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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for the partial fulfillment of the requirements for the degree of Philosophiae Doctor. The thesis consists of a summary of the research, four manuscripts of original research articles emerging out of research work, and associated appendix to aid overall understanding of the topic.

This doctoral work has been performed at the Department of Industrial Economics and Technology Management (IØT), NTNU, Trondheim, with Professor Annik Magerholm Fet as the principal supervisor. Additionally, Professor Helge Brattebø and Associated Professor Christofer Skaar are also involved in this research as co-supervisors.

The Ph.D. has been performed as a part of NTNU's strategic research area on Sustainability with an overall theme of "Environmental and sustainability analyses and sustainable business models." NTNU sustainability provided 3-year funding, while IØT funded the fourth year through duty-work at the department. This extra year funding helped me in making my research findings more profound. Finally, the research conducted for this Ph.D. is primarily inspired by the EU-NPA project "Circular Ocean" (2015-2018). The overall goal and research questions are grounded in the objectives of the Circular Ocean.

Acknowledgments

In retrospect, my personal and professional journey as a Ph.D. candidate, so far, has been immensely gratifying. During the work of this thesis, I have been fortunate to meet several knowledgeable and inspiring researchers and expert stakeholders on this research topic.

First and foremost, I would like to thank my supervisor, Professor Annik Magerholm Fet, for her constant support, encouragement, trust, and belief in my work and choices that I made throughout my Ph.D. tenure. I cannot imagine crossing the final step without your support and motivation throughout this journey. Your enthusiasm, ability to multitask, and manage the entire research group continue to amaze me, and I hope to inculcate these skills in my personality apart from all the other lessons I learned from you along the way.

I would also like to thank my co-supervisor, Professor Helge Brattebø, for always being there for my doubts. I will forever cherish the brainstorming sessions we had during our meetings. Your clarity and depth on the relevant subject matter have always been inspiring to me, and I hope to follow that approach in my professional life.

Another special mention goes to my second co-supervisor, Professor Christofer Skaar. I must admit spending my duty-work in assisting you for TIØ4195 was one of the most rewarding phases of a Ph.D. I could not have asked a better person to guide me along with these Ph.D. ways where needed. Your ability to change the hats as per one's needs is phenomenal, and I would always appreciate the various roles that you have played throughout my Ph.D. journey, be it as a mentor, supporter, friend, and sometimes just as a listener. Thank you for everything.

Research outcomes are one of the critical measures of success for any Ph.D. I consider myself extremely fortunate to get an opportunity to interact with and inspired by various mentors, teachers, and co-authors. Some of the distinct personalities that added significant value to my work through brainstorming, critically evaluating, and through teachings are worth a mention here. Therefore, special thanks go to Dina Aspen, Gaspard Philis, Cecilia Haskins, Haley Knudson, and Magnus Sparrevik for contributing to my research outcomes directly or indirectly. Each one of you is unique and skilled in your respective fields, and I consider myself blessed to have spent time with you throughout my Ph.D. tenure.

The Ph.D. pursuit brought me to NTNU Norway, where I spent the last four years working and interacting with various colleagues at the Department of Industrial Economics and Technology Management (IØT). Having no prior social circle in Norway, my work colleagues became my first friends here. Therefore, a special mention goes to all with whom I got an opportunity to share professional and personal facets. Distinctive appreciations go to Haley, Sigurd, Michael, Faheem, Jon, Therese, Kinga, Marie, Synne, John Eilif, Rikke, Kristin, Eirik, Trond, and Erling. Thanks to each one of you for all the good times that I have had throughout my tenure at IØT.

Regional and local stakeholders are the backbone of this thesis work. Without their engagement and information sharing, this thesis would not have been possible. Therefore, sincere regards go to all the expert stakeholders', 114 fishers, waste collectors, producers, managers, regulatory agencies (Fiskeridirektoratet and Miljødirektoratet), Hold Norge Rent, SALT, Container Service AS and many others for sharing insightful information and active participation during the data collection phase. I sincerely tried to make the best use of your knowledge in contributing to the sustainable management of fishing gears resources in the region.

My family back home played a crucial role in making me eligible for doctoral studies. Therefore, although no words can express my gratitude towards my family, a distinct mention goes to my parents, and my sister for always motivating me, believing in me and being supportive throughout the problematic phase. I am also eternally thankful to my wife, Nayan, for bringing positivity, creativity in my life. I am astonished by your achievements, and your presence made me work extra hard to achieve my goals. Thanks for being my most sincere critique. A special mention also goes to Indian families and friends in Trondheim for providing a social platform during my stay.

In the end, I would want to extend my gratitude towards my mentor Professor Shyam Asolekar of Indian Institute of Technology Bombay (IITB), and my Master's thesis supervisor Professor Berit Balfors of KTH Royal Institute of Technology, for nurturing my research skills and inculcating critical thinking and ethical aspects of research in me as an early researcher.

Summary

Sustainable management of resources often presents complex problems that demand integration of systemic, collaborative, and transdisciplinary approaches to mitigate effects and find innovative solutions. The objective of this thesis is to contribute to the science of resource management through the application of systems engineering. The case of marine plastic waste from commercial fishing gears (FGs) is used to demonstrate the application of the presented systemic framework.

Marine plastic is a complex transboundary problem that adversely affects coastal and marine ecosystems. Among the total marine plastic waste, a particularly troublesome waste fraction is *Abandoned, Lost or Discarded Fishing Gears (ALDFG)* that continues to trap marine life for years upon release, and has significant adverse environmental effects on marine wildlife. However, lack of scientific data of the extent of marine plastics from ALDFG, end-of-life management of derelict FGs, and associated reasoning hinders the management of FG resources across the globe. The threat of ALDFG is particularly relevant to countries characterized by long and productive coastlines. Geographic location and strong dependence on commercial fisheries make Norway among the most vulnerable countries affected by the detrimental effects of ALDFG.

Aiming to fill the knowledge gap, this thesis applies a systems engineering problem-structuring framework to identify stakeholders and values, map their needs, and find alternatives to support decision-making and evaluation. Contrary to traditional resource management studies, this thesis prioritizes the involvement and engagement of resource users to achieve the desired goal of sustainable life cycle management of FG resources. The life cycles of six FGs commonly deployed by the Norwegian commercial fishing fleet are studied, namely trawls, seines (Danish and Purse), longlines, gillnets, and traps. Structured and semi-structured interviews and a questionnaire were primarily used to collect data from key stakeholders involved in the system. Based on data from gear producers, suppliers, fishers, collectors, authorities, and waste management facilities, annual flows of plastic polymers (PP, PE, and Nylon) from fishing gears are modelled.

The thesis furthermore explores the application of multi-criteria decision analysis (MCDA) to assess end-of-life management alternatives based on the values of sustainability. The UN Sustainable Development Goals and the EU's circular economy strategies for plastics are used to outline values for sustainability, while expert stakeholders from the region are used to prioritize assessment criteria. Finally, insights from stakeholder engagement are used to ascertain potential barriers in realizing principles of circular economy and recognizing opportunities for establishing circular business models in the region. Although the suggested outcomes are limited to the case of the commercial fishing sector of Norway, knowledge can be adapted and exchanged with similar ecosystems in other contexts.

The main contributions of this thesis are:

- Adaption and application of systems engineering methodology for problem structuring
- Development of research methods to extract information and ensure active engagement of resource users
- Modelling annual plastic flows through the system life cycle of commercial FGs used in Norway
- Adaption of MCDA to assess sustainability in the end-of-life management of fishing gears
- Identification of opportunities and barriers in realizing circular economy strategies for FG resources in Norway

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Abbreviations

ALDFG	Abandoned Lost or Discarded Fishing Gears
CBM	Circular Business Models
EC	European Commission
EIP	Eco-Industrial Partnerships
EOL	End-of-life
EPR	Extended Producer Responsibility
EU	European Union
FAO	Food and Agricultural Organization
FFL	Fishing for Litter
FG	Fishing Gear(s)
HDPE	High-density Polyethylene
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LCM	Life Cycle Management
LDPE	Low-density Polyethylene
LEK	Local Ecological Knowledge
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis
MFA	Material Flow Analysis
MoP	Mass of Plastics (PP, PE, and Nylon)
PE	Polyethylene
PP	Polypropylene
PRF	Port Reception Facility
SBM	Sustainable Business Model
SDGs	Sustainable Development Goals
SE	Systems Engineering
SES	Socio-Ecological System
UNCLOS	United Nations Convention on the Law of the Sea

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1 Introduction

"In the absence of a well-designed and tailor-made management strategy for end-of-life plastics, humans are conducting a singular uncontrolled experiment on a global scale, in which billions of metric tons of material will accumulate across all major terrestrial and aquatic ecosystems on the planet." [1]

1.1 Sustainable Resource Management: Global Context

Policies and programmes for sustainable development (SD) have undergone significant shifts in focus since the concept's introduction at the first global conference on the environment in Stockholm in 1972 [2]. With the prospect of a rising global population, accelerating development, increase in resource use, and the associated environmental impacts, the definition of sustainability has broadened from mere concern with pollution and biodiversity to the promotion of resource management [3].

The science of resource management involves generating a systematic understanding of the processes that lead to improvements in or the deterioration of natural or anthropogenic resources. The management of resources is relatively more straightforward, especially when the resources and use of the resources by users can be monitored, and the information can be verified and understood in a non-complex way [4]. In the terminology of resource management, *information* refers to the real knowledge about stocks, flows and processes within the resource system, as well as about the human-environment interactions affecting the system [5]. Highly aggregated information may ignore or average out local data, which is essential for identifying future problems and developing sustainable solutions [4].

Historically, local and regional governments have been deemed responsible for managing resources through political instruments, and resource users have been assumed incapable of reversing the tragedy of commons [6]. Dietz, Ostrom [4], and Johannes [7], however, provided strong arguments advocating the necessity of studying not only the resource itself but also the local methods, traditions and knowledge associated with its use. As all humanly used resources are embedded in complex, social-ecological systems (SES) [8], one needs to incorporate both ecological and socio-technical knowledge in describing the resource system. Accordingly, Ostrom [8] proposed a multilevel, transdisciplinary framework for analysing the sustainability of resource systems. The framework was designed to capture the complex interactions among the system and subsystems.

A system is 'a combination of interacting elements organized to achieve one or more stated purposes' [9]. In this thesis, a system of fishing gear (FG) resources is studied for developing sustainable strategies in the life cycle management of FGs. The interacting elements or *subsystems* are defined by adapting the SES framework proposed by Ostrom [8], which is modified to represent the SES of FG resources in Norway. **Figure 1** provides an overview of the framework, showing the relationships between the four core subsystems of an SES that affect each other, as well as linked social, economic and political settings and related ecosystems. The central system and associated subsystems for management of the selected anthropogenic resource are:

Main SES: Fishing Gear Resources.

A. **Resource system**: The Norwegian commercial fishing sector.
B. **Resource units**: Plastics from commercial fishing gears and ropes.
C. **Governance systems**: The regulatory framework and governing institutions.
D. **Resource users**: Fishers and other stakeholders.

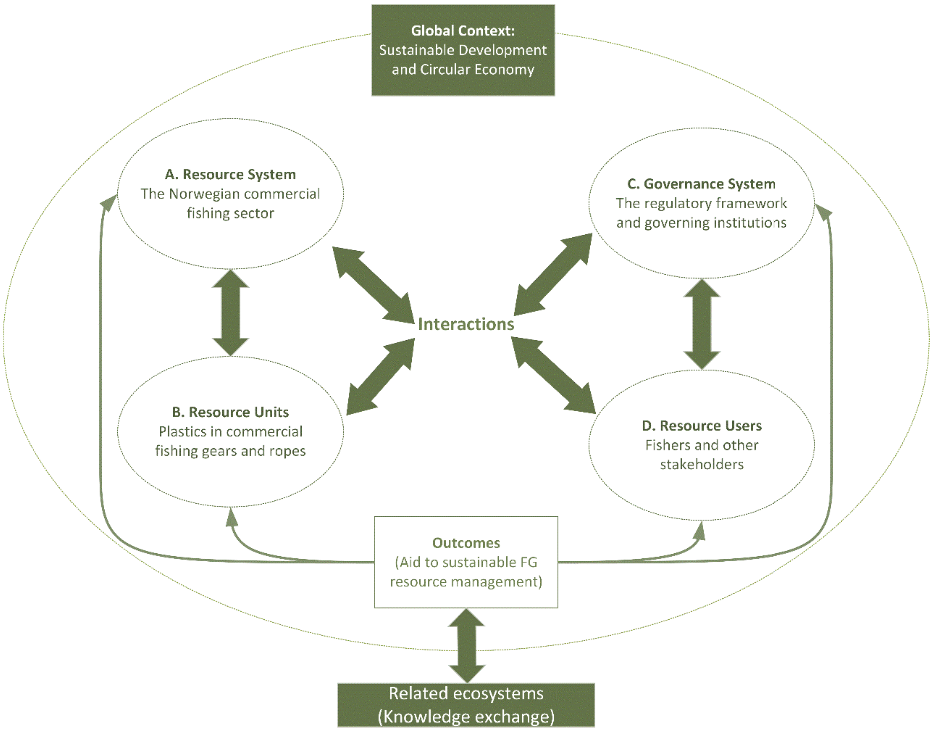

Figure 1: The core subsystems in a framework for analysing the social-economic system of FG resources [modified and adapted from 8].

The framework highlights the need for interaction and engagement between the four subsystems to gather holistic social and ecological scientific information about the system. SD and the circular economy provide a global context to define and outline the improvement of FG resource management in the region. This thesis suggests outcomes in the form of strategies and mechanisms for achieving the overall goal of sustainable life cycle management of FG resources in Norway. Although the suggested outcomes are limited to the case of the commercial fishing sector of Norway, the knowledge can be adapted to similar ecosystems elsewhere.

1.2 Background

Plastic pollution has now become a global concern as plastic debris is found in all the oceans of the world, adversely affecting marine biodiversity, human livelihoods, and the economy [10]. 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 is used for essential applications in many industrial sectors, its growing use in short-lived applications lacks reuse or cost-effective recyclability. Consequently, related production and consumption patterns have become increasingly inefficient and linear [11].

Contrary to the linear economic model, the notion of a circular economy (CE) has recently gained traction in policy, business, and academia to advocate the transition from a linear 'take-make-dispose' model towards a circular model. Under circular thinking, waste is a resource that is valorised through recycling and reuse [12]. The appeal of the CE is that it promises to reconcile environmental and economic goals by reducing resource use and stimulating economic growth at the same time [13].

In the EU, the principles of CE were seen as essential measures for ensuring the sustainable management of plastic waste. On the 16th of January 2018, the European Commission (EC) adopted the 'European strategy for plastics in a circular economy', which recognises plastics as a significant source of marine litter [14]. In the elaborated action plan, additional action on plastics from 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 [15].

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' [16]. The design and material of FGs vary based on the type and purpose of the gear. Plastic polymers (PP, PE, and nylon) remain the primary building blocks of any FGs, constituting approximately 60–90% of FG material [17]. Therefore, plastic polymers from FGs are considered 'resources' in developing management strategies throughout this thesis. ALDFG is considered a particularly troublesome part of the total plastic waste entering the oceans, as it may continue to trap marine animals for decades upon release [18, 19]. The amount, distribution and effects of ALDFG have risen substantially over past decades with the rapid expansion of fishing operations and fishing grounds, and the transition to synthetic, more durable and more buoyant materials used for FG [20, 21]. In addition to the threat to marine ecology, the loss of fish stocks due to ghost fishing and the expanded cost of valuable resources on lost or abandoned FGs also cause significant economic setbacks [22].

Although ALDFG is proven to be the most dangerous fraction of marine litter [23], little or no information is available on the regional flows, sources and fate of plastics from the fishing sector.

Jambeck et al. [24] identified this knowledge deficiency about plastic flows from fishing activities in the quantification of total plastic in marine debris. This lack of scientific evidence has resulted in a strong dependence on precautionary principles or conservative methods to manage FG resources in coastal countries. The risk of ALDFG accumulation is ever pertinent to countries characterised by a long and productive coastline. Norway's geographic location and strong dependence on fishing activity make it among the most vulnerable countries in the EU-EEA region to the detrimental effects of ALDFG pollution. Consequently, there is a pressing need to build a holistic and systemic understanding of the fate, transport, sources, sinks, and end-of-life (EOL) management alternatives for the regional plastic flow from the fishing sector. Additionally, the lack of scientific data on FG resources necessitates the need to incorporate alternative information sources into assessment models.

Therefore, this thesis aims to fill the knowledge gap through the application of the systems engineering (SE) framework. This framework facilitates problem-driven, interdisciplinary research to comprehend the dimensions of sustainability in managing a system of FG resources in Norway. The extensive research goal and specific research questions are elaborated further.

1.3 Research Goals and Questions

Grounded in SE, the overall goal of this thesis is to:

Explore strategies for sustainable life cycle management in the system of commercial fishing gears in Norway, demonstrated by the application of systems engineering.

All of the elements of the research goal are complex scientific concepts: SE framework, sustainable resource management and plastic pollution. This complexity demands further segmentation of the research goal into concrete and case study-specific themes. Therefore, the progression of the research is defined through the following research questions.

1. How can a system of FG resources be modelled?
2. What information is essential to aid system performance analysis and improvement?
3. What research methods can be useful in assessing sustainability in the EOL management of FG resources using an SE framework?
4. What is the best way to assess sustainability in implementing CE strategies in managing FG resources?
5. What are the barriers and opportunities in creating business-scale closed-loop solutions for plastics from the fishing sector?

1.4 Thesis Contribution

The research work has resulted in four publications published in or submitted to peer-review journals. The six-step SE model [modified after 25] constitutes the backbone of the proposed framework. **Figure 2** illustrates the research outcome in relation to the six steps of the SE framework, along with the methods applied to address the selected research questions.

The *first paper* provides a conceptual SE framework to ensure the sustainable management of FG resources in Norway. The approach presents a multidisciplinary process initiated by system and stakeholder analysis before developing relevant sustainability goals, targets and indicators.

The *second paper* presents a questionnaire-based survey designed to extract fishers' local ecological knowledge (LEK) on commercial FGs. The collected information from the regional fishers is then translated into quantitative data following standard statistical procedures. The method proved useful in quantifying total lifespan, repair-reuse patterns, annual loss and disposal rates of selected FGs.

The *third paper* presents an elaborate material flow analysis (MFA) generating crucial evidence on regional-level plastic pollution from the fishing sector and highlights possible mechanisms that may aid in proposed improvements. These findings provide a critical science and technology input for the environmental and fishery authorities of Norway, aiding the formulation of policies to monitor and minimise plastic pollution from the commercial fishing sector.

Finally, the *fourth paper* presents a multi-criteria decision analysis (MCDA) framework adapted to assess the environmental, economic and social impacts of landfilling, incinerating and recycling FG waste in Norway. The findings help to ascertain potential barriers in realising the principles of CE and to further recognise opportunities for establishing circular business models in the region.

Apart from the mainstream research publications, selected parts of the research findings have contributed to the dissemination reports of the Circular Ocean project funded under the EU-NPA Interreg. Program.

1.5 Thesis Structure

This thesis is structured as follows:

Chapter 1 establishes the background of the problem and further introduces the main objective, research questions, and briefly describes the thesis structure and contribution.

Chapter 2 sets the theoretical foundations of the leading research themes used in this thesis, namely: SE, industrial ecology, local ecological knowledge, and decision theory.

Chapter 3 provides a brief overview of the research methods employed.

Chapter 4 explains the case of the commercial fishing sector of Norway and FGs deployed by the fishers in Norway.

Chapter 5 presents the analysis results of the case study.

Building on these results, **Chapter 6** identifies the strategies and mechanisms for aiding the sustainable management of LCM of FG resources.

Chapter 7 contains a summary discussion of the research questions, outcomes, and identifies potential areas for future research.

