four sub-criteria for each main criterion, and b) weight these sub-criteria using the MAVT equation defined in the Methodology section. The final weights and selected sub-criteria are described in Table 2. According to the stakeholders' perspectives, sub-criteria such as energy recovered (27%) and fossil fuel depletion (28%) are more important than GHG emissions (23%) and marine eutrophication (22%) in the environmental criteria. All the sub-criteria under the economic dimension obtained uniform weights from the interviewed stakeholders. Finally, for the sub-criteria belonging to the social dimension, stakeholders identified the need for EIPs (29%) as the most critical criterion to realize CE principles while managing EOL FGs and ropes. Following the selection of primary and sub-criteria, the MAVT model tree was developed (presented in Fig. 6).

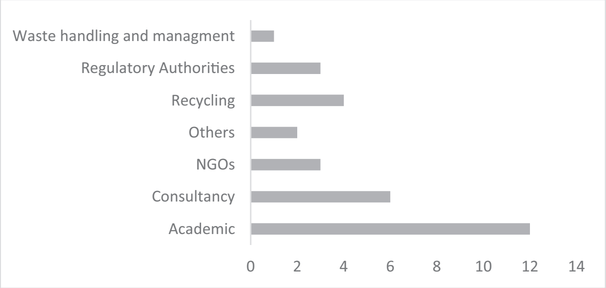

Fig. 5. Distribution of survey samples based on professional expertise.

Table 2
Weights of sustainability dimensions and assessment criteria derived from stakeholders' workshop.

Assessment criteria	n	Mean	Std Dev	Weight
1. Environmental	31	2.26	0.5	0.34
2. Economic	31	2.81	0.4	0.42
3. Social	31	1.55	0.6	0.23
E1. Depletion of fossil fuel	31	4.06	0.72	0.28
E2. GHG emissions	31	3.29	1.22	0.23
E3. Marine eutrophication	31	3.19	1.03	0.22
E4. Energy recovery	31	3.87	0.91	0.27
C1. Resource conservation	31	3.74	0.95	0.25
C2. Revenue generation	31	3.74	0.98	0.25
C3. Total cost	31	3.58	0.75	0.24
C4. Transport cost	31	3.77	0.91	0.26
S1. Job creation	31	3.35	0.74	0.23
S2. Eco-industrial partnerships	31	4.29	0.77	0.29
S3. Awareness and public participation	31	3.55	0.91	0.24
S4. Technology capacity	31	3.71	0.68	0.25

4.2. Performance assessment of alternatives

The data collected from relevant stakeholders were processed to estimate the performance of the quantitative criteria. Although the technology used to recycle plastics from EOL FGs and ropes was considered the same, the resources and revenue generated within the system boundary of Norway were considered. Therefore material emissions and monetary cost-benefits occurring outside the system boundaries were excluded from the assessment. Consequently, energy recovered, plastic resources conserved, and revenue generated from recycling (export) was considered zero.

Similarly, the cost of recycling (export) is neglected, and only transport costs were considered. The screening LCA results indicated that apart from GHG emissions, recycling (export) is outranked by the other three alternatives. GHG emissions from recycling (export) are moderate compared to the alternatives as emissions from recycling processes were excluded from the calculations to respect the system boundary. Energy is recovered (E4) from recycling (inland), as 40% of the rejected waste from the recycling process is sent to incineration for energy recovery. The analysis of all the quantitative criteria and calculations are detailed in SI.

The social criteria were assessed based on stakeholder interviews. Landfilling and incineration are established EOL alternatives in Norway and hence there are limited possibilities for new job creation. On the other hand, recycling (inland) is an upcoming EOL alternative that demands the establishment of mature supply chains, improvement in collections, segregation for recycling, and research and development efforts to advance recycling technology. Additionally, the current recycling capacity in Norway is limited and demands more industrial-scale recycling to tackle available waste fractions. Considering all the factors, experts argued that recycling (inland) has the greatest potential for creating new jobs. The transport of waste FGs and ropes out of Norway for recycling is included as jobs created by recycling (export). The jobs created outside of Norway while recycling waste FGs and ropes were omitted from the current assessment.