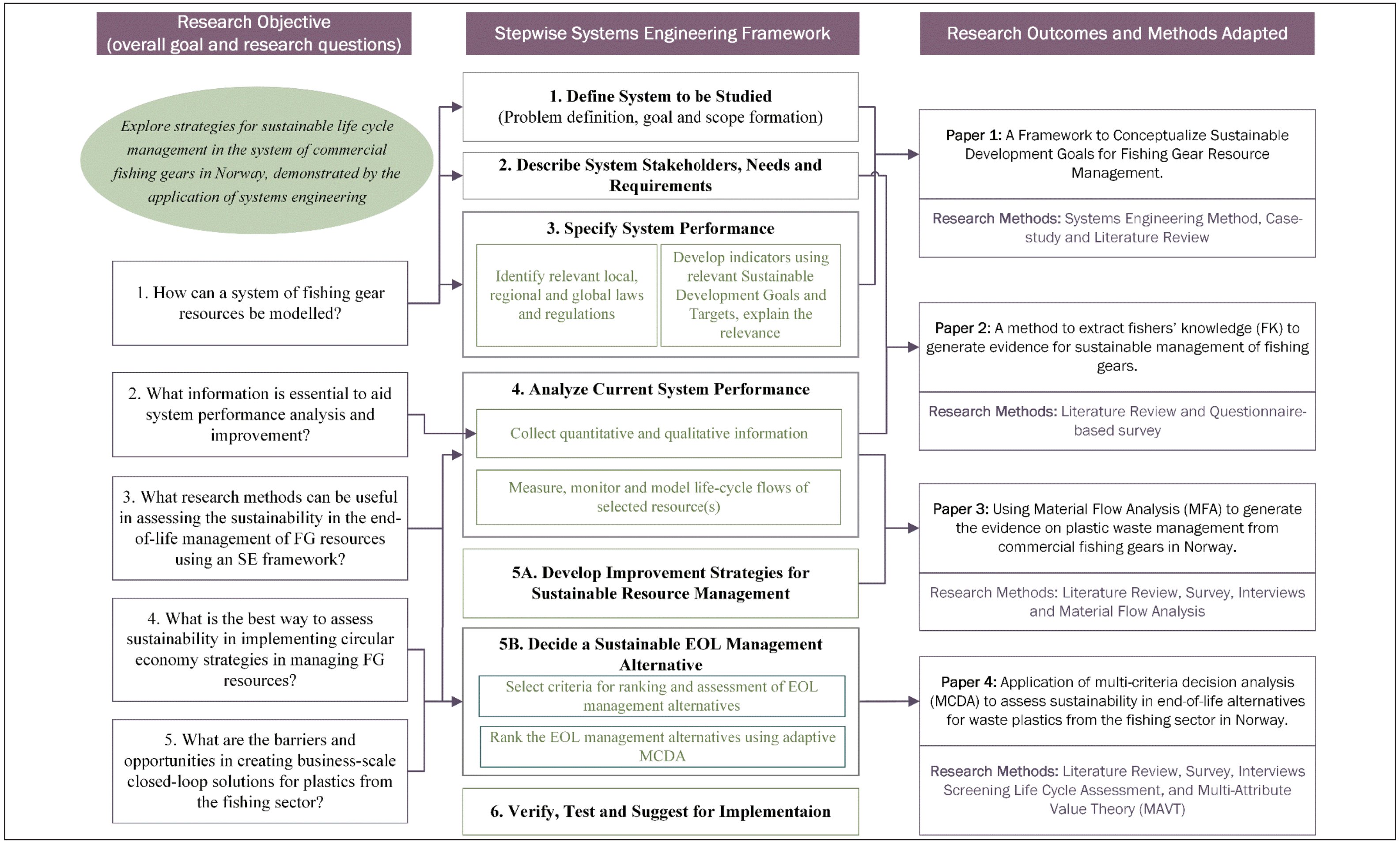

Figure 2: Research structure and outcome

2 Theoretical Foundation

"Scientific theory is a contrived foothold in the chaos of living phenomenon." ***Wilhelm Reich***

This research builds on and contributes to the overarching theoretical concepts of SE, industrial ecology, local ecological knowledge and decision theory. These theories are elaborated here, along with their relevance to the present research.

2.1 Systems Engineering

SE theory is useful to help design and maintain the scope and boundaries of this research. The SE process involves series of steps, undertaken in a logical manner, directed at providing a holistic view which takes into consideration the total system life cycle and other interrelated life cycles (e.g., material and cash flow) [25]. This holistic assessment is a vital feature of systems engineering methods (SEM) for structuring and scoping complex research problems. Blanchard and Fabrycky [26] identified four key characteristics of SE that allow for a holistic understanding of a given problem:

1. A top-down approach where the system as a whole can be viewed.
2. A life cycle orientation where all phases of the system are addressed.
3. A thorough identification of system requirements.
4. An interdisciplinary collaborative approach to ensure that objectives are met in an effective manner.

The principles of SE were used to develop methods aimed at solving complex problems related to resource management and sustainability. SEM follows a stepwise approach in which system description, problem definition, stakeholder mapping, needs and requirements, system elements and performance analyses, design, test, evaluation and iterations act as a structuring guideline [25]. Systems theory is a key element in industrial ecology (IE) related analytical tools [27] and has been applied effectively together with life cycle assessment [28], eco-industrial network [29], life cycle management and corporate social responsibility [30]. Hence, in this thesis, systems theory was chosen to ensure a holistic understanding and assessment of the system under consideration. IE-based tools and methods were chosen to complement the systemic assessment of the selected case.

2.2 Industrial Ecology (IE) and Sustainability

In addressing the question of how societies can transition toward sustainability, the concept of IE has proven effective. Indeed, Allenby [31] called IE the 'science of sustainability.' Industrial ecology is industrial in the sense that it focuses on product design and manufacturing processes. It views firms as agents for environmental improvements through the successful execution of products and processes with environmentally-informed design [27].

Lifset and Graedel [27] presented two ecological connections that inspired IE. First, biological ecosystems are especially productive at recycling resources and thus are held as exemplars for the efficient cycling of materials and energy in industry. Additionally, IE places industrial activity in the context of a broader ecosystem that supports it, examining the sources of resources used in society and the sinks that may act to absorb or detoxify waste. The latter sense of 'ecology' suggests that economic systems must be viewed not in isolation from their surrounding systems but in coherence with them, which forms the conceptual basis of IE. Combining all these elements, Ayres and Ayres [32] defined IE as:

> "Industrial ecology is how humanity can deliberately approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding system, but a concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material to finished material, to component, to product, to obsolete product to ultimate disposal."

In practice, developments in IE can be broadly classified into two dimensions given by Ehrenfeld [33]: paradigmatic or normative, and descriptive or analytic. In this thesis, the main focus is on the analytical dimension of IE. **Section 3.2.4** discusses some of the standard tools used in IE and their relevance to solving the selected research questions.

2.2.1 The Circular Economy and Circular Business Models

The development of IE has also resulted in the emergence of new concepts such as green engineering, design for sustainability, eco-design, eco-industrial network and the CE. CE mainly gained traction in policy, business and academia, and advocates the transformation of industrial systems from a traditional linear 'take-make-dispose' model toward a circular model in which waste is a resource that is valorised through recycling and reuse [34]. For the business sector, three elements of CE provide a relevant means to operationalise SD in practice:

- increase the efficiency of resource utilisation, thereby improving competitiveness and profitability [14];
- provide an alternative to the current economic development model [35];
- promote an environmentally friendly use of resources [12].

Although there have been several attempts to define the scope of CE, critics claim that it means many different things to different people [36]. In this study, plastics from FGs are considered resource units; hence, the understanding of CE and circular business models (CBM) is grounded to the EU's strategy for plastics in the CE [14]. By adopting its plastics strategy, the Commission set three key objectives:

- to improve the economics and quality of plastic recycling, ensuring a stable market for recycled plastics with clear growth prospects;
- to ensure new economic opportunities combined with social innovation;
- to curb plastic waste and littering.

In this study, IE and CE concepts are used to build regional resource management strategies. IE methods are used to map the product life cycle and to assess the sustainability of EOL management alternatives for plastics from FGs in Norway, while principles of CE are used to explore strategies to realise closed-loop business opportunities for plastics from FGs in Norway.

2.3 Local Ecological Knowledge (LEK)

Resource users develop a comprehensive knowledge of their resources and their environments, which is rarely collected systematically. Scientific attempts to collect such knowledge in highly structured formats can elicit large amounts of information on the ecosystem and its constituent elements [37]. This type of knowledge is often referred to as LEK, where a group of individuals holds a cumulative body of often site-specific knowledge about an ecological system [38]. LEK includes the knowledge local people have of nature; their perceptions, classifications and understanding of ecological dynamics and functions (ethnoecology); as well as their beliefs [39]. It is often based on long-term observations of the local ecosystem considering local variations and behavioural patterns, focusing on the essential resources/species of the concerned ecosystem [40]. Practical applications of LEK range across a variety of systems, including but not limited to small-scale agriculture, horticulture, forestry and fisheries [41]. Johannes [42] and colleagues played a crucial role in establishing and documenting the use of LEK in the fishery management sector in their work between 1980 and 2000. In his first study on applying fishers' knowledge, Johannes [7] emphasised the variety and depth of information local fishers possess on marine ecology and conservation, fish behaviour/habitats, fishing practices, FG types and other ecosystem concepts. Further, Johannes, Freeman and Hamilton [43] argued that by ignoring such readily available and inexpensive sources of knowledge while studying local systems, humanity runs the danger of 'missing the boat' on fisheries sustainability. The information captured through LEK has proven critical for resource management studies, especially in systems with limited or no data.

Although fishers possess a valuable stock of information, integrating and translating that information into the science of resource management demands creativity in applying suitable scientific methods [41, 44]. So far, the application of LEK has been used to manage biodiversity and marine protected areas [7, 45], to study fish species, habitats and catch patterns [46, 47], to manage fishery resources [40, 41, 48] and to understand the impacts of fishing methods and equipment [49, 50].

This study contributes to the science of capturing information from fishers' LEK. A systematic survey was designed using the Delphi method to extract fishers' knowledge on handling and management of six different FGs commonly deployed by commercial fishers in Norway, namely: trawls, purse seines, Danish seines, gillnets, longlines and traps/pots. Further, the fishers' LEK was then analysed to quantify the average rates of listed FGs to understand their repair and disposal patterns and to quantify the number of FGs contributing to the ALDFG problem from Norwegian capture fishery.

2.4 Decision Theory

The science of decision making has a long history, and many methods are available for understanding it. Decision making deals with the systematic modelling of a decision maker's preferences in choosing among options which can involve several often conflicting objectives. Decision making becomes difficult when the nature of the problem at hand is complex, reflects conflicting viewpoints and changes with time. These difficulties arise due to the cognitive limitations of the human brain for computing multi-variable problems, and thus frameworks, methods and techniques to compute and aggregate decision-alternative performance are necessary [51]. Real-life decision-making problems involve the selection of alternatives based on more than one criterion and are often referred to as multiple-criteria decision-making (MCDM) problems [52], while analytical methods proposed for such decision making are called MCDA.

> "MCDA provides a mathematical methodology that incorporates the values of decision-makers and stakeholders as well as technical information to select the best solution for the problems under consideration; it allows for a more logical and scientifically defendable decision making [53]."

Although the MCDA approach seeks to find the best solution for a complex problem among several alternatives, subjectivity remains inherent in all decision-making attempts. Therefore, the aim of MCDA is not to provide the 'right' answer but to help decision-makers through a better understanding of the problem and stakeholders' perspectives, so that they can make a better-informed choice. More than 50 MCDA frameworks and methods are documented in the literature, ranging from the highly sophisticated to simple rating systems [54]. These models can be classified into three major categories [adapted from 51]:

1. *Value Measurement Models* in which numerical scores are constructed to represent the degree to which one option is preferred over another. The scores are developed initially for each criterion and are then synthesised in order to aggregate into a higher-level preference model.
2. *Goal or Reference Level Models* in which desirable levels of achievement are established for each of the criteria. The assessment process is then applied to seek the option that is closest to the target goals.

3. *Outranking Models* in which alternative actions are compared pairwise, initially in terms of each criterion, in order to identify the extent to which a preference for one over the other can be asserted. By aggregating such preference information across all criteria, the model seeks to establish evidence favouring the selection of one alternative over another.

In this study, an MCDA from value measurement models, multi-attribute value theory (MAVT), was used to perform multi-criteria analysis on the selected case study. **Chapter 3.2.6** elaborates on the characteristics and rationale behind selecting MAVT.

3 Research Methods and Tools

"*We are the recipients of scientific method. We can each be a creative and active part of it if we so desire.*" ***Kary Mullis***

3.1 Research Design and Worldviews

There is more than one way to carry out scientific research; the field is broadly divided into four worldviews, namely, positivist/post-positivist, constructivist, transformative, and pragmatist.

Positivism had been the standard philosophical view of natural science for many years. It stresses facts (objective knowledge) through direct observations and rejects theories based on qualitative or social science [55]. As a result, quantitative research methods are heavily used by scholars with a positivistic worldview. *Post-positivism* emerged to overcome the significant flaws possessed by the positivistic approach highlighted by Blaikie [56]. Unlike positivism, the post-positivistic approach acknowledges that the theories, hypotheses, background knowledge and values of the researcher can influence what is observed [57]. However, post-positivists continue to follow objectivity in research and strive to develop general laws and theories to define socio-natural systems.

The constructivist worldview is often combined with interpretivism and is typically seen as an approach to qualitative research methods [58]. The constructivist approach attempts to build understanding based on researchers' observations. This form of research begins with individual observations followed by the emergence of patterns that eventually lead to the formation of theory. Constructivist researchers, therefore, develop the subjective meanings of their experiences—meanings directed toward certain things or objects [58].

The transformative worldview advocates the need for research to confront social oppression by interacting closely with politics and a political change agenda [59]. Typically, participatory action research methods follow the transformative worldview [55]. It places central importance on studying the lives and experiences of diverse groups that have typically been marginalised.

A more recent addition to the worldviews of science is pragmatism. *Pragmatism*, as a worldview, arises out of actions, situations and consequences rather than pre-existing theories [60]. In pragmatic science, instead of focusing on methods, researchers emphasise the research problem and use all approaches available to holistically understand it [61]. Mixed-method research follows the philosophical underpinnings of pragmatism in many ways. Pragmatism is not committed to any one system of philosophy, and mixed-method research allows the researcher to draw liberally from both quantitative and qualitative assumptions in research [55, 58]. Thus, for the mixed-method researcher, pragmatism opens the door to different methods, worldviews, assumptions and forms of data collection and analysis.

This thesis adheres to the pragmatic worldview and adopts a mixed-method research approach to address the proposed research questions. The overarching themes of the CE, sustainability and marine pollution demand transdisciplinary and collaborative research, and mixed methods are preferred as they allow the use of both qualitative and quantitative methods to provide the best understanding of the research problem.

In this thesis, mixed-method research is applied to solve the real-world problem of marine plastic from the fishing sector in Norway. Although mixed methods provide flexibility and choice to the researcher about the use of methods, Creswell and Creswell [58] stress the need to recognise the purpose of mixing the methods. Therefore, the selection and application of research methods were accomplished by carefully following the *scientific attitude* proposed by Robson [55]. The scientific attitude ensures that the research is carried out *systematically*, *sceptically* and *ethically* and thereby provides the rationale for method selection. Robson defines the systematic, sceptical and ethical aspects of the scientific attitude as:

> Systematically means giving serious thoughts to what you are doing and how and why are you doing it. Sceptically refers to subjecting the researcher's ideas to possible disconfirmation. Ethically means that a researcher should follow a code of conduct for the research, ensuring that the interests and concerns of involved stakeholders are safeguarded. [p. 15 in 55]

The selected research methods and their relevance to the current case are discussed and elaborated here. **Figure 3** demonstrates the application of the listed methods concerning research questions and papers.

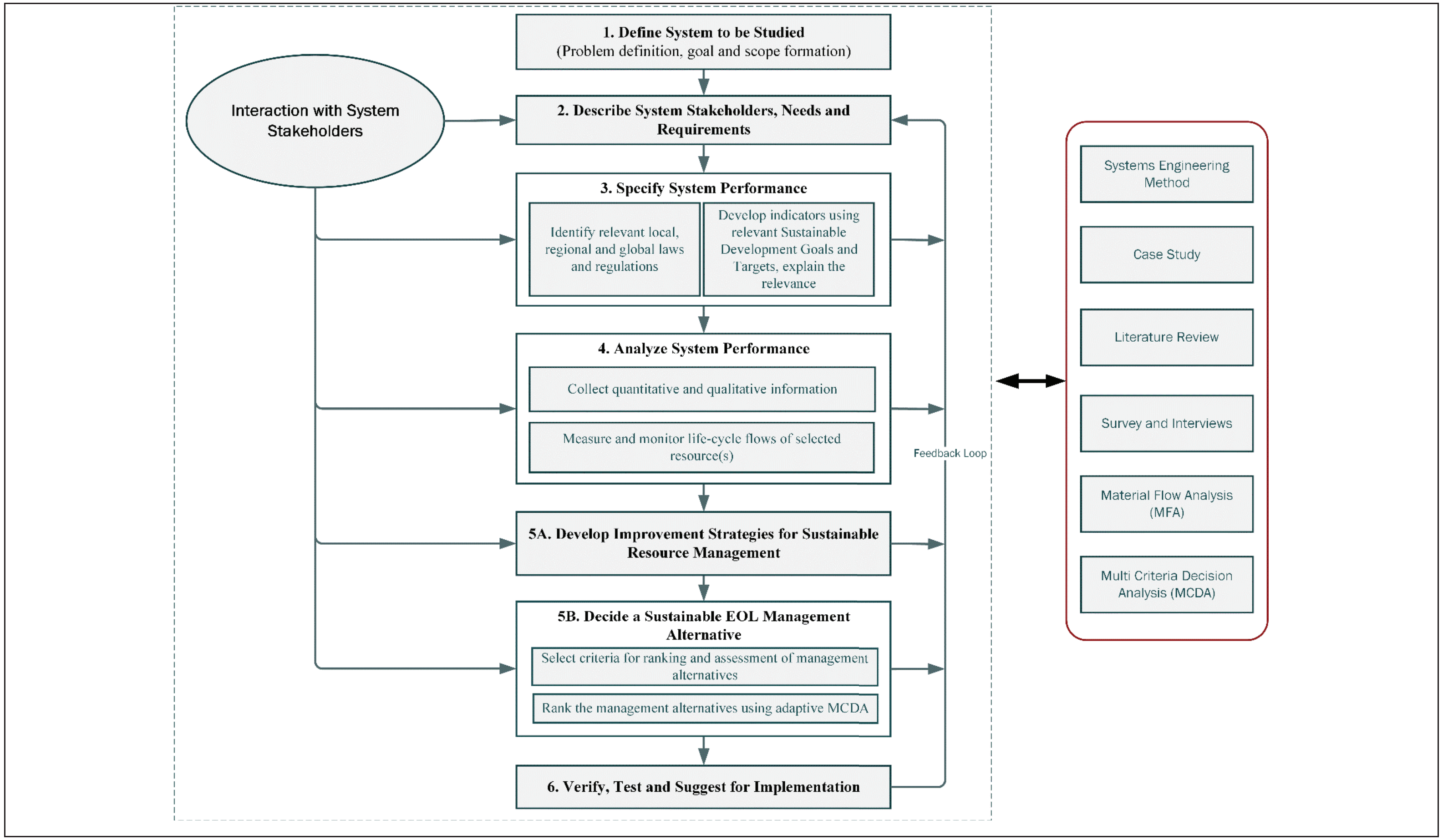

Figure 3: Stepwise systemic model for doctoral research work [adapted from 25].

3.2 Research Methods

The research model presented in **Figure 3** shows that SE forms the backbone of this thesis. The stepwise SE framework was primarily applied to structure the problem and to further determine the steps for applying the multiple methods to address the research questions. Insights on the research problem were gained through literature review, while quantitative data and information on the system were obtained through structured questionnaire-based surveys and semi-structured interviews with relevant stakeholders. Standardised tools and methods were used to process the data and to answer the research questions.

3.2.1 Literature Review

The literature review is an established part of research in the scientific community because, in practice, we all start our research from the work of our predecessors; that is, we hardly ever start from scratch [62]. Among the several purposes, reviewing literature provides insights that help the researcher to limit the scope to a needed area of inquiry. Moreover, it relates a study to the broader, ongoing dialogue in the scientific community and aids in filling knowledge gaps or extending prior studies [58]. Literature reviews can be broadly classified into two categories, a thorough literature review or a narrower review [63]. The thorough review is generally broad and all-encompassing, while the narrow review is aimed at filtering limited literature to address specific research questions with a focus on relevance rather than comprehensiveness.

In this research, a narrow literature review was used to collect background information and gain insights into Norwegian fisheries, identify gaps in the field of marine pollution from FGs, to map the stakeholders and conduct a sustainability assessment of CE strategies. The review is presented in the attached **Papers 1 to 4**.

3.2.2 Case Study

Case study research is an established method in social sciences. It is often used for ‘how’ and ‘why’ questions. Yin [64] defines a case study as ‘a strategy for doing research that involves an empirical investigation of a particular contemporary phenomenon within its real-life context using multiple sources of evidence.’ The strength of a case study is in its ability to encompass the collection of a variety of documents, interviews, artefacts and observations, which supports the triangulation of the results. There are five different processes in case study research: explanation, description, illustration, exploration and meta-evaluation [55]. Here, a single-case study of the Norwegian commercial fishing sector is explored using mixed-method research. Single case-study research along with the incorporation of sub-units of analysis often adds significant opportunities for extensive analysis and enhanced insights into the single case [64]. Accordingly, sub-units were explored to gain detailed insights and holistic analysis for the selected case in this thesis.

3.2.3 Systems Engineering

SE is defined by the International Council on Systems Engineering as ‘an interdisciplinary approach and means to enable the realization of successful systems [65]’. It deals with the analysis, design, operation and maintenance of large integrated systems in a total life cycle perspective and helps to maintain the scope and boundaries of a multidisciplinary research problem [26].

Building on SE theory, Fet [25] developed a six-step model inspired by Blanchard and Fabrycky's [26] stepwise approach **(Figure 4)**. The Fet model demonstrates system configuration through the top-down iterative process of requirements definition, functional analysis, synthesis, optimisation, design, testing and evaluation, which follows Blanchard and Fabrycky's [26] definition of SE [Blanchard in 25]. The various steps mentioned in the Fet model are briefly described and explained below:

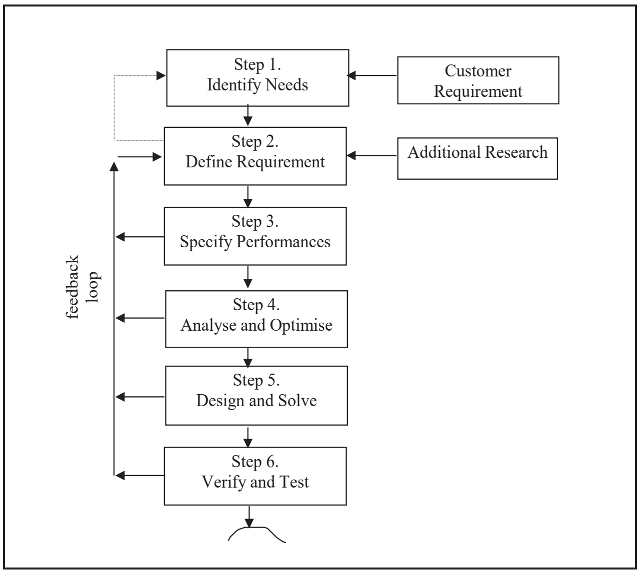

Figure 4: Six-step model for systems engineering [25].

<u>Step 1: Identify Needs</u>

Identifying needs is the starting point of the SE process, where stakeholders and their needs are recognised and mapped. This step generally finds the answer to questions such as 1) what is needed, 2) why is it needed, and 3) how may the need be satisfied? The information from this step provides the input to Step 2.

Step 2: Define Requirements

The requirements are the solutions to the questions raised in the earlier step. According to Fet [25], these requirements represent the category of functional, operational and physical performance requirements and should try to answer the questions posed in Step 1.

Step 3: Specify Performance

After defining the requirements, they should be translated into system performance specifications. These specifications are definable and measurable performance criteria for the total system and subsystems. The first three steps in the model are closely linked such that the outcome of the third step is the final quantification of the needs identified in the first step and defined in the second. As suggested by the feedback loop, any of these steps may be iterated as necessary to provide clarification throughout the entire process.

Step 4: Analyse and Optimise

Analysing the performance of the selected system is an essential part of the SE process, which takes the inputs from performance specifications and then calculates a representative system configuration. Analysis and optimisation form a continuous analytical effort including activities for evaluating different system design alternatives by considering trade-offs between different and often conflicting system requirements.

Step 5: Design and Solve:

In this step, based on the analytical output from Step 4, a preferred alternative is chosen. The solution is designed and implemented.

Step 6: Verify and Test

In this final step, system performance should be tested according to the requirement set in Step 2. It should also be validated that the system satisfies the requirements set by the stakeholders and other functional characteristics that were initially determined. The use of this top-down and iterative systemic model was successfully demonstrated by Fet and Schau [66] in developing a decision support framework for complex environmental analyses of fish food production systems.

In this research, the six-step SE model was adapted and applied to design the overall research structure and to propose a stepwise systemic approach for assessing the complex SES of FG resources as presented in **Paper 1**.

3.2.4 Survey and Questionnaire

A survey provides a quantitative or numeric description of the trends, attitudes or opinions of a population by studying a sample of that population. From sample results, the researcher generalises or draws inferences to the population [58]. Most surveys involve the use of questionnaires, which can be applied in three main ways [55]:

Self-completion: Respondents fill in the answers themselves.

Face-to-face interviews: An interviewer asks the questions to the respondent or the respondent fills in the questionnaire in the presence of an interviewer.

Telephone interview: The interviewer records the responses from the respondent via telephone conversation.

Due to the lack of available data, the research conducted in this thesis relied mostly on information from stakeholders. A questionnaire was designed and face-to-face and telephone interview methods were used to obtain data from fishers. The details on survey design, administration and analysis of responses are presented in **Paper 2**.

A questionnaire-based survey was also used to select and rank the criteria used for MCDM assessment. Face-to-face interviews and self-completion method were used to record the responses from the participants involving experts in the field, and the results are documented in **Paper 4**.

Apart from the structured questionnaire, site visits and semi-structured interviews were used in this research to gather additional information from various stakeholders. Kvale [67] defined an interview as a conversation with a structure and purpose. The research interview goes beyond the spontaneous exchange of views of everyday conversations and becomes a careful questioning and listening exercise to obtain thoroughly tested knowledge. In this study, the semi-structured interview method [67] was used to gather critical information from stakeholders essential to answering the research questions.

3.2.5 Material Flow Analysis (MFA)

MFA is a widely used tool from the toolbox of IE. The basic principle of MFA is the conservation of matter and energy in a defined system, delimited by the boundaries of time and space and following the mass-balance principle [68]. It is a decision-support tool applied for evaluating technology efficiency and industrial practices, and for managing resources and environmental impacts [68]. Typically, the MFA of a selected substance includes the main life cycle stages: production, manufacturing, use, maintenance and disposal [69].

In this research, MFA was applied to measure the annual loads of plastic through the life cycle of commercial FGs in Norway. The static MFA model was built to represent the 2016 stocks and flows of plastics from FGs because of the maximum data availability obtained through the data collection phases. Static models provide insight into systems at a specific time, allowing the holistic assessment of their current state [70, 71]. The primary MFA model, results and findings are presented in **Paper 3**.

3.2.6 Multi-Criteria Decision Analysis (MCDA)

Emerging environmental challenges, coupled with increased stakeholder awareness and concerns, call for more effective stakeholder involvement processes in environmental management [72]. Environmental problems often involve complex science, and many stakeholders and potential management solutions often involve conflicting criteria. Linkov and Moberg [53] documented the application of MCDA methods to solve real-life case studies of environmental and resource management. The necessary steps in the MCDA method involve problem identification, problem structuring, criteria selection, model building, model assessment and communication of outcomes [51]. The systematic and logical approach offered by MCDM methods found a suitable application in decision making for sustainability, which requires the consideration of trade-offs between multiple attributes such as socio-political, environmental and economic impacts and is often complicated by differing stakeholder views [53]. Hence, MCDA emerged among scientists, policymakers and businesses as a formal methodology to use available technical information and stakeholder values to support sustainability decision making.

Of the many MCDM methods, MAVT was selected for addressing the research questions in this study. MAVT involves different amelioration alternatives, which are ranked by the stakeholder groups involved in order to find the 'best' solution [73]. Interviews with representatives of stakeholder groups help to reveal their preferences. Apart from flexibility in handling both qualitative and quantitative information, MAVT is also known for its simplicity, transparency and robustness in eliciting stakeholder preferences [74]. Applications of MAVT range from technology assessment [75] and risk management [76] to sustainable site selection [77]. In this thesis, MAVT is used to assess the environmental, economic and social effects of EOL management alternatives for FGs in Norway, presented in **Paper 4**.

3.2.7 Method Selection and SE Framework

Figure 3 presents the adapted stepwise SE framework for this research. The SE method was used to structure the problem, and the qualitative and quantitative research methods were applied to address the specific questions related to the commercial fishing sector in Norway. Here, the steps of the SE framework and the rationale behind the method selected for each step are elaborated.

The literature review was primarily used to define the system (Step 1 of SE framework), map system stakeholders (Step 2), and to identify relevant local, regional and international laws specifying system performance (Step 3). MFA was used to analyse system performance (Step 4) through mapping and quantifying flows of plastics throughout the FG life cycle. In the absence of information to conduct MFA, questionnaires, semi-structured interviews and stakeholder surveys were used to collect the information necessary to validate the MFA model.

Further, MCDA was used to decide on and develop sustainable management strategies for FG resources (Step 5). The essential information for MCDA model inputs was obtained through site visits and questionnaires delivered to relevant stakeholders. Step 6 of the SE framework is not addressed in this thesis as verifying and testing the suggested strategies are out-of-scope for this doctoral research project. As indicated in Figure 3, stakeholder inputs were used throughout the SE framework to collect information, understand system structure, select performance assessment criteria and validate the research results. Additionally, the iterative nature of the SE framework allowed for constant revisions through feedback loops at every step. This iterative characteristic is reflected in research through data collection, revisions and validations of results together with the system stakeholders.

4 Description of Subsystems

*"Never doubt that a small group of thoughtful, committed citizens can change the world; indeed, it is the only thing that ever has." **Margaret Mead**.*

Revisiting **Figure 1**, the four core subsystems in the main SES of FG resources are:

A. **Resource system**: The Norwegian commercial fishing sector;
B. **Resource units**: Plastics from commercial FGs and ropes;
C. **Governance systems**: The regulatory framework and governing institutions;
D. **Resource users**: Fishers and other stakeholders.

These four subsystems are explored and elaborated in this chapter. In exploring subsystems, this chapter also contributes to the first three steps of the SE framework (**Figure 3**), namely defining the system structure, describing the system scope, stakeholder needs and requirements, and specifying system performance. The system structure and scope are presented in **Section 4.1** and **Section 4.2** through describing and discussing the Norwegian commercial fishing fleet and scoping the system through the system life cycle of FGs. The specification of performance is discussed in **Section 4.3** by identifying international, regional and local regulatory frameworks relevant to the FG system, while **Section 4.4** maps out the stakeholders and their needs.

4.1 Resource System: The Norwegian Commercial Fishing Fleet

The first step of the six-step SE framework defines the scope and structure of the system under consideration. Norway is a northern European country surrounded by water to the south (Skagerrak), the west (the North Sea and the Norwegian Sea) and the north and north-east (the Barents Sea). With a marine resource-rich coastline of more than 25,000 km, Norway is a European leader regarding both commercial fishery and aquaculture [78]. Commercial fisheries have always played a critical social and economic role, both nationally and regionally, and have been the basis for settlement and employment along the entire Norwegian coast [79]. The commercial capture fishery sector is segmented into the coastal and ocean fishing fleet. The coastal fishing fleet is comprised of smaller vessels operated by 1–5 fishers with vessel sizes ranging from 10–20 metres. The ocean fleet is known for its sophisticated deep-water fishing practices, where fishing vessels are generally more than 28 metres in size, and crew members can vary up to 20 persons or more [79, 80].

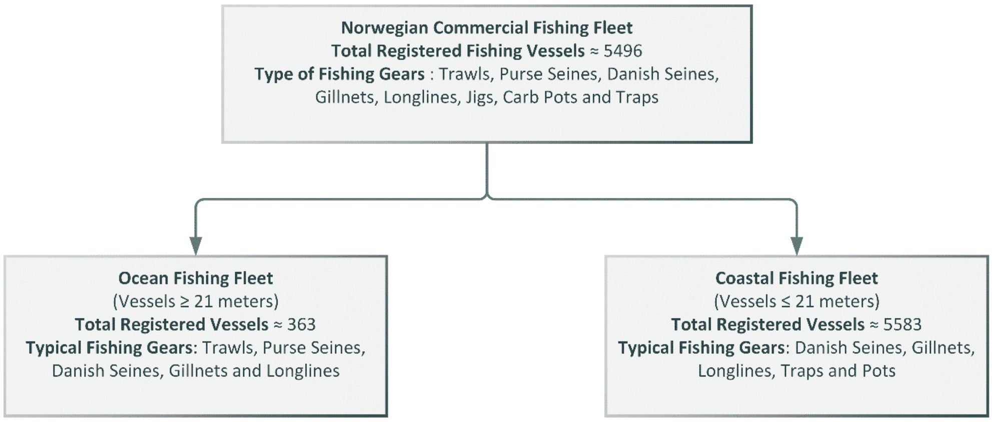

Figure 5: Structure of the commercial fishing fleet of Norway 2016–2017 [80]

In 2016–2017, a total of 5,946 vessels were registered in Norway, out of which approximately 90% are coastal vessels with the rest ocean fishing fleets [80]. The primary capture species include herring, cod, capelin, mackerel, saithe, blue whiting and haddock. A few additional species are caught in smaller quantities but with high commercial value such as prawns, Greenland halibut and ling. **Figure 5** shows the diversity of the fishing fleet concerning the number of vessels, type of FGs they use and the typical target species. In Norway, leisure fishers and foreign vessels perform fishing activities in Norwegian waters through quota agreements. However, only fishing activity through the commercial fishing fleet of Norway was considered for assessment in this study.

4.2 Resource Units: Plastics from Commercial FGs

FGs were selected as resource units in this study. FGs are defined using an expansive definition proposed by the Food and Agricultural Organization (FAO). According to the FAO, FGs are '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'[16].

Six major FG types, namely trawls, purse seines, Danish seines, gillnets, longlines, traps/pots and their associated ropes, are considered in this study. Polyethylene (PE), polypropylene (PP), and nylon are the primary building blocks of any FG [23], and all three are referred to using the term 'plastics' throughout the text. Although the FG unit contains other materials such as metals, lead, polyvinyl chloride (PVC) and wires, plastics constitute around 60% to 90% of any gear type [17]. Furthermore, the plastic of the FG unit possesses the additional threat of ghost fishing in comparison to metal parts that sink to the ocean floor upon gear loss. Therefore, this study focuses on plastics from FG units as a resource unit.

Fishing practices, design and use of FGs vary considerably depending on the fishing community, target fish species, fishing grounds, size of the fishing vessel and local fishing regulations. FGs are divided into two categories, active and passive. *Active gears* (seines and trawls) dynamically hunt the targeted species, whereas *passive gears* (lines, gillnets, and traps/pots) are fixed gears aimed to catch active fish [81]. Passive gears are usually cheap, making them accessible for small-scale fishers. The design, usage and material of construction are some of the criteria that were selected to discuss the six FGs. **Table A1** in **Appendix A** presents a brief description of the selected gear types, methods of operation and application in catching target species.

4.2.1 System lifecycle of FGs

Figure 6 presents the typical lifecycle processes of commercial FGs used by the Norwegian fishing fleet. The commercial fishing fleet of Norway is controlled by the Norwegian Directorate of Fisheries [80]. Every year, fishing companies purchase FGs to equalise their stock after annual losses from deployment or disposal after EOL. In the use-phase, fishers deploy FGs in the ocean to catch a target species. Deployed FGs or their parts may get lost during operation for a variety of reasons namely irregular topography, gear conflicts and failures, ship collisions, abandonment, human error, and vandalism as listed by Graeme Macfadyen [82].

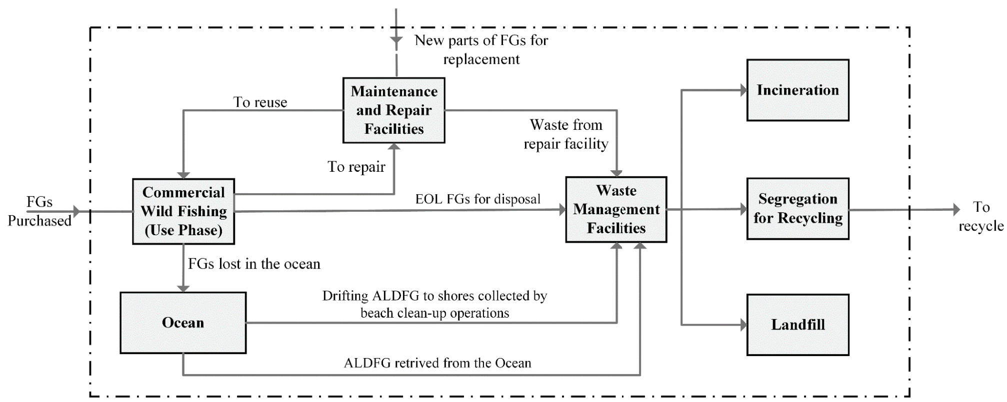

Figure 6: Processes involved in the system life cycle of commercial FGs in Norway.

Additionally, fishing activities cause wear and tear to the gear used and, consequently, fishers must frequently maintain and repair their FGs. Some repairs involve the replacement of damaged or lost parts. In this study, repairs that involve the replacement of FG parts are considered 'major repairs'.

Major repairs need external intervention and are carried out by either the fishing company or dedicated repair facilities managed by FG producers. It is essential to note that most FGs undergo continuous minor repairs after each fishing activity. Minor repairs include stitching, tying and adjusting broken parts of the gear without any significant replacement of parts. Such minor repairs are excluded in this system, as they have no significant impact on mass flows.

The EOL pathways of FGs are manifold. Firstly, fishing companies dispose of waste FGs in the nearest waste management facilities (WMF), while lost FGs and parts are retrieved through annual ocean clean-up surveys to minimise the risk of ghost fishing and the associated damage to the marine environment. Floating fractions of ALDFG end up on shores, dragged by the wind and waves. Some of those FGs and gear residues are further collected during annual beach clean-up operations conducted across the Norwegian coastline. ALDFG collected from land and ocean ultimately ends up at WMFs, along with waste generated during FG repairs. At the end of the value chain, waste managers segregate waste FGs into different fractions, which include the recyclable fraction, the fraction for landfill, and the incinerable fraction for energy recovery. The segregated fractions are then transported to their respective facilities.

Paper 3 presents an in-depth discussion of each process and the flows and stocks of the FG lifecycle. It also presents the associated data collection and analysis of plastic flows.

4.3 Governance Systems

Step 3 of the SE framework demands to specify system performance, which is governed through governing agencies and regulatory frameworks. Ostrom [8] defines the governance system as organisations that manage the system through a specific set of rules and regulations related to operational aspects of the system. In this study, vital legislative instruments at the local, regional and international scale were identified based on their ability to manage the FG system. Legislative instruments come in many forms, including conventions, action plans, programmes, policies, regulations or agreements [83]. It is important to note that the instruments for tackling FG pollution often overlap with other legislative mechanisms that address similar issues, such as marine pollution, marine litter, biodiversity and water quality. Although related, only those mechanisms specifically addressing the operation and management of FGs were included in this study. Each instrument is introduced according to its level of implementation: international, regional or national.

4.3.1 International

The International Maritime Organization (IMO) developed the *MARPOL 73/78 Annex V* as a principal international instrument that addresses ocean-based litter pollution from ships. Overall, this instrument bans the discharge of all garbage from ships at sea except in a few defined circumstances. MARPOL Annex V requires vessels to log the loss of any FG by recording where the gear was lost, the characteristics of the lost items and which precautions were taken to prevent the loss. Also, the MARPOL instrument requires ports to provide adequate waste reception facilities without causing delays to ships.

The UN's Convention on the Law of the Sea and the London Convention are other critical legislative instruments controlling marine litter in international waters. The role of these instruments is to assess the status of marine litter, provide a platform for cooperation and partnerships for managing marine litter between groups such as governments and the private sector. The Norwegian Maritime Authority ratified the convention and the annexes of MARPOL and is therefore under the legal obligation to implement their regulations.

4.3.2 Regional

In EU member states, commercial fishing is a primary activity in which wastes from FGs are regulated through a range of regional instruments, including OSPAR and the EU Waste Framework Directive [83]. Furthermore, two EU directives, the Marine Strategy Framework Directive (adopted on 17 June 2008) and the 2000 Water Framework Directive, are crucial for the protection of Norwegian sea areas, for example, against long-range transboundary pollution. As per the 2018 amendment, *EU Directive 2000/59/EC* on port reception facilities (PRF) now mandates all EU-EEA member states to ensure availability of a PRF and a waste handling and management plan on all ports within the region. PRFs are defined as 'any facility, which is fixed, floating or mobile and capable of receiving ship-generated waste or cargo residues.' Additionally, to reduce the impact of marine plastic on the environment, the EU has committed to improving the collection of fishing equipment containing plastics under the EU action plan for the CE [84].

4.3.3 National

In Norway, commercial fishing activity is governed by the Norwegian Directorate of Fisheries. The directorate controls the number of vessels licensed to practice commercial fishing in the state every year. Additionally, species quota allowances for the national and international fleet and registration of lost FGs from ocean fleet are regulated under the Directorate of Fisheries [80, 85]. The Norwegian Environment Agency controls the management and handling of fishing-related waste through the *Marine Resource Act* and the *Waste Regulation Act*.

Although Norway has a dedicated *Marine Resource Act* which ensures the enforcement of the EU's PRF directive within the region, Norway has so far failed to fulfil its obligations as only 1,514 of

4,443 registered ports and landing sites had showcased the availability of waste reception and a handling plan. Norway's *Maritime Safety Act* prohibits the dumping of gear, moorings and other objects in the sea that may injure marine organisms, impede harvesting or damage gear. It also demands that fishers report gear losses to authorities if they failed to retrieve them. Finally, the *Waste Regulation Act* provides the guidelines for the handling and management of waste within the region.

A complete list and description of additional legislation governing the FG system can be found in **Appendix B.**

4.4 Resource Users: Fishers and Other Stakeholders

Step 2 of the SE framework deals with identifying system stakeholders and mapping their needs. Users and other stakeholders are individuals or groups of individuals who use the resource system in diverse ways for sustenance, recreation or commercial purposes [8]. The classification and mapping of stakeholders can be carried out in several different ways based on the applicability and relevance to the problem. Here, stakeholders are classified based on their ability to provide information on the phases of the FG system lifecycle as presented in **Figure 6**. Purchase, use and EOL are the three main lifecycle phases of FGs. Stakeholders that are directly involved in one or more lifecycle phases are presented in **Table 1**. Surveys and interviews were primarily used for data collection. As resource users, fishers possess the most vital information on all the lifecycle phases of FGs, knowledge which is not documented or captured in the scientific literature. Therefore, a dedicated questionnaire was designed and one-on-one interviews were conducted with 114 fishers to retrieve information on FG purchase, use and disposal patterns. The method used to extract fishers' local knowledge of fishing equipment usage patterns is elaborated in **Paper 2**. Additionally, the methods used and information retrieved from other stakeholders was further processed to map annual flows of plastic from the Norwegian commercial fishing practices (**Paper 3**).

Additionally, **Paper 1** adapts the approach presented by Samoura, Bouvier and Waaub [86] to distinguish and map the needs of stakeholders in terms of their economic, social, regulatory and political interests associated with the system.

Table 1: List of stakeholders and their relevance to the life cycle stages of the FG system.

Stakeholders'	Pre-Use (Purchase)	Use-Phase	End-of-Life Phase	Other
Directorate of Fishery			X	
Ports and harbours		X	X	X
Fishers and fishermen associations	X	X	X	X
FG producers/suppliers	X			
Relevant NGO's	X		X	X
Research & consultancy companies and academia			X	X
Waste management companies			X	
Waste collection and recycling companies			X	X

According to the SES framework presented in Figure 1, an understanding of the interactions between the four core subsystems is deemed essential in the holistic assessment of the system. Here, the interaction of the four subsystems is analysed through the flow of information in the form of data collected from the stakeholder meetings, and semi-structured interviews. These interactions are further used to analyse system performance (Step 4 of SE framework), presented in **Chapter 5**.