In the second criterion, alternatives were evaluated based on their potential to create EIP within Norway. Landfill and recycling (export) generate no resources or energy in treating 4000 tons of waste FGs and ropes in Norway. Therefore, the EIP potential for landfilling and recycling (export) is considered minimal. Through recycling (inland), conserved materials and energy can be utilized by other sectors as raw materials. Hence, recycling (inland) scores best in the criteria of EIP potential, followed by incineration, recycling (export), and landfill.

Similarly, the third social criterion involves assessing the ability of an alternative to raise awareness and public participation within the region. Local stakeholders argued that incineration and landfilling are

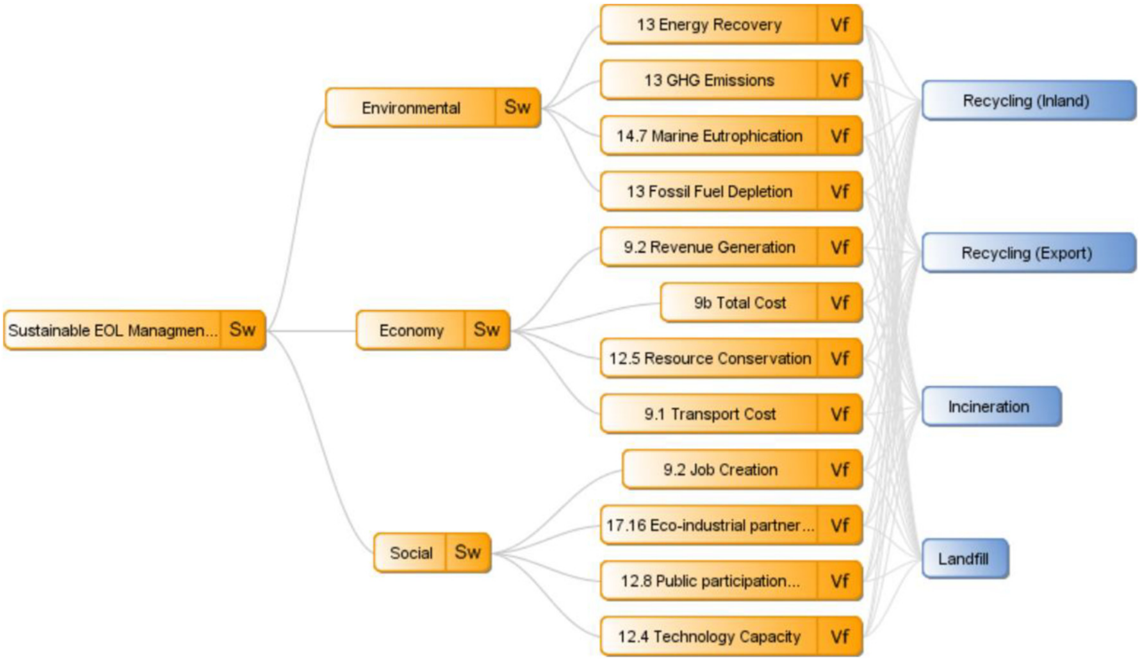

Fig. 6. MCDA model for proposed alternative evaluation in selecting sustainable EOL management alternatives for FGs and ropes.

established alternatives and handle even non-FG related waste. However, the advancement of recycling within Norway demands coordinated efforts in the collection, transport, and segregation of waste FGs and ropes. Therefore, both recycling alternatives are likely to drive a positive change in public participation and overall awareness-raising within the region, irrespective of the location of the recycling industry. Finally, the last social criterion aimed at examining the annual capacity of EOL alternative to handle 4000 tons of waste FGs and ropes. Apart from recycling (inland) (3000 t/yr), all the other EOL alternatives are capable of handling the estimated amount of waste FGs and ropes and, hence, are preferred over recycling (inland). Table 3 presents the performance of four alternatives against the quantitative and qualitative criteria.