5 Research Results: Current Status

*"Scientific discovery and scientific knowledge have been achieved only by those who have gone in pursuit of it without any practical purpose whatsoever in view." **Max Planck***

A robust management strategy builds on available scientific information about the system under study. An overview of current system performance aids in identifying potential problems and improvement mechanisms. Step 4 of the SE framework (**Figure 3**) deals with analysing system performance. Accordingly, this chapter presents the analysis of system performance in two parts:

i. Identifying the status of the FG system life cycle.
ii. Assessing sustainability in the current EOL management of FGs.

5.1 Current Status: Plastic flows from Commercial Fishing Sector

In the terminology of resource management, *information* refers to the real knowledge about stocks, flows and processes within the resource system as well as about the human-environment interactions affecting the system [5]. For this study, static MFA was applied to track physical flows and stocks of the mass of plastic (MoP) from FGs in Norway through use and post-use processes. In MFA, static models provide insights into systems at a specific time, allowing the holistic assessment of their current state [70, 71]. Based on data from gear producers, fishers, collectors and waste and recycling management companies, an MFA model was established to quantify the annual stocks and flows of plastic polymers (PP, PE and nylon) from the FGs deployed by the Norwegian fishing fleet. Data from fishers was used to estimate the average annual rates (transfer coefficients) of FG repair, disposal and gear loss for selected FGs. These rates are presented in **Figures 7** to **9** and are further used to calculate the flows of plastic through selected processes. **Figure 10** presents the MFA of plastics from the six types of FGs used by commercial fishers in Norway. Flows and stocks in the system were calculated through the purchase, use and EOL phases of FGs.

5.1.1 Purchase phase

The total MoP in the form of newly purchased FGs ($F_{0,1}$) in 2016 is estimated to be 2,626 ± 143 tons. Additionally, 1,755 ± 681 tons of MoP were purchased as FG parts for replacements during major repairs ($F_{0,2}$). The weight of metal components in FGs, such as trawls, purse seines, Danish seines and traps/pots, were excluded from the model calculations. A fishing fleet typically purchases the selected FGs to equalise their stock of owned FGs. Responses from 114 fishing companies were used to calculate the turnover coefficient of selected FGs. The total estimated stock of FGs owned by the Norwegian fishing fleet in 2016 was 18,413 ± 3,676 tons MoP.

5.1.2 Use phase

Information on the use phase was obtained from the resource users, fishers. In total, 114 responses from fishers were collected in the span of seven months from the four major fishing ports, Bergen, Ålesund, Trondheim and Måløy in Norway [87]. Fishers' annual meetings and fishing product-related conferences and exhibitions were targeted to conduct face-to-face questionnaire-based surveys. The collected sample responses were further analysed using statistical methods to extract information on FG repair-reuse patterns, disposal and gear loss rates.

5.1.2.1 Repair patterns

The responses from the 114 fishers about typical repair-replace patterns for the six gears are presented in **Figure 7**. The results indicate that repair of large and expensive gear, such as trawls and purse seines, is frequent, with more than 80% of total trawls and more than 50% of total purse seines subject to major repair every year. On the other hand, only one-third of the inexpensive FGs, such as gillnets, traps/pots and longlines, undergo major repairs.

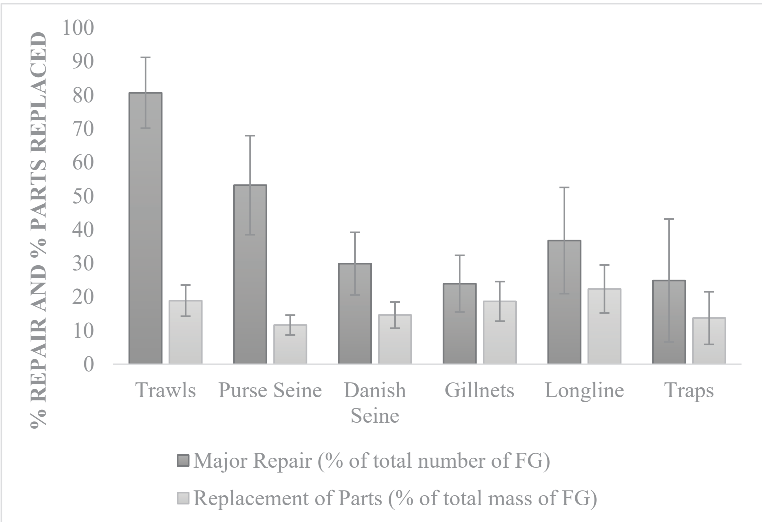

Figure 7: Annual repair and replacement patterns of six commercial FGs used in Norway.

The replacement of gear parts is a continual process at repair facilities as parts of trawls, purse seines and Danish seines are lost and damaged during operation. The fishers' survey responses highlighted that the FG types that undergo major repairs require the replacement of parts that make up 15% to 25% of the total mass of the gear. For instance, fishers informed us that during the deployment of trawls, they sometimes lose or damage the net extremity known as the 'cod-end.' As a result, they must replace the part, which represents 15% to 20% of the total weight of the gear, more often than any other parts of the trawl.

5.1.2.2 Deployment losses

Fishers reported the risk of damaging FGs and of losing part or all of the gear upon deployment in the ocean. Survey responses showed that not all the commercial FG types are equally prone to being lost in the ocean, with significant differences in their probabilistic loss rates. Additionally, it is essential to note that the rate of FG losses estimated in this study only includes FGs that are lost upon deployment either accidentally or due to operational damage; the deliberate abandonment of FGs is not considered in this study. Responses from the fishers (**Figure 8**) provide the annual loss rates of the six FGs and their parts occurring in Norwegian waters upon deployment.

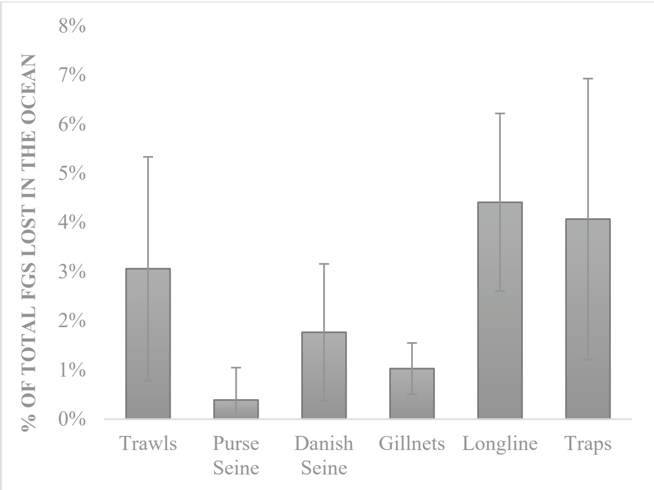

Figure 8: Annual rates at which commercial fishers lose their FGs upon deployment.

Longlines and pots have higher chances of loss on deployment. Indeed, around 4% to 7% of total longlines and traps/pots owned by the Norwegian fishing fleet end up in the ocean every year. By contrast, purse seines and Danish seines have proven robust and are rarely lost upon deployment. Gillnets are the primary source of derelict gear, as although only 1% to 2% of total gillnets are reportedly lost upon deployment, the number of gillnets used by commercial fishers exceeds most other types of gear. Thus, lost gillnets also pose a significant threat to the marine ecosystem.

5.1.2.3 Typical disposal patterns of fishing gears

If not lost during operation or able to be repaired effectively or economically, fishers must dispose of FGs at the end of their usable life. These EOL FGs are disposed of either at PRFs or the nearest WMF. Fishers' responses showed the variability in the operational lifespan of the studied FGs. Sophisticated and expensive gears like purse seines and Danish seines last the longest because of the way they are used (slow deployment in the open sea) that minimises wear and tear. FGs like gillnets and longlines, on the other hand, are cheap and display an operational life of between one and three years, implying frequent disposal. Consequently, almost one-third of gillnets and longlines, and one-fourth of trawls, are disposed of by the fishing companies every year (**Figure 9**).

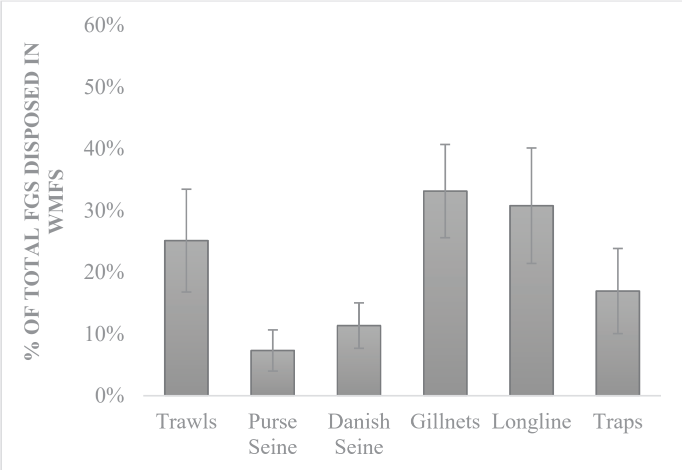

Figure 9: Annual rates at which commercial fishers dispose of their gears to the WMFs.

Purchase and repair rates are used to estimate the MoP entering the system from the purchase of FGs and the replacement of gear parts, while disposal and gear loss rates are used to estimate MoP disposal after EOL of FGs and from operational losses. As shown in **Figure 10**, significant uncertainty is associated with estimating listed flows. This uncertainty in calculations can be attributed to considerable variation in the plastics used in each FG design, weights of gear parts and availability of aggregated information. The uncertainty calculations and associated reasoning are explained in the supplementary material of **Paper 3.**

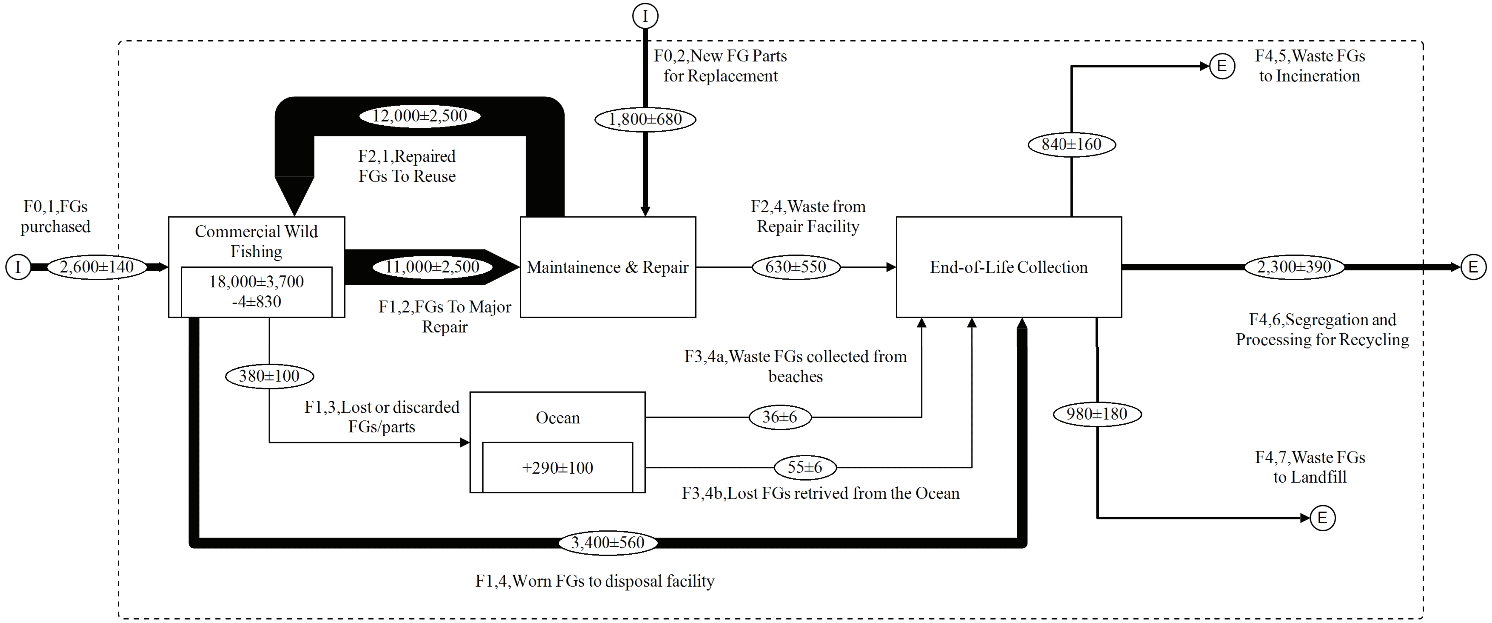

Figure 10: MFA of plastic (PP, PE and Nylon) from six FGs used by the commercial fishing fleet of Norway in 2016 (tons/yr.)

5.1.3 End-of-Life phase

5.1.3.1 Collection of gears from beaches and the ocean

Marine litter that is accumulated on the coastline is cleaned throughout the year through clean-up efforts. Analysis of the collected litter reveals that plastic from FGs constitutes up to 30% of the total marine litter found on the beaches in Norway [88, 89]. Personal interviews with the managers of beach clean-up operations informed the estimation of the average weight range of waste FGs collected during clean-up operations. The fraction of waste MoP removed from registered beach clean-up operations in Norway accounts for 36 tons per year ($F_{3,4a}$). This waste fraction is sent to the nearest WMF for further management.

The amount of plastic collected through listed ocean clean-up operations was calculated from the raw data, excluding metal and other non-plastic components of the FGs. An estimated 55 tons MoP is retrieved from Norwegian waters annually from the two main ocean operations: annual gear retrieval surveys by the Norwegian Directorate of Fisheries and the recovery of waste FGs through Fishing for Litter (FFL) ($F_{3,4b}$). It is not possible to know the source of these FGs or the year in which they entered the ocean.

5.1.3.2 Handling of FGs by WMFs

All the waste FGs from fishers, repair facilities and collected from the land and water ends up in the nearest WMFs. Responses from 13 WMFs were recorded, from which patterns of handling waste FGs were derived. 4,100 tons of plastic FGs are disposed of in WMFs in Norway annually. Out of the collected amount, around 55% are segregated and sent to recyclers for further processing, while 21% are sent for incineration and 24% are landfilled.

The detailed data collection routines and flow analysis are presented in **Paper 3.**

5.2 Sustainable End-of-Life Management of FGs

The MFA results indicate that, annually, around 4,000 tons of waste plastic is disposed of and collected at WMFs in Norway. Until the end of 2017, industrial-scale recycling of waste plastic was unavailable in Norway and consequently, the entire recyclable fraction of EOL FGs was sent out of Norway for the mechanical recycling of PP, PE and nylon. However, industrial-scale recycling for obsolete plastics from the fishing and aquaculture sector began in Norway in the latter half of 2017. Although recycling began in the region, a still significant fraction is sent abroad for further processing and recycling. Therefore, to assess the sustainable EOL management alternative for FG resources, four scenarios were selected: landfilling, incinerating, recycling (inland) and recycling (export).

Sustainable management is defined as ‘the ability of EOL management alternatives to manage 4,000 tons of waste FGs annually through maximizing environmental and economic and social benefits while minimizing the negative effects.' The Sustainable Development Goals (SDGs) and targets are considered useful in assessing the three dimensions (environmental, economic and social) of sustainability proposed by Elkington [90]. The SDGs primarily address some of the systemic barriers to SD and contain better coverage of and balance between the three dimensions of SD and their institutional and governmental aspects [91]. The criteria for assessment were chosen to reduce the uncertainty, increase the understanding of the FG system and measure the performance of the EOL alternatives against the defined goal.

Based on the qualitative and quantitative data from relevant stakeholders, MCDA was adopted to rank the EOL alternatives based on their ability to manage 4,000 tons of plastic waste from FGs in Norway within the defined sustainability criteria. **Figure 11** presents the value tree developed for the decision analysis problem. The analysis was performed using DECERNS (Decision Evaluation in ComplEx Risk Network Systems) software [92]. The three core criteria, environmental, economic and social, and associated sub-criteria, were chosen through experts' judgement. Additionally, the performance of four alternatives against the selected sub-criteria was calculated through site visits and personal interviews with waste managers and recyclers within the region. MAVT was selected for addressing the research questions due to its flexibility and suitability for the participatory process [93]. A typical MAVT outcome ranks different management alternatives using the opinions of relevant stakeholder groups to find the 'best' solution.

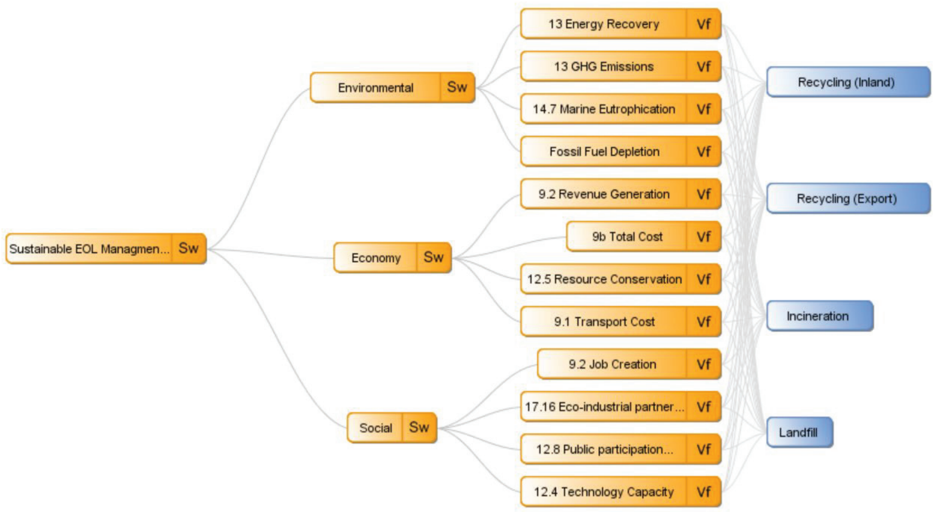

Figure 11: MCDA model for proposed alternative evaluation in selecting sustainable EOL management alternatives for FGs and ropes.

In this study, responses from 31 expert stakeholders were recorded through the questionnaire. A simple questionnaire was formulated and distributed among the list of attendees in a scientific workshop organised in Tromsø, Norway, on 21 Jan 2019. The workshop was part of a research project on marine plastic pollution in the Arctic region, making the stakeholders particularly relevant in the context of this research. The responses were converted to assign weights to the core and sub-criteria and to shortlist the sub-criteria.

After recording the weights and 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 **Figure 12**. For the given alternatives, recycling (inland) emerged as a preferred choice over the other three while recycling (export) scored the last for given criteria weights.

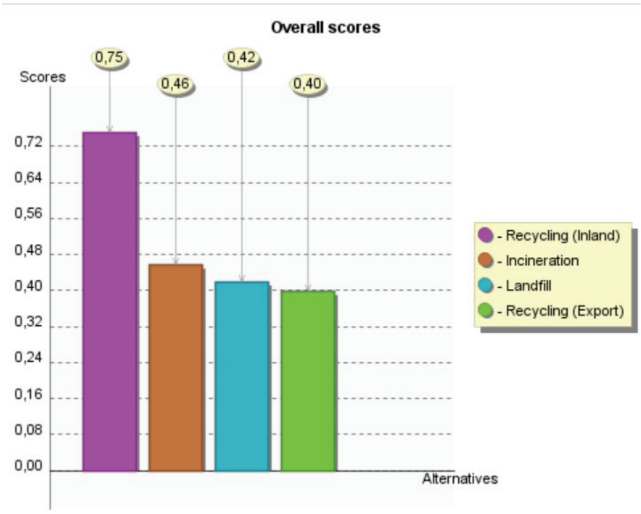

Figure 12: Ranking of EOL management alternatives using MAVT and LCA screening

The results strongly suggest the importance of the location of waste recycling facilities. Recycling operations within the region show the maximum positive effects on the environment and society with additional economic benefits from resource conservation and energy recovery.

The details on data collection, stakeholder assessment and quantitative and qualitative criteria analysis and associated discussions are presented in **Paper 4**.

6 Research Results: Strategies for System Improvement

"Scientific knowledge is as much an understanding of the diversity of situations for which a theory or its models are relevant as an understanding of its limits." ***Elinor Ostrom***

Step 5 of the SE framework (**Figure 3**) is to develop improvement strategies. Building on the understanding of regional flows of plastics from FGs, strategies and mechanisms were identified to aid the sustainable management of FG resources. Systemic improvement can prevent the detrimental effects of ALDFGs and generate CE opportunities through closing the FGs plastic loop. Improvement strategies are segregated in two categories based on their effect to

i. Prevent or mitigate ALDFG pollution
ii. Realise opportunities and barriers to generate value out of waste using principles of CE.

6.1 Strategies for Managing ALDFG Pollution from Commercial Fishing

In the study region, beach and ocean-clean-up operations are considered the most effective solution to the marine litter problem. The MFA results show that even with several regional clean-up operations, a significant amount of plastic remains in the ocean from commercial fishing practices, necessitating the exploration of alternative strategies. **Table 2** gives an overview of the strategies considered relevant to preventing and mitigating plastic pollution from the Norwegian commercial fishing sector, modified from Deshpande and Aspen [22]. The proposed strategies are presented along with their application within the FG lifecycle phases.