4.3. Final ranking of alternatives

After recording weights and the performance of alternatives against assessment criteria, a linear value function was evaluated for each alternative. The output from DECERNS software using MAVT provided the final ranking of EOL alternatives, as presented in Fig. 7. For the given preference, the recycling (inland) alternative emerged as the preferred choice over the other three, while recycling (export) scored in last place for given criteria weights.

4.4. Sensitivity analysis

The weighting and ranking of alternatives using MAVT tends to be subjective. Therefore, sensitivity analysis is essential to check the robustness of the model outcome. From a technical perspective, sensitivity analysis provides an objective examination of the effect of changes in input parameters on the output of the model (Belton and Stewart, 2002). In this study, the input parameters are the value functions, scores, and weights determined by the stakeholders. The sensitivity analysis was performed by varying each of the three primary criteria (environmental, economic, and social) independently while leaving the other two to vary according to the original scores (results are presented in Fig. 8). Additionally, the sensitivity performance of sub-criteria was evaluated and an objective examination of the changes in the model outputs was recorded (presented in SI).

In the first chart (Fig. 8a), the sensitivity of the alternative outcomes is assessed by varying environmental criteria. It is evident from the chart that at the current weight of 0.34 for environmental criteria, recycling (inland) is the most favored alternative, and recycling (export) is ranked as the least favored alternative. The rankings of the alternatives changes when the weight of environmental criteria is reduced to 0.21, with recycling (export) outranking landfill as the third favored alternative. Additionally, the final changes in the ranking can be

Table 3
Performance of the alternatives against the selected assessment criteria.

Assessment criteria	Unit	Recycling (inland)	Recycling (export)	Incineration	Landfill
Depletion of fossil fuel	kg oil eq	−1105.2	247.5	−157.3	27.4
GHG emissions	ton CO2-eq./year	159.4	95.3	769.9	8.7
Marine eutrophication	kg P eq	1.2	15.3	10.3	1.9
Energy recovery	GWh	2.78	0	6.95	0
Resource conservation	Tons	2400	0	0	0
Revenue generation	mNOK	16.3	0	4.65	0
Total cost	mNOK	10	0	3.6	5.6
Transport cost	mNOK	757.5	1010	6060	505
Job creation	Ranking	1	0.25	0.25	0.25
Eco-industrial partnerships	Ranking	1	0	0.5	0
Awareness and public participation	Ranking	1	1	0	0
Technology capacity	Ranking	0.75	1	1	1

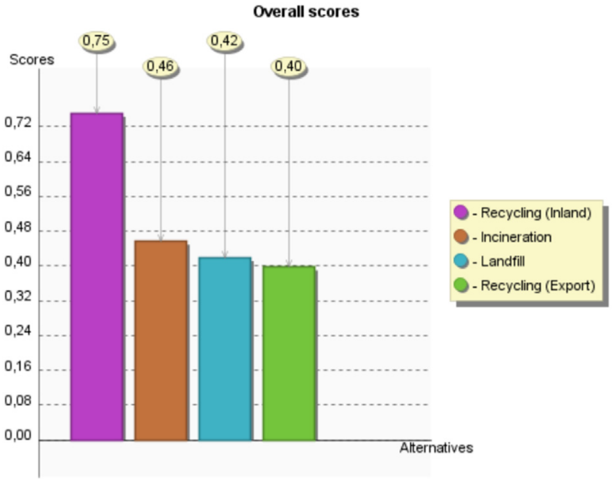

Fig. 7. Ranking of EOL management alternatives using MAVT and LCA screening.

observed when the weight of environment criteria is incremented to 0.58. At this point, landfill outranks incineration to become the second favored alternative.

In the second chart (Fig. 8b), the sensitivity of outcomes is observed against changes in economic criteria. The chart suggests that the rank of recycling (inland) and incineration are robust to the changes in the weights of economic criteria and remains as the top two favored alternatives throughout the change in the criteria weight. However, recycling (export) outweighs landfills to become the third favored alternative when the criteria weight is decreased to 0.2 from 0.42.

The last chart (Fig. 8c) shows the sensitivity of outcomes against changes in the social assessment criteria. The initial weight assigned to social criteria was 0.24 from the experts' judgment. Similar to economic criteria, recycling (inland) remains unaffected by the changes in weights of social criteria and scores as the top priority among the other alternatives. However, the second preferred alternative, incineration, is outranked by recycling (export) at a weight of 0.53. Recycling (export) emerged as a clear second preferred alternative after the social criteria are weighed 0.53 and above.

Finally, the overall sensitivity analysis revealed that recycling (inland) remains the most favorable choice for the management of EOL FGs and ropes in Norway, irrespective of the dominance of any of the three criteria. However, incineration may outrank the landfill to become the second preferred alternative in the economy or socio-centric criteria. The sensitivity analysis of 12 sub-criteria presented in SI reaffirms the robustness of presented rankings.

5. Discussion

5.1. The recycling paradox

The MCDA results show that recycling is the most sustainable alternative compared to landfill and incineration, essentially confirming the principles of CE. We considered two different alternatives to mimic the reality of recycling in Norway: the first one being recycling within Norway, and the other one being the recycling of waste outside of Norway. The results indicate that exporting a waste fraction for recycling is the least sustainable management alternative from a Norwegian perspective, with significant adverse environmental and economic impacts. Several causal factors cumulatively result in different rankings for the two recycling alternatives. The rankings are strongly affected by the selection of system boundaries. Therefore, benefits from recycling, such as resources conserved, energy recovered, and revenue generated is not counted under recycling (export).

The paradoxical nature of the recycling process demands the critical scrutiny of current recycling practices. Recycling is considered a crucial pathway to a CE in the EU's strategy for plastics. This preference for recycling is mainly due to its ability to achieve economic decoupling, and is even more relevant due to China's ban on importing plastic waste from other countries. The results in this study, however, show that focus must be placed on the location of recycling to ensure its positive effects on the environment and economy.

The results presented here also extend the discussion on whether exporting recyclable fractions is a part of problem shifting or a missed opportunity to create value from waste. Exporting the recyclable fraction questions the aims and scope of the CE strategy proposed by the EU and presents the need for developed countries to find alternative solutions to minimize waste and reshape circularity by promoting strategies like extended producer responsibility (EPR) as discussed by Liu et al. (2018). The relevance of CE is increasing as the result of recent geopolitical advances in sustainability and resource management. The results from this study provide solid arguments advocating the need to establish local recycling infrastructure instead of shifting the problem through the transboundary export of waste. This study shows, if recycled within the region, up to 2400 tons of recycled polymers (HDPE and LDPE) can be generated from waste plastic EOL FGs at the optimum capacity.

Furthermore, if thermodynamically suitable and economically feasible, the waste from recycling can be incinerated to recover energy. Several plastic manufacturers in Norway have demonstrated the use of recycled polymers in the injection molding process to create new products. Research and testing are also underway to check the suitability of the replacement of virgin polymers by recycled material in producing components for the aquaculture sector (Vildåsen, 2018). Advancements in regional recycling not only gain economic benefits, but it may aid in avoiding the negative impacts resulting from the production of virgin raw materials and energy. The conservative management approach of exporting plastic waste elsewhere may transfer the local pollution loads and also miss the opportunity to realize economic value from waste, contrary to the EU's strategy on CE.

5.2. Recycling of FGs (inland): challenges and opportunities

The results of the analysis clearly show recycling (inland) as the most sustainable alternative from a Norwegian perspective, above the other options. However, to date, there have been very few attempts to recycle plastics from EOL FGs and ropes at the industrial scale in Norway. Interaction with stakeholders revealed several techno-political factors hindering the growth of the recycling industry in the region, which are presented in Table 4. Realizing the goals of CE demands a holistic understanding of the system. A systemic view mainly aids in understanding the potential challenges in closing the material loop, thereby paving the way to new opportunities for establishing CBMs.