6.1.1 Pre-use phase

Gear marking or gear identification is an essential strategy for responsible fishing and for controlling the ALDFG problem. Marking can enable fishers to minimise the risk of losing FGs upon deployment, as well as aid authorities in improving the collection and management of waste FGs. The Fisheries Department of the FAO published systemic guidelines encouraging member states to incorporate gear marking in their policies. According to these guidelines, gear marking aids in providing an understanding of the location, scale and nature of FGs in the water [16]. Some of the proposed marking identifiers include electronic tagging, coded wire tags, barcoding, colour-coded ropes, metal stamps or metal/steel tags incorporated into the FG. Information on gear location and ownership aids in estimating the position of the FG and in tracing the owners responsible for lost FGs.

Furthermore, the Norwegian government is considering 'extended producer responsibility' (EPR) as a strategy to minimise plastic pollution from FGs at a regional scale. Under the EPR, companies who produce, import or distribute FGs (the entire value chain up to the user of the equipment) will be responsible for the collection of the gear after use and for ensuring that it is appropriately recycled [94]. In 2018, the Norwegian Directorate of the Environment conducted a feasibility assessment for the EPR scheme, which highlighted the need for an in-depth understanding of the FG system's lifecycle (flows and stocks) to aid in the selection of the relevant mechanisms for its implementation. This study may provide background evidence to support EPR policies before their implementation in Norway. A 'take-back mechanism', a reward scheme for end-users to promote the collection of EOL FGs, is an example of an effective way to realise EPR at the regional scale. Introducing an environmental tax on the sale of fishing equipment is another proven strategy to internalise the costs of EOL collection and waste treatment in market prices. Nevertheless, stakeholder perception and market readiness must be assessed before implementing such a strategy at the regional scale.

6.1.2 Post-use handling and collection of FGs

Currently, in Norway, marine litter caught during fishing can be handed in at the calling port. The costs associated with the reception of ship-generated waste are covered through the collection of a fee from all ships, irrespective of whether the ship-generated waste is delivered to the reception facility [EU 95]. According to a recent judgement by the EFTA Court [96], Norway has failed to fulfil its obligations under the EU directive, as only 1,514 of 4,443 registered ports and landing sites had showcased the availability of waste reception and a handling plan. A large number of landing sites without any dedicated waste management system has led to the improper collection of fishing-related waste in the country. The absence of adequate facilities to collect ship-generated waste can result in illegal dumping, burning or stocking the waste in ports, and severely hinders the collection and treatment of waste FGs through appropriate channels [97]. The availability of PRFs is essential to reduce the amount of marine plastic pollution resulting from fishing and maritime activities. There is furthermore a need to develop a strategic plan to incorporate harmonised PRFs across Norway, with the help of the relevant stakeholders.

Strategies such as economic incentives and penalty schemes for fishing vessels may be considered to ensure the effective use of PRFs [21]. Additionally, stakeholder awareness campaigns may help to minimise the illegal dumping of marine litter on beaches and at sea, while training workshops that highlight best practices in handling FGs can prevent avoidable loss. Volunteering and deliberate clean-up campaigns are already proven mitigation measures for marine litter in Norway.

6.1.3 Closing the loop for plastics from FGs

Based on CE principles, capacity building and technical support are critical to extracting value from waste. Currently, there exist numerous challenges in closing the loop for plastics from waste FGs. EOL collection, segregation capacity, and the availability of recyclers are among the critical concerns in realising the economic benefits of material recovery.

Personal communication with waste managers in Norway revealed several challenges for handling waste FGs. One of the significant challenges of WMFs is the lack of a best practice guide or harmonised technical expertise in cleaning and segregating waste FGs. Most EOL FGs are covered with rotten biomass, fish oil and dirt. Since many WMFs lack the facility to clean such waste, there are elevated rates of incineration or landfill within the waste fraction. Furthermore, the absence of industrial-scale recyclers' results in the export of the entire recyclable fraction out of Norway, thereby missing an opportunity to extract value out of locally produced waste FGs. Existing mechanical recycling technologies for PP and PE result in the formation of HDPE (high-density polyethylene) and LDPE (low-density polyethylene). These can be used effectively to replace virgin plastic polymers in products made by injection-moulding technology. Additionally, nylon polymers retain their properties through several recycling cycles, making nylon an economically attractive by-product for recovery from waste FGs.

Although both chemical and mechanical technologies are available for closing the material loop, the industrial-scale recycling of FGs faces many economic and operational challenges. Personal communication with the recyclers revealed that the transport and segregation of waste FGs from source to gate pose a significant economic burden to recyclers. The presence of metal wires in ropes and other parts of FGs makes it difficult to cut them into transportable pieces. Furthermore, these metallic parts cause wear and tear to mechanical recycling units forcing frequent maintenance and repairs. The design and composition of modern FGs and lack of technical expertise at the waste collection facilities cumulatively hamper the maximum material recovery from waste FGs.

Finally, to make the recovery of plastic sustainable, there is a need to create a harmonised network of downstream actors involved in the EOL collection and management of FGs, and to ensure that they have sufficient capacity. Additionally, research on the eco-design of FGs must be emphasised to explore alternative FG material that allows efficient and profitable recycling without hampering its effectiveness in commercial fishing.

Table 2: Proposed strategies to aid sustainable lifecycle management of FG resources [modified after 22]

Areas of Improvement	Suggested strategies	Description
Pre-use phase (design and supply)	Gear identification marking	Gear identification entails the marking of a fishing vessel, thus allowing gears to be identified both when fishing or if it becomes an ALDFG [16].
	Extended producer responsibility	Extended producer responsibility is a strategy where the FG manufacturers bear the EOL treatment costs of the FGs. The producers carry the responsibility and the cost of managing old plastic-containing FG once it is landed [84]. In effect, this removes the inconvenience and cost factors associated with waste management from the fishers.
	Take back schemes	Take back mechanism is part of the extended producer responsibility, and applies when the collection of products after their EOL is not mature. In the case of FGs, manufacturers are responsible for taking back the sold FGs from fishers at the end of the products' useful life or may partially finance collection and recycling.
	Environmental service tax	An environmental tax increases the price of a good or service to reflect the cost of the environmental stress it imposes on the natural environment. This principle can be used to internalise the costs of FG loss and EOL management.
Use phase (Operation, handling, and disposal of FGs)	Penalty schemes	Vessels that do not discharge waste in ports are financially penalised unless they can provide proof of delivery at another port. The penalty must be enough to make the vessel lose money by illegally discharging FGs waste at sea [19].
	Harmonised port reception facilities	The presence of waste reception facilities in ports qualifies as a service that a port provides to its users, as defined by the Port Services Regulation [97]. Fishing vessels can use this service to deposit the waste FGs for a fixed fee, thereby reducing the illegal dumping of waste FGs on land or in the oceans.
	Ocean and beach clean-up operations	Organised initiatives to collect ALDFG from the ocean and from the beaches to remove plastic pollution. Examples of such systems are FFL and the annual clean-up operation from the Norwegian Directorate of Fisheries. In Norway, beach cleaning operations are conducted by Hold Norge Rent (Keep Norway Beautiful).
	Awareness-raising measures	Public and stakeholder involvement initiatives to create awareness about the marine litter problem and the effects of ALDFG. These ensure public ownership of the problem and build public support for regulation. Training workshops for fishers to

Areas of Improvement	Suggested strategies	Description
		learn the best handling and management practices for FGs can also aid in curbing FG losses.
	Reward schemes	Reward schemes for fishers to deposit their own EOL FGs and lost FGs retrieved during fishing operations.
End-of-Life Phase (Closing the loop for plastics from FGs)	Landfill tax	These increase the price of landfill waste to encourage other forms of treatment (such as recovery, recycling or reuse) that are higher up in the waste treatment hierarchy. These landfill taxes not only cover the costs of a landfill's operation and maintenance but also offer an incentive to reduce the amount of landfilled waste [98].
	FG product design for recycling	The mix of polymers in the manufacturing of FGs along with metal components makes them challenging to recycle. FGs should be designed with homogeneous material to improve recycling efficiency.
	Opportunities for industrial symbiosis	Mechanical and chemical recycling methods are available to recover PA, PP and PE from waste FGs. These recovered polymers can be fed into relevant sectors as a replacement to virgin polymers to create the business case of closed-loop solutions.
	Capacity building to improve recycling	WMFs that handle FG waste must be well informed and properly equipped to segregate and sort the gear, to improve the percentage of recycling in the recycling facility.

6.2 Realising a Circular Economy: Challenges and Opportunities

The MCDA results clearly show that regional recycling (inland) is the most sustainable alternative for dealing with FG waste from a Norwegian perspective. However, to date, there have been very few attempts in Norway to recycle plastics from EOL FGs and ropes at the industrial scale. Interaction with stakeholders through semi-structured interviews during data collection rounds revealed numerous techno-political factors hindering the growth of the recycling industry in the region, which are presented in **Table 3** and elaborated on here. Realising the goals of the 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 creating opportunities for establishing CBMs.

Raw Material Availability

Norway is the EU leader in both aquaculture and capture fishery [99], making it a key player in generating waste from these sectors. An estimated 4,000 tons of waste plastic is created annually from commercial fishing practices alone in the region. Apart from commercial fishing, leisure fishing and aquaculture 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.

Supply chain

Supply chains aimed at transporting EOL FG waste fractions to recycling industries in Norway are immature or non-existent. By contrast, several organised collectors operate within the region to segregate and transport recyclable EOL FG fractions out of Norway. The lack of a reliable supply network is listed as one of the main reasons preventing the establishment of CBMs or EIPs between plastic recyclers and manufacturers in the region [100]. A harmonised network of actors responsible for the collection, segregation and transportation of waste FGs within the region would significantly increase and promote local recycling.

Table 3: Key factors for realising 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

Recycling technology

The feasibility, availability and sustainability of mechanical recycling of waste plastic polymers (PP, PE and nylon) are well documented in the literature [101, 102]. While suitable technology is available, there are only a limited number of recyclers dealing with fishery-related waste in Norway. The interview with recyclers confirmed the deficit in 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 material. The lack of local recycling capacity was reflected in the assessment of criteria S4 where recycling inland remains the only alternative that cannot handle 4,000 tons/year of waste plastics.

Ease of recycling

Typically, discarded FGs and ropes are laden with rotten biomass, fish oil and dirt [17]. Most WMCs in the region lack the technical expertise to clean and segregate waste FGs, making it difficult for recyclers to recycle it economically. Furthermore, the netting of FGs is commonly made of three plastic polymers: PP, PE and nylon. Among the three polymers, nylon best retains its properties after recycling, providing maximum economic benefits, while the other two show 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, metal wires in ropes require their own separation processes to avoid wear and tear of the mechanical recycling unit. Different materials, the lack of adequate cleaning methods and intricate gear design make waste FGs one of the most difficult types of waste to recycle.

Policy Drivers

The dedicated EU strategy on CE underlines the need for collaboration between industry and governments to address the marine plastic pollution [103]. However, interaction with local recyclers and waste collectors revealed the ambiguity in Norway's waste regulation policies that allows plastic waste to be landfilled. Chapter 9 of the waste regulation miljødepartementet [104] states that '9.6. All waste must be treated before landfilling, and landfilling is allowed if the processing and treatment of waste fraction are socio-economically non-viable.' Local stakeholders identified two key factors that result in a preference for landfilling over recycling or incineration: transport and processing costs for the waste FGs and ropes. The processing cost of the plastics from discarded FGs and ropes is higher than the landfill and heat recovery fee. 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.

Awareness

The stakeholder interaction confirmed growing awareness among regional and coastal communities regarding the detrimental effects of ALDFG, already identified by Jacob [88] and Falk-Andersson and

Berkhout [105] who provided the status of community involvement in beach clean-up operations in Norway. There is, however, the need to raise awareness about 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 a lack of local recycling capacity in the region. Social awareness and the creation of economic value from obsolete FGs are listed among the key strategies useful in curbing the problem of abandonment of waste FGs in the region [17].

Market Economy

Mechanical recycling results in the production of HDPE and LDPE polymers. The successful use of these polymers in injection-moulding technology has been demonstrated by various plastic industries in the Nordic region. In Norway, pilot testing is underway to confirm the quality and properties of recycled material when replacing virgin polymers in the production of fish farming brackets and walkways [100]. Success in the pilot tests could result in the development of a CBM, in which product-to-product recycling is realised. The underlying driver for regional plastic industries to replace virgin polymers is to reduce dependence on material suppliers and thereby increase the flexibility of their supply chain. Furthermore, Vildåsen [100] 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 its current conservative practices to a more circular approach. Such a transformation demands the establishment of robust supply chains among the waste collectors, recyclers, plastic manufacturers and consumers at the regional and global levels. Instituting such an eco-industrial network between the fishing and plastic industries demands an assurance of the quality and quantity of recycled polymers, agreement among consumers to raise the demand for the use of environmentally friendly products, and the support of regional policies. Stabilising all the factors may improve the market acceptance of products with recycled polymers and may result in elevated demand for such products.

7 Discussion, Conclusions and Future Work

"Knowing is not enough; we must apply. Willing is not enough; we must do." ***J. W. von Goethe***

This thesis explored the application of an SE framework for the case of the Norwegian commercial fishery sector, intending to develop strategies for the sustainable handling and lifecycle management of FG resources. Here a brief description is provided on the research contribution, reflections on the research process, limitations and applicability of the conducted research. Additionally, this chapter provides brief thoughts on future work.

7.1 Research Contribution

As a result of the transdisciplinary research methods used in this research, the outcomes, too, contribute to the transdisciplinary themes of resource management, sustainability assessment, SE and stakeholder theory. The contributions are elaborated here in more detail using the research questions posed for the Doctoral research work.

RQ1. Modelling FG system

Historically, the management of anthropogenic resources is done by studying the system lifecycle of the selected resource. To improve the system of FG resources, therefore, flows within the industrial system, as well as interactions with the natural system, must be modelled, analysed and evaluated. The motivation for studying the FG resource system is to develop improvement strategies that can help to mitigate environmental problems resulting from existing practices in the system across all lifecycle phases. The main issues to consider are:

1. Reducing impacts from ALDFG on the environment, communities, and economy.
2. Realising value creation and circular business opportunities from better waste management and recycling practices.

In this thesis, the lifecycle processes were mapped through rounds of consultation with relevant stakeholders in the region. With no background in commercial fishing, this exercise led to a holistic understanding of commercial FGs, their types, applications and modes of operation. Incineration, landfill or recycle/reuse are among the typical EOL pathways for many anthropogenic resources. However, FGs present additional EOL scenarios, including being abandoned, lost or discarded on land or in water. If not recovered, these pathways cause the accumulation of ALDFG on land or in water contributing to the more complex problem of ghost fishing or marine litter. Consequently, the need for better management of FG resources was reaffirmed while mapping the lifecycle processes of FGs.

Paper 1 presents the lifecycle processes of the FG system, while **Paper 3** presents the MFA model of plastic flows from FG resources.

RQ2. Scientific Information for System Performance Analysis

Scientific information is the backbone of any resource management strategy. Information on three critical factors is considered essential in analysing the performance of the FG resource system.

1. Composition of the commercial fishing fleet and stakeholders.
2. Sources, sinks and flows of resources throughout the system lifecycle of commercial FGs.
3. EOL handling and management of FGs.

After finalising the lifecycle processes for FGs, MFA was used to analyse the system lifecycle sources, flows and sinks of plastics from commercial FGs in Norway. Plastic (PP, PE and nylon) is a significant building block of commercial FGs and also listed as one of the most troublesome fractions of ALDFG, causing ghost fishing. Hence, in managing FGs, a specific focus was placed on plastics.

In the terminology of resource management, 'information' refers to the real knowledge about stocks, flows and processes within the resource system, as well as about the human-environment interactions affecting the system. In typical MFA studies, information on flow quantities of the selected material is obtained through literature, government or industrial statistical records, and other scientific literature on the selected material. In the case of FGs, the collection of information proved most challenging due to the lack of information on all the process flows. Highly segregated, generally outdated, non-uniform and unscientific estimates of FG lifecycle phases resulted in an overall absence of the information necessary to conduct MFA on FGs. In natural resource management studies, resource users are acknowledged as a vital source for generating scientific information. In fisheries management studies, fishers' knowledge was successfully applied to study fish species, habitats and catch patterns, and to understand the impacts of fishing methods and equipment. This thesis explored the previously unexplored part of fishers' knowledge of the handling and use of FGs. **Paper 2** presents the methodology used to extract both qualitative and quantitative information on purchase, repair, gear loss and disposal rates of commercial FGs. Additionally, information on FG material composition, sale and disposal was obtained through gear manufacturers and suppliers, repair facilities, and waste collectors and managers across the region. The data on waste FGs retrieved through ocean and beach cleaning operations was obtained through the agencies responsible for such clean-up operations.

All the collected qualitative and quantitative data is used to estimate the annual lifecycle flow of plastics from commercial FGs in Norway. The MFA model presented in **Paper 3** provides the first estimate of regional plastic flows from the fishing sector of Norway. In a global estimate of plastics in the ocean, Jambeck and Geyer [24] identified missing information from plastic flows from the fishing sector. Therefore, the results presented in **Paper 3** act as valuable regional information for the better management of plastics from FGs.

System analysis is followed by system improvement. The MFA results provide the current state of the system and thereby highlight the potential hotspots in need of improvement. The overall goal of this thesis is to assess the sustainability of EOL management of FGs in the Norwegian commercial fishing sector. Therefore the information on current handling and management of EOL plastics from derelict FGs was inspected using MCDA. The data was collected from FG collectors, waste managers and recyclers within the region to assess the environmental, social and economic impact of current EOL alternatives for managing waste FGs. Interaction with expert stakeholders also aided in finding potential opportunities and barriers to realising business-scale circular strategies for managing FGs (**Paper 4**).

RQ3. SE framework and the relevance of selected research methods

The science of resource management demands a transdisciplinary approach to studying complex socio-economic systems. Historically, two approaches were used for resource management: a *systems approach* of adaptive management or a more *people-oriented approach* of managing resources with the help of resource users. In this thesis, mixed methods were used to couple both the systems approach and the people-oriented approach, by including the local ecological knowledge of resource users in determining the sustainable management strategies for FG resources. A systems approach is useful as it replaces the notion of resources as discrete entities in isolation from the rest of the ecosystem and social system. In this thesis, SE was used as a backbone for structuring the problem. SE deals with analysis and design, operation and maintenance of large integrated systems in a total lifecycle perspective [26], and helps to maintain the scope and boundaries of a multidisciplinary research problem.

To identify the current state of the FG system, MFA was selected among the other methods from the IE toolbox. Static MFA studies have been used for the regional resource management of selected materials. In this thesis, MFA was particularly relevant due to the overall lack of information on FG lifecycle processes. Notably, information on the operation phase was missing in the literature. Therefore, a questionnaire-based survey and semi-structured interviews were used to collect relevant information from stakeholders. The people-oriented approach relies on extracting the knowledge of resource users and, accordingly, in this thesis a questionnaire was developed together with the fishery experts (Fishers Association), FG manufacturers, environment and resources consultants and researchers in marine and fishery sciences. Expert opinion was used to evaluate the language, structure and clarity of the designed questionnaire for fishers.

After establishing the current status of FG management, MCDA was used to assess the environmental, economic and social impacts of existing EOL management alternatives in the region. The screening LCA was used to evaluate environmental impacts, whereas raw data from recyclers and waste managers were used to calculate economic impacts. Structured and semi-structured interviews with stakeholders were used to select assessment criteria, evaluate social impacts and to further identify potential mechanisms to improve sustainable aspects of EOL FG management.

RQ4. Sustainability Assessment of Circular Economy Strategies in EOL Management of FGs

As shown in **Figure 1**, sustainability and the CE are global socio-political factors controlling the system. In the EU, the principles of CE have been seen as essential measures to mitigate the impact of plastic waste and safeguard its sustainable management. On the 16th of January 2018, the EC adopted the 'European strategy for plastics in a circular economy', which recognises plastics as a significant source of marine litter and advocates improvements in the recycling of waste plastics. Many strategies fall under the overarching umbrella of CE, namely, reduce, repair, repurpose and remanufacture, to list a few. Here the focus is on recycling to mimic the reality, while strategies for the sustainable lifecycle management of FGs were suggested following the overall CE umbrella framework.

In studying the state of the FG system, two different recycling scenarios can be seen, separated by the location of recycling. In **Paper 4**, MCDA is used to assess the environmental, economic and social impacts of the two recycling alternatives along with landfilling and the incineration of waste FGs. The MCDA method was modified to include the opinion of relevant expert stakeholders within the region. Preferences from stakeholders were used to select and weigh the criteria for assessing sustainability in selected EOL alternatives.

MCDA provides a robust framework for ensuring the representation of all the dimensions of sustainability in assessing the alternatives. The MAVT method allows the use of qualitative and quantitative information in the final assessment of alternatives. This feature of MAVT provides flexibility in criteria selection and thereby promotes the holistic assessment of sustainability. The results show that although recycling is promoted within the EU region, the location of recycling and its ability to create eco-industrial partnerships within the system are critical factors in maximising the positive effects of sustainability. **Paper 4** presents a detailed sustainability assessment of EOL alternatives for FG management and further provides a critique of system improvements for realising CE strategies.

RQ5. Barriers and Opportunities in Realising CE

The MFA model presented in **Paper 3** estimates that 4,000 tons of waste plastics are collected annually at waste companies in Norway from commercial fishing alone. Interaction with regional and local waste managers, collectors and recyclers established that waste FGs could be recycled at the industrial scale using mechanical recycling technology. The mechanical recycling of plastics from EOL FGs results in the production of HDPE and LDPE polymers, the effective use of which has been demonstrated in injection-moulding technology by various plastic industries in the Nordic region. The availability of recyclable waste, technology and the possibility of reusing recycled material as a replacement for virgin polymers in injection-moulding technology presents important opportunities for achieving closed-loop networks for waste plastics from FGs.

Interaction with industrial stakeholders made clear the possibility of replacing virgin polymers in the production of fish farming brackets and walkways used in the aquaculture sector with recycled polymers from the fishing sector. Currently, plastic producers in the region are exploring these opportunities through pilot projects and physical tests on recycled polymers. If successful, this endeavour may provide the prospect of establishing a closed-loop supply chain or eco-industrial network among the fishing and aquaculture sectors of Norway, where waste from fishing can act as a raw material for the aquaculture sector.

Although there are strong synergies that help to create an eco-industrial network for plastic, realising these opportunities demand infrastructural change, socio-political support and inputs from research to make FG recycling more efficient and cost-effective. Intricate gear design, a dearth of technical expertise at waste management companies to segregate and clean waste FGs, lack of synergy among waste collectors and recyclers, and an unfavourable market economy are among the significant local barriers in closing the loop for EOL plastics from FGs.

Several challenges and socio-political factors hindering the realisation of business-scale closed-loop solutions are discussed extensively in **Paper 4**.

7.2 Reflection on the Research Process

SE was used in this thesis to scope and structure of the research case. In retrospect, it appears that SE was useful and effective in scoping the elements of the research structure. However, the full potential of the six-step SE model was not utilised as Step 6 of the proposed model was out of the scope of this thesis. Step 6 demands the implementation and testing of improvement strategies, which is controlled by the governing (regulatory) actors in the system.

Additionally, for addressing the overall research goal, necessary scientific information was either segregated, outdated or absent. This lack of information on FG system lifecycle processes and flows demanded the use of MFA. However, conducting MFA on FGs was challenging owing to significant variation in all of the six selected FGs. All the quantitative and qualitative information was obtained through several rounds of face-to-face or telephone interactions with stakeholders in the region. The data collection took almost 20 months, followed by verification of results through the stakeholders. Verification proved to be a critical step as converting all of the information to a uniform quantitative form resulted in uncertainties. Through verification, the uncertainties were minimised and robust results communicated.

Dealing with stakeholders, and especially fishers, was a distinctive experience. As a primary resource user, fishers possess an abundant source of information, but extracting that information for scientific purposes was challenging. While designing the questionnaire, an emphasis was given on constructing lucid, concise and apt questions in the local language (Norwegian) with the help of the *Fishers Association* in Trondheim and the *Institute of Marine Research* in Bergen to avoid ambiguity in the questions. The face-to-face survey method was used to minimise confusion in the survey responses. However, uncertainty in survey responses can be attributed to responders speculating while answering specific questions where they lack knowledge. In the present study, the aim was to capture the annual repair, loss and disposal patterns of FGs. Therefore, survey questions required fishers to summarise the past 10 to 20 years of fishing practices, which could lead to memory bias and unavoidable subjectivity. Additionally, statistical variations in responses from fishers are due to differences in fishing practices, target species, fishing grounds (coastal or deep-water), fishing quotas and experience, among other things. The dependence of this MFA on survey results came from the lack of data on fishing practices, which highlights the need for improved monitoring of the Norwegian fishing fleet.

Finally, MCDA was adopted in this thesis to assess sustainability in EOL management alternatives for plastics from the fishing sector in Norway. The MAVT approach was particularly suitable for answering the research questions as it reduces the limitations of unstructured individual interviews and provides a platform for involving focused group discussions that lead to transparency in assessing weights and scores. Aligning the assessment criteria to SDGs aided the active communication with engaged stakeholders as SDGs provided a common language to translate complex sustainability principles into assessment criteria. The MAVT method is characterised by some limitations, as it uses experts' judgement in ranking the alternatives against the assessment criteria. Also, MAVT is widely used in the qualitative performance assessment of alternatives, causing apparent subjectivity.

In retrospect, the contributions arising from this thesis were only possible due to the engagement and support of various stakeholders in the region. Hence, although subjective and uncertain, the results presented in this study were able to generate valuable evidence on the management of a resource system that was previously considered subject to mismanagement due to a lack of scientific knowledge.

7.3 Practical Applications

The results presented in this thesis are characterised by multilevel stakeholder involvement; hence, the findings are of direct relevance for improving the FG system in the region. The findings from the MFA uncovered the state of plastic waste management from commercial fishing practices in Norway. The static

MFA shows that, irrespective of local land and ocean clean-up efforts, an estimated 300 tons of plastic accumulates annually as ALDFG in the ocean ecosystem from the commercial fishing alone. Furthermore, the model reports that in 2017, around 55% of collected waste FGs are sent out of Norway for further recycling due to the absence of industrial recycling facilities. Therefore, with the background of EU policies on the CE and the recent Chinese ban on the import of plastic waste, the findings presented here show the need to establish the infrastructure to promote regional recycling and eco-industrial partnerships.

Furthermore, the MFA findings are already becoming a critical science and technology input for the Environmental and the Fishery Authorities of Norway, aiding the formulation of policies to monitor and minimise plastic pollution from the commercial fishing sector. The results also contributed to the feasibility assessment study conducted by Sundt [94] for the Environmental Directorate on the EPR strategy for commercial fisheries in Norway. Additionally, the results are likely to create a future paradigm for monitoring and implementing the new *European Strategy for Plastics* and *Port Reception Facilities* directives (2018/012 COD). The reported annual quantities of plastic waste collected in the EOL stage are considered vital evidence for regional recyclers and waste managers that aim at closing the material loop from FG resources in Norway.

Lastly, the stepwise SE framework presented here uses the principles of natural resource management for the sustainable management of anthropogenic resources. The adapted SE framework is transferable, especially in the cases of data-less or data-limited resource management. However, it is essential to apply it in another context with local adaptations to validate its robustness.

7.4 Future Work

This thesis adopted and demonstrated the use of the SE model for assessing the sustainability of the lifecycle management of commercial FGs deployed by the Norwegian fishing fleet. The thesis provides estimates for plastic flows from the fishing sector, and as plastics in the ocean are a transboundary problem, the results from this study can prove a starting point for both regional and global studies. The immediate focus, however, should be placed on:

1) Development of multi-regional (EU-EEA) and global rates of FGs loss in the ocean. Building global rates of gear loss will further aid in establishing regional and global estimates for plastic flows from the fishing sector.
2) Development of a framework to assess toxicity, risk and environmental impacts of plastics in the marine ecosystem.
3) Development of predictive models to map the movement of ALDFG through ocean currents and gyres to aid effective retrieval operations.
4) Exploring innovative solutions to ‘recycle, reuse, repair and reduce’ the marine plastic waste from industrial sources.

5) In-depth cost-efficiency analysis of suggested improvement strategies to assess their economic feasibility. This exercise is essential in realising sustainable CBM in the region and may aid the development of eco-industrial networks.

As for all case study research, some of the findings are general and applicable elsewhere, whereas others are more specific and need contextual interventions before adopting them. Therefore, while it is essential to generate evidence on plastics from other regions, understanding local fishing practices and engaging local resource users are highly recommended to avoid misinterpretation.

Additionally, as shown in **Figure 2**, this thesis work addresses the first five steps of the six-step SE model. The last step of the model deals with verifying and testing the suggested management strategies. This step needs the political will to transfer scientific findings into policy instruments aimed at systemic improvements for FGs in the region. Furthermore, effective performance monitoring is necessary while implementing the policy instruments and proposed strategies. This step is essential in highlighting the shortcomings of selected management alternatives and may aid in further improvement in the FG system.

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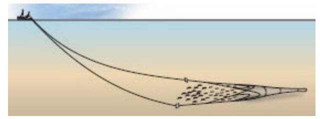
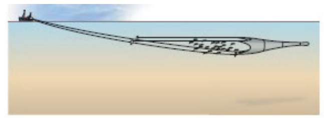
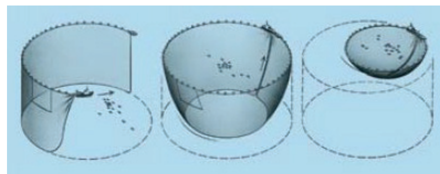
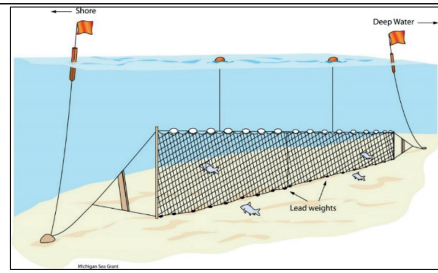
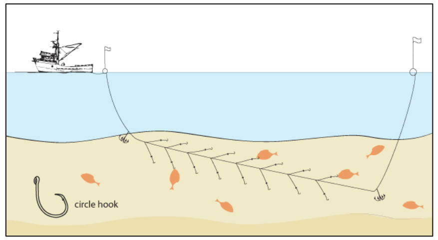
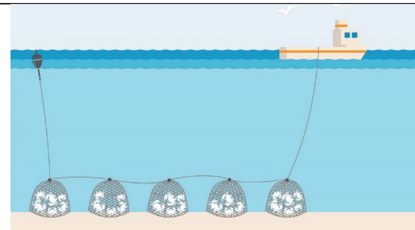
Appendix A

Description of Commercial Fishing Gears (FGs)

Table A1: Description of fishing gears (FGs) commonly deployed by commercial fishing companies in Norway.

Nr.	FG type	Description	Target species	Schematic Diagram
1	Trawls	A trawl is a tunnel-shaped fishing net that is towed through the water. The water strains out through the mesh entrapping the fish and retaining them in the cod-end of the trawl. The shape and size of the trawl vary significantly based on fish behavior, seabed conditions, selection devices (grating and mesh selection), and the vessel's power (Fisheries, 2010). Trawling is that fishing method and suitable for both smaller to larger fishing boats. Trawls are typically classified into two categories, bottom-trawls and pelagic or mid-water trawls. Bottom trawls are used to tow the fish species along the seabed, whereas; pelagic trawls are deployed to catch the fishes from the mid-water column (Oxvig, 2007).	Bottom Trawls: Cod, haddock, saithe, shrimp (Norwegian economic zone), blue whiting, Norway pout, and sandeel (North Sea) Mid-water Trawls: herring, mackerel, blue whiting, greater argentine, and capelin (Fisheries, 2010)	 Bottom Trawl[1]  Pelagic/Mid-water Trawls[1]
2	Seines	The Seine is an active fishing method which shares many of the characteristics of trawling, but which does not employ trawl doors. The two main types of Seines are *Danish* and *Purse Seines*. In Norway, fishers use the Scottish method of fishing using Danish Seines (Fisheries, 2010). Seine Fishing in Norway usually takes place in the North of Norway. The fishing takes place by launching a buoy then the vessel drives out a rope and launches the seine before the last piece of rope (arm) is set. Once the seine has been set, the buoy is taken on board, and the hauling commences, while the vessel retains its position using engine power. The modern purse seine vessels are amongst the most polyvalent fishing vessels today in Norway. Purse seines are massive fishing tools that are laid out in a large circle around a shoal of fish. The electronic equipment located on the fishing vessel generally locates the fish shoal. The Purse seine, actively surround the fish shoal and trap them inside (Oxvig, 2007).	Herring, mackerel, capelin, sandeel, Norwegian pout	 The Danish Seine[2]  Purse seine[1]

[1] **Source**: OXVIG, U. A. H., JES ULRIK 2007. *Fishing Gears,* Denmark, The Fisheries Circle.
[2] AS, U. 2015. Danish Seine nets. *In:* NETS, D. S. (ed.). Unimar AS.

Nr.	FG type	Description	Target species	Schematic Diagram
3	Gillnets	A gillnet is a large net wall that hangs vertically in the water. Floats line the top of the net, while weights line the bottom. The net is made of a thin monofilament line, so fish are unable to see it. Fishers vary the mesh size depending on the size of the species they want to capture. The mesh size is designed to be large enough for the head of the fish to pass through, but not his body. If the gillnet is suspended in the top or mid-depths of the water column, it is a mid-water gillnet or a drift gillnet. If it is set on the bottom of the ocean floor, it is a bottom gillnet (Fisheries, 2010).	Cod, saithe, Greenland halibut, redfish, ling, and monkfish	 Set Gillnets[3]
4	Longlines	Longlines are fished within both open-ocean and near coasts and can be set at any depth by using a combination of floats and weights. If the longline is suspended in the top or mid-depths, it is a pelagic longline. If it is near the ocean floor, it is a bottom longline. A line is a length of rope (mainline) onto which hooks are attached at regular intervals. The rope or line attaching the hook to the mainline is called a snood. A row of lines, also called stub, is set up in the same way as a chain of gillnets. The length of the stub varies according to fish concentrations, seabed conditions, and the fishing area (ocean vs. coastal). The line was trailing behind the vessel and hauled in using a mechanical jig (Fisheries, 2010).	Cod, haddock, Greenland halibut, ling, tusk and catfish	 Longlines[3]
5	Traps or Pots	Stationary traps, or pots, typically made from wood, wire netting, or plastic, are used to catch crustaceans such as lobsters and crabs. Though the size and shape of traps may vary, all feature a cone-shaped entrance tunnel allowing fish to enter but preventing them from moving back. Traps are usually deployed in the series by fishers. Typically traps are used in shallow water to capture eel, prawns, crabs, lobsters (Muus and Nielsen, 1999).	Eel, prawns, crabs, and lobsters	 Traps and Pots[4]

[3] FISHERIES, D. O. 2010. Description of Relevant Fishing Gear and Fishery Activities in the Norwegian Economic Zone. Norway: Directorate of Fisheries, Norway.
[4] MSC 2018. Pots and traps. *In:* TRAPS, P. A. (ed.). Marine Stewardship Council (MSC).

Appendix B

Description of Relevant Regulatory Framework (International, Regional and National) for Commercial Fishing Gears

Table B1: Summary of relevant legislative instruments governing Fishing Gear Resource System at International, regional, and national levels.

Scope	Legislative Instrument and Governing body and Year	Brief Description	Compliance Level M: Mandatory O: Optional
International	UN Convention on the Law of the Sea (UNCLOS)	The UNCLOS is the international agreement that defines the rights and responsibilities of nations concerning their world's oceans. The agreement establishes guidelines for geopolitics, commercial activities, the environment, and the management of marine resources. The provisions do not specifically refer to marine litter, but they require that states protect and preserve the marine environment.	M
	MARPOL 73/78, Annex V	Annex V of MARPOL 73/78 is a primary international instrument that addresses explicitly ocean-based litter from ships. Annex V provides an updated framework for controlling garbage generated by ships. It imposes a general ban on all garbage dumping from ships at sea unless expressly noted. Also, it requires that ships provide a garbage record book and that port reception facilities handle waste from ships without delay.	M
	London Protocol	The London Protocol is an instrument that prohibits the dumping of industrial waste and other substances from human-made structures (ships, etc.). The participating parties also are required to implement measures that prevent, reduce and eliminate contamination by dumping (where possible).	M
	Sustainable Development Goals (SDGs) /UN/2015	SDG 14 of the 17 sustainable goals launched by the UN in 2015 focuses specifically on "Life below water." Target 14.1 of the Sustainable Development Goals (SDG): "by 2025, prevent and significantly reduce marine pollution of all kinds. Other goals advocate the sustainable production and consumption of products, resource efficiency, and reduction of carbon footprints.	O
Regional	EU Port Reception Facility (PRF) Directive/EU/2002& 2018	The PRF Directive was created in response to MARPOL's requirement for member states' ports to provide incoming vessels with adequate waste reception facilities. This PRF Directive requires advance notification of a vessel's waste deposit. It also outlines guidelines for reporting systems, cost-recovery fee systems, and enforcement schemes. The new, updated PRF Directive was launched in 2018	M

		where the EU mandates necessity of PRF at every port of EU-EEA states. (EC, 2018a)	
	OSPAR	OSPAR fits into the UNEP Regional Sea Program and is a mechanism that legally requires cooperation among member states to protect the marine environment of the Northeast Atlantic region. OSPAR aims to harmonize PRFs and fee systems, implement “fishing for litter” projects, harmonize enforcement schemes, and identify essential waste items from the fishing industry and aquaculture.	M
	EU marine strategy framework directive	The Marine Directive aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020. Indicators that define GES include characteristics of litter and impacts of litter on marine life. It incorporates work by the Technical Subgroup on Marine Litter (TSG ML)	
	Bonn Agreement	In the convention's preamble, that they state that they aim "to ensure good order and conduct on the fishing grounds in the North Atlantic Area." The convention covers rules for gear marking.	M
	Global Partnership on Marine Litter (GPML)	The Bonn Agreement is a mechanism designed for the North Sea States and EU to work together in fighting marine litter in the North Sea Area. Its policies are focused mainly on preventing maritime disasters and chronic pollution from ships/offshore platforms.	O
	The Marine Group (HAV) within the Nordic Council of Ministers (NCM)	(builds on Honolulu Strategy) Voluntary multi-stakeholder coordination mechanism, which all agree to work together to reduce further and better manage marine litter. Mainly focused on land-based activities.	O
	Convention on Conduct and Fishing Operations in the North Atlantic	Since 2013, HAV has prioritized environmental aspects of marine litter in Nordic waters with projects including plastic loading in Northern Fulmars, marine litter, and its sources in Nordic waters.	
	UNEP's Regional Sea Programme (RSP)/ UNEP / 2003	The Regional Sea Programme developed a Global Initiative on Marine Litter to organize and implement regional activities for addressing marine litter in 12 regional seas. These activities include: assessing marine litter, preparing a regional management plan for marine litter, organizing beach clean-ups, and meeting/collaborating with national authorities to address marine litter.	O

	Honolulu Strategy	The Honolulu Strategy was formulated at the Fifth International Marine Debris Conference in 2011. The framework has three goals and 19 strategies that serve as a practical reference for national parties. The three goals include: 1. reduce land-based litter 2. Reduce sea-based litter including ALDFG and 3. Reduce the impact of marine debris	O
	EU Strategy for Plastics in Circular Economy	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, 2018b). In the elaborated action plan, additional action on plastics from fishing gears (FGs) and aquaculture were stressed owing to the hazardous nature of abandoned, lost, or discarded fishing gears (ALDFG) and an increase in commercial fishing activity in the EU waters (EC, 2018c).	O
National	Norway's Marine Resources Act (6/6/2008)	Norway's Pollution Control Act has been modified to enforce the regulations required by the PRF Directive into Norwegian Law. It outlines guidelines for the delivery and reception of waste and cargo residues from ships calling port	M
	Norway's Pollution Control Act	Discharge from ships are regulated nationally by environmental safety laws	M
	Norway's Maritime Safety Act	Prohibits dumping of gear, moorings, and other objects in the sea that may injure marine organisms, impede harvesting, or damage gear. Any person that loses a net must attempt to remove the object from the sea. If this is not possible, this loss must be reported to authorities. Any person that salvages gear is entitled to reward. It also addresses gear marking.	M
	Norway's Waste Regulation	Waste regulation provides the guidelines on handling and management of waste within the region. The regulation promotes recycling and energy recovery, and loads of waste to landfills are regulated.	M

EC 2018a. DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on port reception facilities for the delivery of waste from ships, repealing Directive 2000/59/EC and amending Directive 2009/16/EC and Directive 2010/65/EU. Strasbourg: European Commission, Directorate-General for Mobility and Transport.

EC 2018b. A European Strategy for Plastics in a Circular Economy.

EC 2018c. Imapct Asscessment Report on Reducing Marine Litter: action on single use plastics and fishing gear. European Comission.

Appendix C

List of Selected Papers

Paper-1: A Framework to Conceptualize Sustainable Development Goals for Fishing Gear Resource Management.

Paper-2: Method Article: A method to extract fishers' knowledge (FK) to generate evidence for sustainable management of fishing gears.

Paper-3: Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway.

Paper-4: Application of multi-criteria decision analysis (MCDA) to assess sustainability in end-of-life alternatives for waste plastics from the fishing sector in Norway.

Paper 1

Deshpande, P. C., & Aspen, D. M. (2018). A framework to conceptualize sustainable development goals for fishing gear resource management. In *Handbook of Sustainability Science and Research* (pp. 727-744). Springer, Cham.

(DOI: https://doi.org/10.1007/978-3-319-63007-6_45)

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available at https://doi.org/10.1007/978-3-319-63007-6_45

Paper 2

Deshpande, P. C., Brattebø, H., & Fet, A. M. (2019). A method to extract fishers' knowledge (FK) to generate evidence for sustainable management of fishing gears. *MethodsX*, *6*, 1044-1053.
(DOI: https://doi.org/10.1016/j.mex.2019.05.008

MethodsX 6 (2019) 1044–1053

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Method Article

A method to extract fishers' knowledge (FK) to generate evidence for sustainable management of fishing gears

Paritosh C. Deshpande[a,*], Helge Brattebø[b], Annik Magerholm Fet[a]

[a] *Department of Industrial Economics and Technology Management, Norwegian University of Technology, NO-7491 Trondheim, Norway*
[b] *Department of Energy and Process Engineering, Industrial Ecology Programme, Norwegian University of Technology, NO-7491 Trondheim, Norway*

A B S T R A C T

The dangerous effects of Abandoned, Lost or Discarded Fishing Gears (ALDFG) is documented in the literature. However, there exists an overall lack of understanding in quantifying the pollution loads of fishing gears (FG) in territorial waters or on the beaches. The lack of data on FG life cycle results in mismanagement of one of the troublesome resources across the globe. In the remote and data-less situations, local stakeholders' knowledge remains the only source of information. Therefore, in this article, we propose:

- A methodology to extract fishers' knowledge (FK) for generating evidence on FG handling and management practices in Norway.
- The stepwise approach includes mapping of relevant stakeholders, drafting and finalizing a structured questionnaire using the Delphi method among experts to build the consensus and finally, statistically analyzing the recorded responses from the fishers.
- The questions are designed to extract both qualitative and quantitative information on purchase, repair, gear loss and disposal rates of commercial FGs.