5.2.1. Raw material availability

Norway is the EU/EEA leader in both aquaculture and capture fishery (FAO, 2016b), making it a key player in generating waste from these sectors. An estimated 4000 tons of waste plastic is created in the region annually from commercial fishing practices alone. Apart from commercial fishing, leisure fishing and aquaculture also generate similar plastic composite material ready for recycling. Therefore, there are several opportunities for exploring circular business cases and EIPs within the region to create value from waste plastic.

5.2.2. Supply chain

Supply chains aiming at transporting waste fractions of EOL FGs to recycling industries in Norway are immature or non-existent. Several organized collectors operate within the region to segregate and transport the recyclable fractions of EOL FGs out of Norway. The lack of a reliable supply network is listed as one of the main reasons hindering the establishment of CBMs or EIPs between plastic recyclers and manufacturers in the region (Vildåsen, 2018). A harmonized network of actors

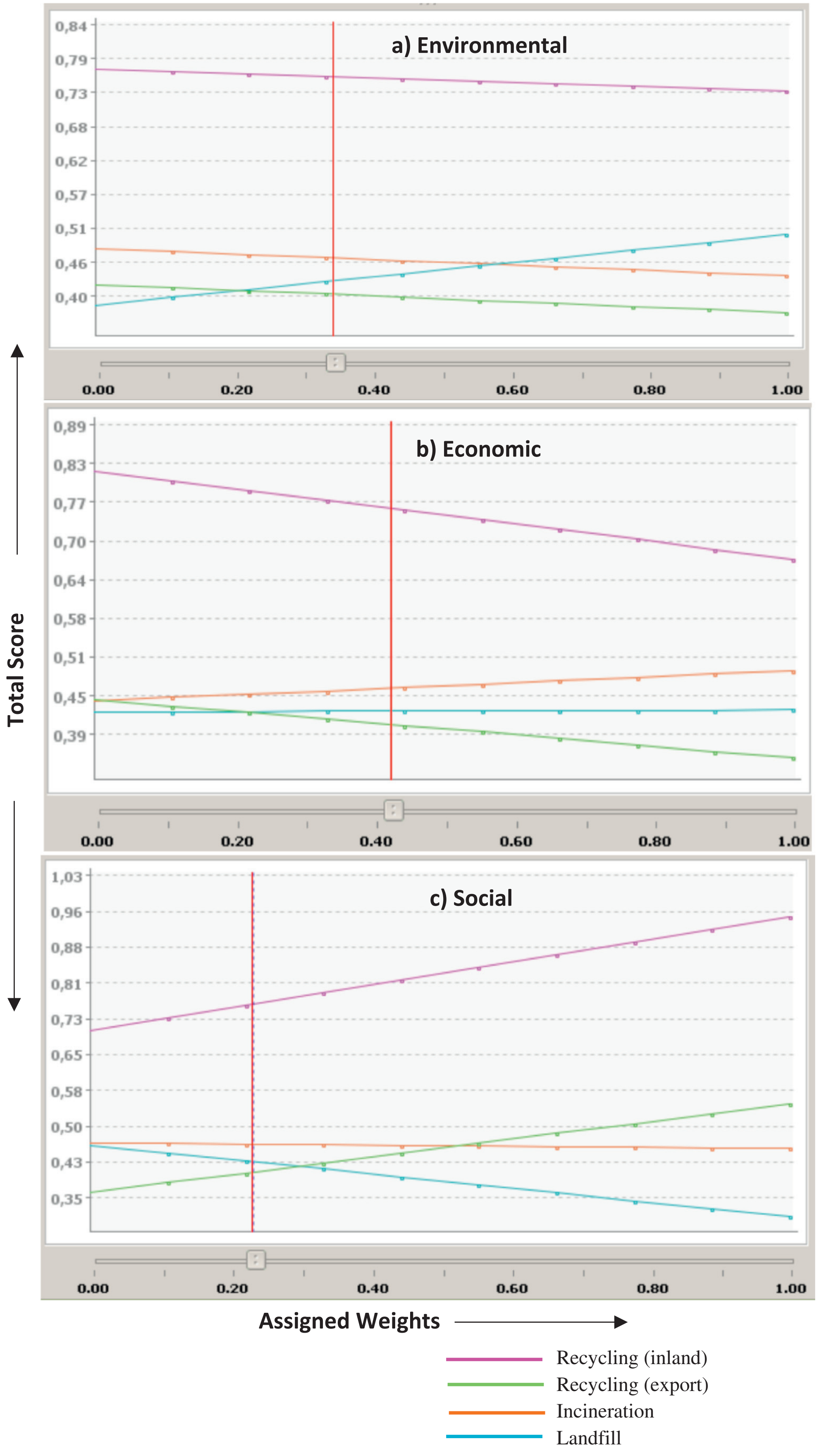

Fig. 8. Sensitivity analysis based on changes in a) Environmental, b) Economic and c) Social impact criteria.

Table 4
Key factors for realizing strategies for the circular economy.

Critical factors for circular business models	Current status
Raw material availability	Available
Supply chain	Minimal
Recycling technology	Available
Ease of recycling	Low
Policy drivers	Minimal
Awareness	Low
Market economy (value creation, proposition)	N/A

responsible for collection, segregation, and transport of waste FGs within the region is envisaged as a significant factor for promoting local recycling.

5.2.3. Recycling technology

The feasibility, availability, and sustainability of mechanical recycling of waste plastic polymers (PP, PE, and nylon) are well documented in the literature (Al-Salem et al., 2009; Gu et al., 2017). While technology is available, a limited number of recyclers are practicing the recycling of fishery-related waste in Norway. The interviews with recyclers in the region confirmed the deficit in the amounts of waste available for recycling and the actual capacity of the recycling industry in the region. At present, only 50–70% of the waste from fishing is handled by local recyclers, resulting in the export of recyclable fractions. The lack of local recycling capacity was reflected in the assessment of criteria S4, where recycling inland remains the only alternative that cannot handle 4000 tons/yr of waste plastics.

5.2.4. Ease of recycling