The responses from 114 Norwegian fishers are recorded, analyzed and presented as a part of method validation.

The evidence from the survey is then used as an input to coin the regional FG handling and management strategies in Norway. The presented method is proven a robust strategy to retrieve scientific information from the local stakeholders' and can easily be replicated elsewhere to build global evidence around the ALDFG problematic.

Abbreviations: ALDFG, abandoned, lost and discarded fishing gears; FG, fishing gears; FK, fishers' knowledge; LEK, Local Ecological Knowledge; MFA, material flow analysis; MoP, Mass of Plastic.

* Corresponding author.
E-mail addresses: paritosh.deshpande@ntnu.no (P.C. Deshpande), helge.brattebo@ntnu.no (H. Brattebø), annik.fet@ntnu.no (A.M. Fet).

https://doi.org/10.1016/j.mex.2019.05.008

A R T I C L E I N F O
Method name: Design protocol of survey based questionnaire
Keywords: Fishers' knowledge, Survey, Fishing gears, Marine pollution, Resource management, Delphi method, Questionnaire
Article history: Received 18 March 2019; Accepted 6 May 2019; Available online 8 May 2019

Specifications Table

Subject Area:	*Environmental Science* *Social Sciences*
More specific subject area:	*Environmental monitoring, Resource management*
Method name:	*Design protocol of survey based questionnaire.*
Name and reference of original method:	The applied method in this study is a stepwise framework used to extract quantitative and qualitative information. The required information is collected from fishers through structured questionnaire designed using Delphi method. The article presents the modification of methods discussed in: Johannes, R. E., Freeman, M. M. R. & Hamilton, R. J. 2000. Ignore fishers' knowledge and miss the boat. *Fish and Fisheries,* 1, 257-271. Leite, M. C. F. & Gasalla, M. A. 2013. A method for assessing fishers' ecological knowledge as a practical tool for ecosystem-based fisheries management: Seeking consensus in Southeastern Brazil. *Fisheries Research,* 145, 43-53.
Resource availability:	One Supplementary Information file is provided with this manuscript: 1 SI-1: Sample survey questions (English version) used to conduct fishers survey.

Method details

Past two decades observed significant surge on adopting Local Ecological Knowledge (LEK) in the mainstream research areas of natural resource conservation and sustainable resource management. LEK refers to a body of knowledge accumulated over time and transformed into an individual's perception of the resource, which is then presented as the communities' collective knowledge [1]. It is often based on long-term observations of the local ecosystem considering local variations, behavioral patterns and focusing on essential resources/species of the concerned ecosystem [2]. Practical applications of LEK ranges from a variety of systems including, but not limited to, small-scale agriculture, horticulture, forestry and fisheries [3]. Johannes [4] and colleagues played a key role in establishing and documenting the use of LEK in the sector of fishery management through their work between 1980 and 2000. In his first documented study on applying fishers' knowledge (FK), Johannes [5] emphasized the variety and depth of information local fishers' possess on marine ecology and conservation, fish behavior/habitats, fishing practices, fishing gear types and other ecosystem concepts. Further, Johannes et al. [6] argued that by ignoring such readily available and inexpensive source of knowledge while studying the local system, humanity runs the danger of "missing the boat" on fisheries sustainability. Although fishers possess a valuable source of information, integrating or translating that information to the science of resource management demands creativity in applying suitable scientific methods [3,7]. So far, application of FK was demonstrated to manage biodiversity and marine protected areas [5,8], studying fish species, habitats and catch patterns [9,10], fishery resource management [2,3,11] and to understand the impacts of fishing methods and equipment [12,13]. In this study, we present a stepwise method to extract FK on fishing gear (FG) use and handling practices in Norway.

In commercial fishing, FGs are one of the vital resources to fishers. Recent advancements in the gear design and technology allowed substantial growth in catch quantities in commercial fishery [14]. Improvements in gear design were initiated with the replacement of natural fibers such as jute, yarn, cotton with the synthetic fibers such as PP, PE, and Nylon. Although, unlike natural fibers, synthetic FGs are functionally resistant to degradation in the water, and, once discarded or lost, these gears may remain in the marine environment for decades as ghost FGs [30,15]. These ghost FG are considered as one of the deadliest fractions of marine waste with adverse impact on marine ecology and fishers economy [15–19], however, lack of quantitative information and evidence crippled the possibilities to make informed decisions on avoiding or minimizing the probabilities of gear loss upon deployment. Additionally, fraction of these lost nets drifts along the tidal currents and may end-up on the beaches or marshes causing land-pollution and pose entanglement risks to birds and marine animals. Furthermore, FGs lost in the ocean or on land is not only damaging to the environment but also a lost opportunity to recycle and reuse the resources.

To develop the management strategies for FG resources, it is essential to build the holistic understanding on typical life span, rates of gear loss, disposal, and repair patterns of commercial FGs. The stepwise framework proposed in this study is aimed at generating evidence to aid the sustainable management of FG resources in Norway.

Commercial fishery of Norway

Norway is a Northern European country surrounded by water to the south (Skagerak), the west (the North Sea and the Norwegian Sea), the north and north-east (the Barents Sea). With a marine resource-rich coastline of more than 25,000 km, Norway is the European leader regarding both capture fishery and aquaculture [20]. The capture fishery has always played a critical social and economic role, nationally and regionally, and has been the basis for settlement and employment along the entire Norwegian coast [14]. Commercial capture fishery sector is segmented into the coastal and ocean fishing fleet. The coastal fishing fleet comprises of smaller vessels manned by 1–5 fishers and size ranges from 10 to 20 meters. On the other hand, ocean fleet is known for its deep-water and sophisticated fishing practices, where fishing vessels are generally more than 28 m in size and crew members can vary from 20 persons or more [14,21]. In 2016, a total of 5946 vessels are registered in Norway out of which approximately 90% are coastal vessels, and the rest is ocean fishing fleets [21]. The primary capture species include herring, cod, capelin, mackerel, saithe, blue whiting, and haddock. A few additional species are caught in smaller quantities but have a high commercial value such as prawns, Greenland halibut, and ling. Fig. 1 shows the diversification of fishing fleet concerning the number of vessels, type of FGs they use.

Material and methods

Survey and questionnaire

Based on the literature on applications of FK in managing fishery resources, surveys in the form of questionnaire is considered to be an effective method to extract the information from local fishers [3,10,13,22–25]. Accordingly, a systematic questionnaire, comprised of both qualitative and quantitative questions, is designed using the Delphi Method to reach the consensus on language,

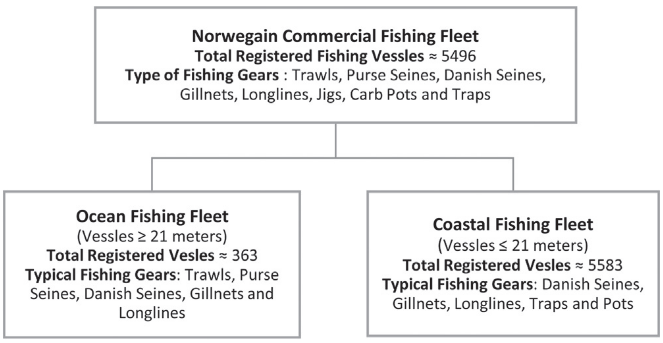

Fig. 1. Structure of commercial fishing fleet of Norway [21].

structure, and content of the questions. Delphi method involves applying rounds of consultations to a set of experts on a selected subject. After each round of consultation, the results of all the responses are summarized and presented individually to each participant. Participants can further change their opinion/views after the newly presented data and the similar rounds of consultation continues until one finds the consensus on the selected subject. The Delphi method is being practiced extensively in social sciences to find consensus, while a fundamental premise is the ability to maintain respondent anonymity throughout the process [23,26].

Fig. 2 shows the systematic stepwise approach and an application of a Delphi method. First, a system life cycle processes of FGs and relevant key stakeholders are identified and presented in Deshpande and Aspen [27]. In the third step, a structured draft of the questionnaire was created to extract information on the handling and management of FGs throughout their life cycle. Six FG types commonly used by the Norwegian commercial fishers are selected for the study namely, Trawls, Danish seines, purse seines, gillnets, longline and traps/pot. The experts in the field of the fishery (Fishers Association), FG manufacturers, environment and resources consultants and researchers in

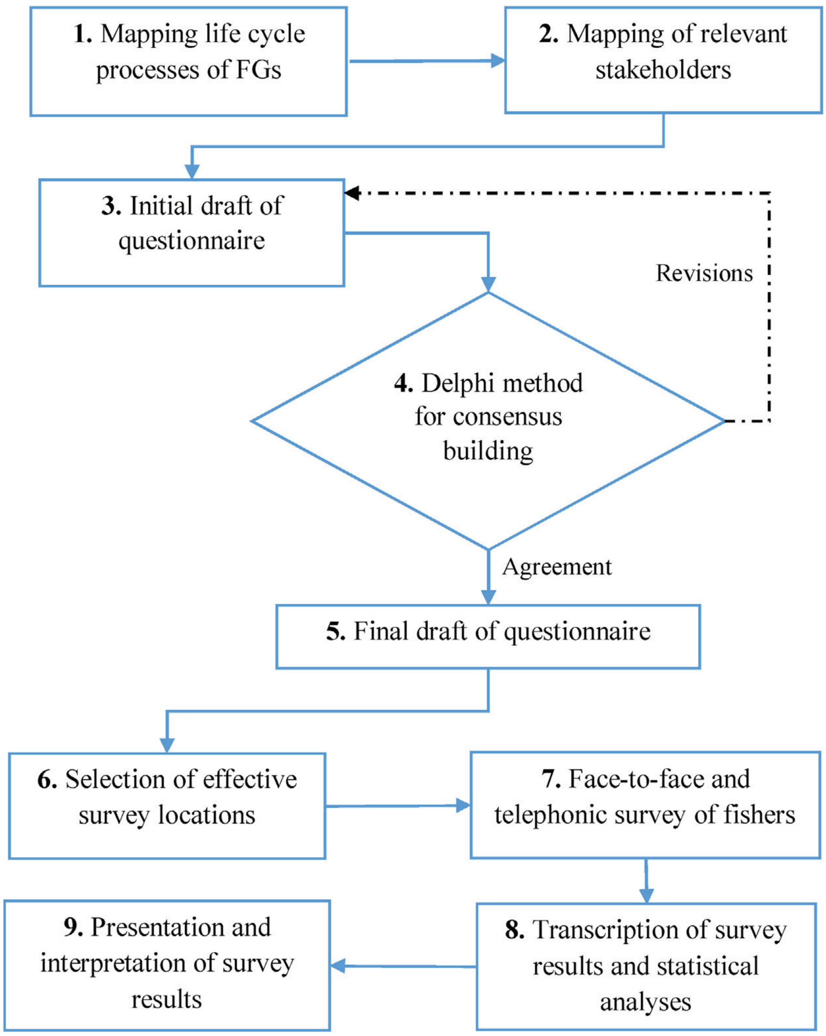

Fig. 2. Proposed stepwise methodology to extract fishers' knowledge using questionnaire.

marine and fishery sciences were contacted and were asked to evaluate and comment on the language, structure, and clarity of the designed questionnaire for fishers. The objective of the survey was to capture the pattern with which Norwegian fishers operate and manage FG types but also design a survey, quick to fill-up andcorrespondingto the fisher's experiences. The consensus was reached after two rounds of revisions as per the Delphi method and a set of 13-questions, consisting of both qualitative and quantitative questions, were finalized covering the following topics:

- Norwegian fishers and fishing vessels
- Selected FG types owned by a fishing company
- Annual purchase patterns for new FGs
- Annual repair pattern and frequency of FGs
- The typical lifespan of selected FGs
- The average annual rate of FG loss in the ocean
- Waste management of FGs

After finalizing the set of questions, survey sites were chosen to interact with fishers. The collected responses are then transported as excel sheets and transfer coefficients are calculated based on the developed formula. Finally, all the results are presented, and interpreted to build the evidence on FG life cycle. The final questionnaire used for data collection is given in the supplementary material.

Statistical analysis

To analyze the data quantitatively, the answers from survey responses were transcribed from the survey software, (e.g. SurveyMonkey), and distributed into answer groups. Quantitative data is treated to estimate the statistical inference, the sample mean, standard deviation and 95% confidence interval of the sample size. The rate of repair, a fraction of part replacement and typical life-span of FGs are estimated using basic statistical operations of a sample mean, standard deviation, and 95% confidence interval. Further, the transfer coefficients (TC) C_{stock}, C_{Lost} and $C_{Disposal}$ are calculated using the following formula.

1 C_{stock} represents the rate of an annual turnover of selected FGs for the sampled fishing companies in Norway. C_{stock} is a ratio of units of FGs available after the loss and disposal of FGs in a given year to the units of FGs purchased by a fishing company in a given year. Knowing the units/mass of FGs sold to the regional fishing fleet, this rate can be used to estimate total units/mass of selected FGs available at any point of time for a given region. In this study, we focused on estimating the mass of plastics (MoP) present in the stock of the Norwegian commercial fishing fleet.

$$C_{stock(a,b,c,d,e,f)} = \frac{\sum_{n=1}^{114} \left(\frac{FG_o - FG_L - FG_D}{FG_P} \right)_{(a,b,c,d,e,f)}}{N_{(a,b,c,d,e,f)}}$$

Where, a = Trawls, b = Purse Seine, c = Danish Seines, d = Gillnets, e = Longlines, f = Traps/pots
FG_O = Number of FGs owned by a fishing company
FG_L = Number of FGs lost annually by a fishing company
FG_D = Number of FGs disposed annually by a fishing company
FG_P = Number of FGs purchased annually by a fishing company
N = Total number of responses for each FG type

2 C_{Lost} represents the typical rate at which fishers lose their FGs in the ocean upon deployment in a given year and is calculated for each FG type as an average of the ratio of reported FGs lost by a fishing company to the total FGs owned by the fishing fleet.

$$C_{Lost\,(a,b,c,d,e,f)} = \frac{\sum_{n=1}^{114}\left[\frac{(FG_L)_n}{(FG_O)_n}\right]_{(a,b,c,d,e,f)}}{N_{(a,b,c,d,e,f)}}$$

Where, a = Trawls,b = Purse Seine, c = Danish Seines, d = Gillnets, e = Longlines, f = Traps/pots, N = Total sample size for respective FGs

3 Similarly, every year fishing companies dispose end-of-life FGs from their stock and deliver it to either waste management facility or at the ports. This annual rate of FGs disposed of by fishing company is calculated for each FG type as an average of the ratio of reported FGs disposed of by a fisher from their respective stocks of FGs by coastal and ocean fishers.

Typical annual rates of gear disposal upon end-of-life (%)

$$C_{Disp\,(a,b,c,d,e,f)} = \frac{\sum_{n=1}^{114}\left[\frac{(FG_D)_n}{(FG_O)_n}\right]_{(a,b,c,d,e,f)}}{N_{(a,b,c,d,e,f)}}$$

Where, a = Trawls, b = Purse Seine, c = Danish Seines, d = Gillnets, e = Longlines, f = Traps/pots, N = Total sample size for respective FGs

Method validation

The finalized questionnaire is then conducted among the commercial fishers in Norway to generate evidence on FG life cycle processes. The critical considerations while selecting the survey site, sample and mode of interaction with fishers are deliberated here to aid the effective implementation of the method and robust analysis of survey samples.

Study area

To avoid the bias and confusion in the responses, a face-to-face survey with fishers is preferred over an online questionnaire. Four, commercially important ports located on the west coast of Norway (Fig. 3) were chosen to interact with fishers. The selected sites namely, Bergen, Ålesund, Måløy, and Trondheim are home to both coastal and ocean fishing companies, FG suppliers and repair facilities. Moreover, these sites also host several fishery-related exhibitions, networking events and workshops for fishers, thereby, provides ample of opportunities to interact with fishers to conduct the desired questionnaire. To reach many fishers from diverse regions at the same time fishery-related exhibitions or conferences in the selected four study sites are targeted to conduct the questionnaire.

In total, 114 responses from fishers were collected in the span of 7-months from the selected sites. Fishers' annual meetings, fishing product related conferences and exhibitions were targeted for conducting the survey. The collected sample responses were further analyzed using statistical methods to extract relevant information.

Demographic and fishing characteristics of interviewed fishers

Commercial fishing practices vary with respect to demography, vessel size, target species and application of FGs. Therefore, it is essential to test the demographic characteristics of surveyed samples before analyzing the transfer coefficients. The response obtained from the questionnaire represents the well-distributed samples both regarding vessel size and the area of fishing activities. In total, 47% of the respondents belong to the coastal fishing fleet, and 53% represents a sophisticated and more massive ocean fishing fleet. Commercial fishing was the primary and full-time profession for most surveyed fishers, and this is consistent with the objectives of this study focusing on commercial fishing practices in Norway. Along the extensive coastlines of Norway, maximum commercial fishing takes place in northern, western and central parts of Norway, accordingly, the survey reflects more

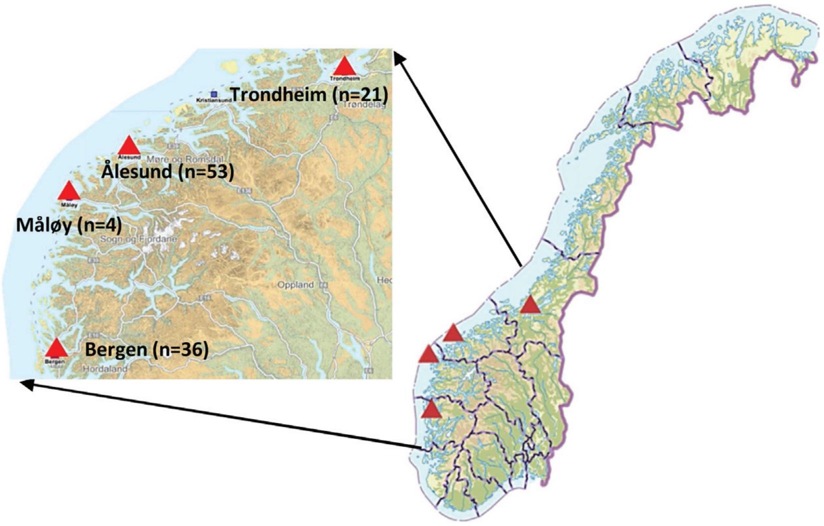

Fig. 3. The map representing Norwegian coastline, fishing territory and selected four sampling locations to conduct questionnaire of local fishers between the period of August 2017 to January 2018 [28].

respondents fishing in the northern, western and central parts along with some minor fishing activities in eastern and southern parts. The demographic characteristics of survey samples are summarized in Table 1 to exemplify the representation of the surveyed samples.

The pattern and use of FGs depend on areas of gear deployment and type of target fish species. A coastal fishing fleet consisting of smaller vessels and use relatively cheap and less sophisticated FGs *namely*, gillnets, longlines and traps/pots. Less than 10% of the total surveyed coastal fishers reported using sophisticated FGs like trawls and purse seines. However, around 21% of the surveyed coastal fishers reported using Danish seines as a replacement to more sophisticated purse seine or trawls. Coastal fishers responded by using all the primary FGs depending on types of fish species they are catching. However, none of the fisher representing ocean fleet reported using traps/pots indicating the rare use of crab pots/traps by deep-water fishers. Ocean vessels generally perform deep-water fishing deploying advanced FG types such as trawls (pelagic, bottom and semi-pelagic), purse seines, Danish seines and multiple sets of gillnets and longlines. Trawls and seines are considered sophisticated/advanced gear types, as they are useful concerning both capacity and efficiency of catching the commercially important fish species. Application of these FGs is one of the underlying reason why the ocean fishing fleet is responsible for around 85% of total catch caught annually by Norwegian fishing fleet [21].

Interpretation of transfer coefficient (TC)

After obtaining the desired and well-distributed sample size, statistical analysis of survey responses (step-8) is conducted to estimate the TCs. The defined TCs and their formulas are detailed in section 2.2. The summary of the sample statistical analysis of the TCs is presented in Table 2. This analysis results in quantifying the annual rates at which fishing fleet loses, repairs or disposes of listed FGs, the life span of gears, FGs present in stock and so on. This quantification can then be represented graphically to interpret the behavior of listed FG type across its system life cycle. This information can further aid decision making for the effective management of FG resources in the given region.

These estimated rates show around Trawls have a life span of around 3 yrs. Moreover, $C_{dispose}$ for Trawls shows that the fishing fleet reportedly disposes of around 25% of the total trawls owned by a fishing fleet every year. Similarly, annual rates at which fishers lose their FGs, fraction total FG type owned by the fishing company needing repair, a fraction of part being replaced during repair, the average life span of FGs can be calculated through survey responses.

Table 1
Demographic characteristics and fishing activity of the surveyed commercial fishing companies in Norway (N = 114).

Variables/Parameters	Coastal Fishing Fleet (V < 28 m)	Ocean Fishing Fleet (V > 28 m)
Number of Samples	55	59
a) Occupation Level		
• Full-time fishing	45 (86%)	57 (97%)
• Part time fishing	7 (14%)	2 (3%)
• Recreational	0	0
b) Area of Fishing		
• North Norway	30 (53%)	11 (19%)
• West Norway	15 (26%)	28 (49%)
• Mid Norway	07 (12%)	18 (32%)
• South Norway	05 (09%)	0 (0%)
c) Type of FGs		
• Trawls	06%	29%
• Purse Seines	06%	28%
• Danish Seines	14%	09%
• Gillnets	39%	17%
• Longlines	19%	17%
• Traps/Pots	16%	0
d) Type of Fish Catch		
• Pelagic Fish species	10%	36%
• Ground-fish species	80%	60%
• Crustaceans and mollusks species	10%	04%

Table 2
Statistical analysis of parameters and estimation of TCs from the responses of commercial fishing companies in Norway.