Typically, discarded FGs and ropes are laden with rotten biomass, fish oil, and dirt (Deshpande et al., 2020). Most of the WMCs in the region lack the technical expertise in cleaning and segregating waste FGs, making it difficult for recyclers to recycle economically. Furthermore, the netting of FGs is commonly made of three plastic polymers, namely, PP, PE, and nylon. Among the three polymers, nylon retains its properties after recycling, providing the maximum economic benefits, while the other two see a decline in quality after each recycling cycle. Due to the different recycling properties of these polymers, recyclers typically attempt to segregate them before recycling. Additionally, the metal wires in ropes require unique separation to avoid the wear and tear of mechanical recycling units. Different materials, lack of adequate cleaning methods and intricate gear design make waste FGs among the difficult waste fractions to recycle.

5.2.5. Policy drivers

The dedicated EU strategy on CE underpins the need for collaboration between industry and innovation to address the marine plastic pollution problem (Timothy Elliott et al., 2018). However, interaction with local recyclers and waste collectors pointed out the ambiguity in Norway's waste regulations that allows plastic waste to be landfilled. Chapter 9 of the waste regulation miljødepartementet (2004) states that "All waste must be treated before landfilling, and landfilling is allowed if the processing and treatment of waste fraction are socio-economically non-viable". Stakeholders identified two main factors that result in a preference for landfilling over recycling or incineration: transport and the processing cost of waste FGs and ropes. The processing cost of the plastics from discarded FGs and ropes is higher than the landfill and heat recovery fees. Additionally, due to the presence of metal parts and intricate gear design, waste FGs require additional routines for sorting and segregation to maintain the quality of recycled products.

5.2.6. Awareness

The stakeholder interaction confirmed growing awareness among the regional and coastal communities regarding the detrimental effects of ALDFG. Falk-Andersson et al. (2019), and Jacob (2016) showed the extent of community involvement in beach clean-up operations in Norway. There is, however, a need for raising awareness on the post-collection treatment of marine waste and ALDFG in particular. Such efforts may provide a strong stimulus to new recyclers to solve the problem of lack of local recycling capacity in the region. Social awareness and the creation of economic value for obsolete FGs are listed among the key strategies useful in curbing the problem of abandonment of waste FGs in the region (Deshpande et al., 2020).

5.2.7. Market economy

Mechanical recycling results in the production of HDPE and LDPE polymers. The successful use of these polymers in injection molding technology has been demonstrated by various plastic industries in the Nordic region. In Norway, pilot testing is underway to ensure the quality and properties of recycled material when replacing virgin polymers in the production of fish farming brackets and walkways (Vildåsen, 2018). Success in the pilot tests could result in the development of a CBM in which product-to-product recycling is realized. The underlying driver for regional plastic industries to replace virgin polymers is to reduce their dependence on material suppliers and thereby increase the flexibility of their supply chain. Furthermore, Vildåsen (2018) lists cost-cutting and reduced environmental impacts as other factors motivating regional plastic industries to aim for circular strategies.

However, substantial efforts are needed to transform the plastic industry from conservative practices to a more circular approach. Such transformation demands the establishment of robust supply chains among the waste collectors, recyclers, plastic manufacturers, and consumers at both regional and international levels. Instituting such an eco-industrial network between fishing and plastic industries demands the assurance of quality and quantity of recycled polymers, agreement among the consumers to raise the demand for the use of environmentally friendly products, and the support of the regional policies. Stabilizing all the factors may help in improving the market acceptance of products with recycled polymers and may result in elevated demand for such products.

6. Conclusion

This study presented the application of MCDA in selecting from sustainable EOL management alternatives for plastics from the fishing sector in Norway. The focus was also placed on scrutinizing the sustainability of recycling as a solution for plastic waste management. The MCDA approach was particularly suitable to answer the proposed research questions as it replaces the limitations of unstructured individual interviews and provides a platform to involve focused group discussions that lead to transparency in assessing weights and scores. The MAVT method is characterized by some limitations as it uses experts' judgment in ranking the alternatives against the assessment criteria. Also, MAVT is widely used in qualitative performance assessment of alternatives, causing apparent subjectivity. Finally, one limitation of this study is that it has not been possible to evaluate the sensitivity of the results related to the MAVT selection method without risking a significantly lower response rate, as the data collection was based on interviews and questionnaires.

In this study, we used both qualitative and quantitative assessment criteria to evaluate the alternative EOL management methods. Furthermore, stakeholder involvement was kept limited to the selection and weighting of assessment criteria. The environmental and economic performance of selected alternatives was assessed using raw data obtained from the regional recyclers and waste manager—this adaption to the MAVT method aided in limiting the subjectivity of the assessment. SDGs were used to define the assessment criteria. Linking the assessment criteria to SDGs aided in producing a focused, measurable, and all-encompassing coverage of the triple-bottom-line aspects of sustainability. Additionally, the SDGs ensured better communication and understanding of the criteria, as stakeholders were familiar with the goals.

Engagement with regional stakeholders is a crucial requirement of the MAVT method. The comprehensive and iterative discussions on the EOL management of FGs resulted in an improved understanding of social-political factors contributing to the system. The main contribution of this study challenges the traditional recycling practices adopted by developed countries, which involve the transboundary export of waste for recycling purposes. The results strongly suggest the importance of the location of recycling waste. Recycling operations within the region potentially show the maximum positive effects on the environment and society, with additional economic benefits from resource conservation and energy recovery. Therefore, to realize the CE strategy, developed countries must explore systems promoting reduce, reuse, and in-house recycling of plastic waste, which is also in-line with the polluter pays principle.

Although the proposed approach provided robust results, backed with sensitivity analysis, they are far from definitive. The MAVT results are characterized by a degree of uncertainty resulting from the lack of coverage of the entire spectrum of relevant stakeholders, underlying assumptions, and uncertainty in quantitative data (e.g. related to the future trends of waste fraction volumes). The assessment was also based on limited assessment criteria. Advanced environmental and economic assessment of individual alternatives is essential to limit the uncertainty emerging from the MAVT results. However, these results can surely act as a sound-board to discuss the EOL management alternative for plastic and act as a step towards the sustainable implementation of the EU's CE strategy for plastics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137353.

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