TC	FG types	Sample size	Mean	Std. Dev	Std. Error	95% conf. interval
Life Span $_{(yrs)}$	Trawls	31	2,8	1,8	0,3	0,6
	Purse seine	30	10,2	5,3	1,0	1,9
	Danish seine	20	3,9	1,8	0,4	0,8
	Gillnets	48	2,1	1,1	0,2	0,3
	Longlines	31	3,0	2,6	0,5	0,9
	Traps/pots	14	6,1	4,6	1,2	2,4
$C_{Disposal\ (\%\ of\ owned\ stock)}$	Trawls	31	25,1 %	23,6 %	4,2 %	8,3 %
	Purse seine	30	7,3 %	9,3 %	1,7 %	3,3 %
	Danish seine	20	11,4 %	8,4 %	1,9 %	3,7 %
	Gillnets	48	33,1 %	26,7 %	3,9 %	7,5 %
	Longlines	31	30,8 %	26,5 %	4,8 %	9,3 %
	Traps/pots	14	16,9 %	13,2 %	3,5 %	6,9 %

Similarly other TCs namely, C_{Lost} (% of owned stock); C_{repair}, $C_{replace}$, C_{stock} can be estimated as per calculation formula given in Section Statistical analysis.

Fishers survey: lessons learnt

In this method article, we proposed a stepwise method for a questionnaire-based survey to extract information from fishers. Although FK is considered as a valuable and abundant source of information in the data-poor field, careful and systematic approach is required to extract vital information from fishers to minimize the bias and confusion. Once the objective of the study is established, much of the emphasis is given to developing the set of questions for the proposed questionnaire. The adopted Delphi method to revise the questions proved to be a useful technique to make the questions lucid, concise and apt with the help of experts in the field. Further, selection of questionnaire language is another critical choice as although many fishers understand the English language, use of local language (Norwegian) in conducting the survey is observed to be a more practical way to avoid confusion and to create a comfortable environment for the respondent.

Furthermore, in coherence with Leite and Gasalla [23], establishing the confidence of fishers is critical in transmitting their knowledge. Three strategies were implemented during the survey to achieve the fishers' confidence, firstly, face-to-face interviews were conducted in most of the study locations and secondly, interviewers introduced themselves as a student with minimal knowledge in the fishery and demonstrated impartiality toward the issues addressed. Finally, surveyed fishers are also well-informed about the anonymity of the process. These three strategies resulted in more open and relaxed discussion with fishers. A friendly environment also resulted in gaining extra information alongside survey questions as many of the surveyed fishers took extra time in sharing their stories and issues in dealing with specific types of FGs along with the historical development of fishing practices in their community.

Although applied widely to extract local knowledge, survey as a method possess some constraints. One of the important one being responders being speculative while answering the specific questions where they lack knowledge. In the present study, the aim was to capture the patterns of FGs repaired, lost and disposed of annually. Accordingly, the presented questions demand summarizing the 10–20 yrs. of fishing practices for some respondents, and they may respond to such answers with a particular bias regarding their memory and report those incidents that hold specific importance to them instead of being objective. Additionally, conducting a face-to-face survey is both time consuming and expensive way of collecting responses. Alternatively, interactive online survey platforms can be explored if the survey questions are relatively simple and unambiguous.

In conclusion, surveying fishers provide an effective framework to extract FK that further assists in building evidence on parameters that are otherwise not measurable. These parameters can be used to estimate regional flows of plastic and other FG materials through material flow analysis (MFA) models. Furthermore, the simplicity of the stepwise method makes it practical and easily reproducible elsewhere to obtain the relevant scientific estimates on studied parameters for respective countries/regions, which is the critical necessity for good science.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.mex.2019.05.008.

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Paper 3

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Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway

Paritosh C. Deshpande[a,*], Gaspard Philis[b], Helge Brattebø[c], Annik M. Fet[a]

[a] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, 103, Gamle Fysikk, Sem Sælands vei 5, 7491, Trondheim, Norway
[b] Department of Biological Sciences, Norwegian University of Science and Technology, Hovedbygget, A428, Larsgårdsvegen 2, 6009, Ålesund, Norway
[c] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Sem Sælands vei 7, 7491, Trondheim, Norway

ABSTRACT

Plastic debris is an ever-growing concern adversely affecting the coastal and marine ecosystem. Among marine plastic waste, a particularly troublesome waste fraction is Abandoned, Lost or Discarded Fishing Gears (ALDFG) that continues to trap marine life for years upon releaseand has significant adverse environmental effects on coastal and marine ecosystems. However, lack of scientific data on the estimated contribution of ALDFG to marine plastics and associated reasoning hinders the management of fishing gear resources across the globe. This study presents a system-wide analysis of the typical fishing gears used in Norway for commercial fishing, i.e. trawls, seines (Danish and Purse), longlines, gillnets, and traps. Based on data from gear producers, suppliers, fishers, collectors, authorities, and waste management facilities, we model the flows of plastics polymers, polypropylene, polyethylene, and Nylon, used as the building blocks of advanced gears. A static Material Flow Analysis (MFA) is used to understand life cycle processes and further monitor gear quantities in and between the processes in the system. Our findings indicate that commercial fishing in Norway contributes to around 380 t/yr. mass of plastics from lost fishing gears and parts. Gillnets, longlines, and traps are the main contributors to ALDFG in the ocean due to gear design, practice, and ground deployment. Additionally, around 4000 tons of plastic waste is collected in Norway annually from derelict fishing gears out of which 24% is landfilled, and 21% is incinerated for energy recovery. The MFA approach shows significant potential as a holistic decision support tool for industry and policy-makers in exercising sustainable fishing gear resource management. The study also generates key evidence on regional level plastic pollution from the fishing sector and highlights possible mechanisms that may aid in proposed improvements.

1. Introduction

Globally, oceans continue to accumulate debris of all forms, making them the biggest landfill on the planet (Schneider et al., 2018). Marine littering, defined as any persistent, manufactured or processed solid refuse discarded, disposed of or abandoned in the marine or coastal environment through human activity, is a growing concern for authorities (Galgani et al., 2010). The scientific reviews conducted by Moore (2008) highlighted the apparent predominance of plastics amongst marine litter, contributing 60%–80% of total marine debris around the globe. A more recent study estimates an annual influx of between 4.8-12.7 million tons of plastic waste entering the ocean (Jambeck et al., 2015) and forming the notable garbage patches in global waters (Lebreton et al., 2018).

Among the total plastic waste entering the oceans, a particularly troublesome waste fraction is Abandoned, Lost or Discarded Fishing Gears (ALDFG) that may continue to trap marine animals for decades upon release (Laist, 1997, Macfadyen et al., 2009). Since fishing gear (FG) made of plastic polymers has a long lifespan and is designed to capture marine organisms, ALDFG is considered one of the most hazardous waste fractions for marine animals (Wilcox et al., 2016). A common problem is ghost fishing, where abandoned, lost or discarded gears, such as gillnets, trammel nets, seines, trawls, and pots, continue to catch fish, crustaceans, birds, mammals and reptiles (Laist, 1997, Brown and Macfadyen, 2007). 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 FG (Derraik, 2002, Gilman, 2015). Upon deployment, FGs may get lost for a variety of reasons including (but not limited to) adverse weather conditions, irregular topography, gear conflicts and failures, ship collisions, abandonment, human error, and vandalism. Such events are the most common causes contributing to the ALDFG problematic (Graeme Macfadyen, 2009, Richardson et al., 2018).

Previous studies demonstrate the deleterious effects of ALDFG on marine ecosystems. Detailed studies investigated problematics including entanglement (Stelfox et al., 2016, Yoshikawa and Asoh, 2004, Laist, 1997), navigational hazards (Hong et al., 2017), impacts on coral reefs (Chiappone et al., 2005, Chiappone et al., 2002, Cho, 2011), and the risk of bioaccumulation through micro-plastics (Chen et al., 2018, Browne et al., 2015, Browne et al., 2010, Foekema et al., 2013, Phillips et al., 2010, Koelmans et al., 2017). In comparison, we know very little

* Corresponding author.

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of the extent of ALDFG pollution generated by commercial fisheries. Jambeck et al. (2015) highlight the knowledge deficiency of plastic flows from fishing activities in the quantification of the total plastic in marine debris.

In EU member states, commercial fishing is a primary activity in which wastes from FGs are regulated through a range of international and regional instruments including United Nations Convention on the Law of the Sea (UNCLOS), London Convention, OSPAR, MARPOL Annex V, EU Waste Framework Directive and EU Marine Strategy Framework Directive (Chen, 2015). Additionally, to reduce the impact of marine plastic on the environment, the EU is committed to improving the collection of fishing equipment containing plastics and highlights opportunities to establish circular business models (EC, 2018b). Nevertheless, there is a lack of monitoring tools to estimate the amount of plastics in ALDFG that enters the ocean and is available after end-of-life (EOL) collections. To build robust resource management strategies and realize sustainable circular business opportunities that are capable of utilizing untapped resources across regions, it is essential to know the amount of plastic available for recycling from the fishing sector.

In this study, Material Flow Analysis (MFA) is applied to track physical flows and stocks of mass of plastic (MoP) from FGs in Norway through use and post-use processes. Based on data from gear producers, fishers, collectors, and recycling and waste management companies, a static MFA model is established to quantify the annual stocks and flows of plastic polymers (PP, PE, and Nylon) from the FGs deployed by the Norwegian fishing fleet.

2. Materials and Methods

2.1. Material flow analysis

The basic principle of MFA is the conservation of matter and energy in isolated systems, delimited by boundaries of time and space and following the mass-balance principle (Brunner and Rechberger, 2004). It is a decision-support tool for evaluating technology efficiency and industrial practices, and for managing resources and environmental impacts (Brunner and Rechberger, 2004). Typically, MFA of a selected substance includes the main life cycle stages namely, mine, production, manufacturing, use, maintenance and disposal (Habib et al., 2014). We used MFA to measure the annual loads of plastic evolving through the life cycle of commercial FG in Norway. This study focuses solely on the Norwegian commercial fishing fleet, through both use and post-use processes. The MFA model was built to present the 2016 stocks and flows of plastics from FGs because of the maximum data availability obtained through data collection rounds. Static models provide insight into systems at a specific time, allowing holistic assessment of their current state (Allesch and Brunner, 2017, Van Eygen et al., 2017). Primary modeling and flow calculations were performed in Microsoft Excel, while STAN v2.6.8 was used for further data reconciliation (Vienna University of Technology, Vienna, Austria). Information on key processes, data collection methods and selected FGs are elaborated in the following sections.

2.2. System Description

In this study, the term Fishing gear (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, 2016). Throughout the text, the term “plastics” includes polyethylene (PE), polypropylene (PP) and Nylon. These three polymers are the main building blocks in the production of modern synthetic FGs (Baeta et al., 2009, Brown and Macfadyen, 2007). Fig. 1 represents the common life cycle processes of commercial FGs used by the Norwegian fishing fleet. In this study we include six major commercial FGs, namely trawls, purse seines, Danish seines, gillnets, longlines, traps/pots, and their associated ropes.

FGs are divided into two categories, active and passive. Active gears (seines and trawls) dynamically hunt the targeted species whereas, passive gears (lines, gillnets and traps/pots) are fixed gears aimed to catch active fish (Muus and Nielsen, 1999). Passive gears are economically cheap making them popular among small-scale fishers. The system boundaries are set to include the annual life cycle processes of FGs deployed by the Norwegian commercial fishing fleet. Commercial fishing from international vessels and leisure fishing from private vessels in Norwegian waters are excluded.

The commercial fishing fleet of Norway is controlled by The Norwegian Directorate of Fisheries (Fiskeridirektoratet, 2017). Every year, fishing companies purchase FGs mainly to equalize the stock after annual losses from deployment or disposal after end-of-life. In the use-phase, fishers deploy FGs in the ocean to catch a target species. Deployed FGs, or their parts, may get lost during operation due to a variety of reasons listed by Graeme Macfadyen (2009). Although causes of FG loss upon deployment are well described by Graeme Macfadyen (2009), Richardson et al. (2018), limited information is available in the literature on the rates of gear loss resulting from fishing activities (Humborstad et al., 2003). Historically, Breen (1987) used fishers’ responses to derive the annual rate of 11% trap loss in the Fraser River Estuary of British Columbia. The FANTRED study conducted by MacMullen (2002) remains the only attempt to estimate the rate of gillnets loss in European waters. However, these studies are obsolete, region-specific and limited to specific FG types, and therefore cannot be used in this study’s context.

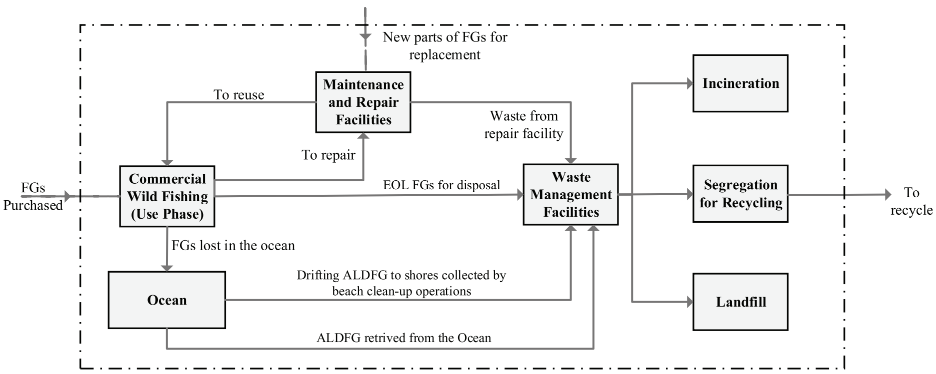

Fig. 1. Processes involved in the system life cycle of commercial FGs in Norway.

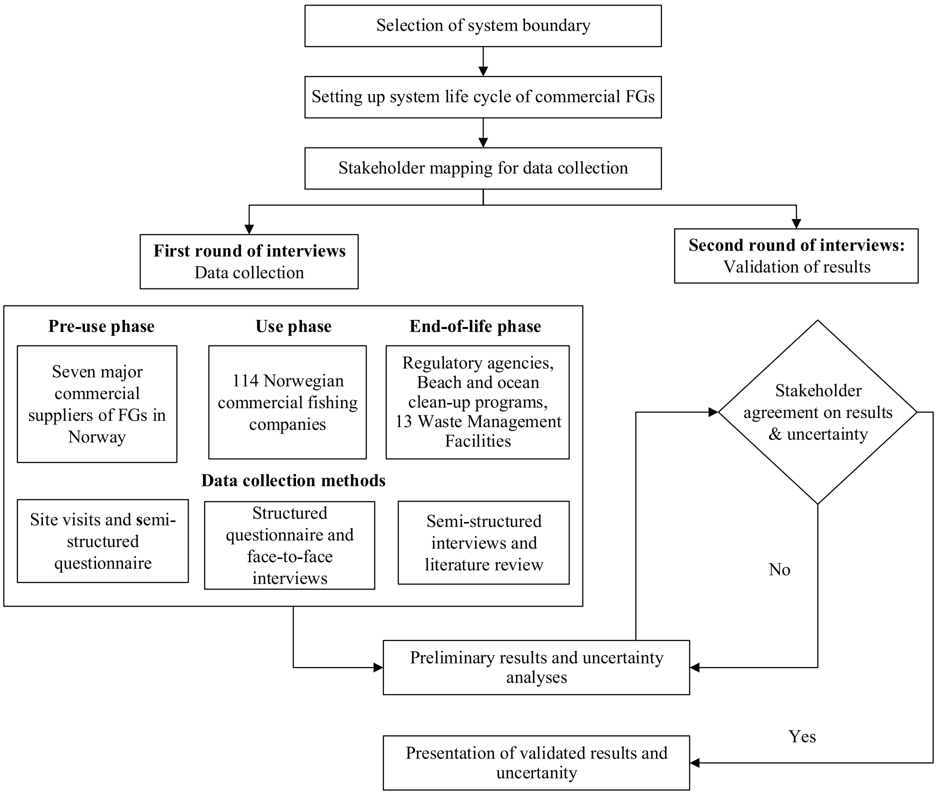

Fig. 2. Stepwise approach adapted for the collection and validation of MFA results.

Additionally, fishing activities cause wear and tear to the gear used, and consequently, fishers must frequently maintain and repair their FGs. Some repairs involve the replacement of damaged or lost parts. In this study, repairs that involve the replacement of FG part(s) are considered "major repairs." Major repairs need external intervention and are carried out by either the fishing company or the dedicated repair facilities managed by FG producers. It is essential to note that most FGs undergo continuous minor repairs after each fishing activity. Minor repairs include stitching, tying and adjusting broken parts of the gear without any significant replacement of parts. Such minor repairs are excluded in this system, as they have no significant impact on mass flows.

End-of-life pathways of FGs are manifold; firstly fishing companies' dispose of waste FGs to the nearest waste handling facilities. In addition, lost FGs and parts are retrieved through annual ocean clean-up surveys to minimize the risk of ghost fishing and associated damage to the marine environment. Furthermore, floating fractions of ALDFG end-up on shores, dragged by the wind and waves. Some of those FGs and gear residue are further collected during annual beach clean-up operations conducted across the Norwegian coastline. ALDFG collected from land and ocean ultimately end-up at Waste Management Facilities (WMF). Waste generated during FG repairs also ends up in WMFs. At the end of the value-chain, waste managers segregate waste FGs into different fractions, which include the recyclable fraction, the fraction for landfill and the incinerable fraction for energy recovery. The segregated fractions are then transported to their respective facilities. A detailed description of the commercial fishing fleet and selected FGs is presented in section S1 of the supplementary material.

2.3. Data Collection

Data collection took place from June 2017 to August 2018. Both top-down and bottom-up approaches were used to collect data for calculating flows and transfer coefficients. Fig. 2 shows the stepwise approach used for data collection, validation of MFA results and associated uncertainty. After identifying the system boundary and life cycle stages for commercial FGs, stakeholder mapping was conducted for targeted data collection. Data was primarily collected using published literature, government statistics, and interviews of stakeholders. Table 1 briefly describes the flows, stocks, equations and data sources used.

In the first round of interviews, information regarding sales volumes and compositions of each FG type were obtained from seven major suppliers and manufacturers of FGs in Norway. Using fishers' knowledge (FK) to estimate local patterns in fishing is common practice in natural resource management (Fischer et al., 2015, Hind, 2014, Johannes, 1998). The survey questionnaire was designed using a Delphi method that seeks the experts' consensus to bring clarity to the proposed questions. The questions were aimed at generating evidence on typical FG life-span, potential causes and rates at which gears are lost in the ocean upon deployment. Repair and reuse are identified as a primary strategy in the circular economy to slow-down the loop of a product lifecycle (EU, 2014). A well-established repair system allows for prolonged product life, which reduces waste generation and thereby promotes circularity in the system. Again, fishers' perception of managing FGs was deemed essential to understand the range of repair and reuse patterns of the six FG types. Survey questions were designed to gather the data to estimate the percentage of FGs owned by a fishing

Table 1
Description of flows, respective data sources and flow equations.

FLOW ORIGIN, SYMBOL	FLOW NAME	DESCRIPTION	DATA SOURCE	EQUATION
$F_{0,1}$	FGs purchased (t/yr)	Mass of Plastics (MoP) in purchased commercial FGs.	Fishing gear suppliers	Σ plastics in purchased FGs (Trawls, Purse Seine, Danish Seine, Gillnets, Longline and Traps)
$F_{1,2}$	FGs to major repair (t/yr)	MoP in FGs sent for major repairs including replacement of parts.	Fishers survey	$\Sigma\ C_{rep} * FG_{owned}$
$F_{1,3}$	Lost FGs and parts (t/yr)	MoP in FGs entering in the ocean from lost FGs or parts upon deployment.	Fishers survey	$\Sigma\ C_{lost} * FG_{owned}$
$F_{1,4}$	Worn FGs to disposal facility (t/yr)	MoP in end-of-life FGs disposed of by fishers at the WMFs or ports.	Fishers survey	$\Sigma\ C_{disp} * FG_{owned}$
$F_{2,1}$	Repaired FGs to reuse (t/yr)	MoP in repaired FGs being reuse.	Mass balance	$F_{0,1} + S_1 - F_{1,4} - F_{1,3} - F_{1,2}$
$F_{0,2}$	New FG parts for replacement (t/yr)	MoP in replacement parts used by repair facilities.	Fishers survey	$\Sigma\ C_{repair} * C_{replace} * FG_{owned}$
$F_{2,4}$	Waste FGs from the repair facility (t/yr)	MoP in the waste from FG generated during repair.	Mass Balance	$F_{0,2} + F_{1,2} - F_{2,1}$
$F_{3,4a}$	ALDFGs collected from beaches (t/yr)	MoP in the collected ALDFG from the beach clean-ups.	Keep Norway Beautiful (HNR)	
$F_{3,4b}$	ALDFGs retrieved from the ocean (t/yr)	MoP in the collected ALDFG from the ocean clean-ups.	The Norwegian Directorate of Fishery and Fishing for Litter.	
$F_{4,5}$	Waste FGs to incineration (t/yr)	MoP in collected waste FGs incinerated at the WMFs.	WMFs survey	$\Sigma\ C_{inc} * (F_{2,4} + F_{1,4} + F_{3,4a} + F_{3,4b})$
$F_{4,6}$	Segregation and processing for recycling (t/yr)	MoP in collected waste FGs sent for recycling abroad.	WMFs survey	$\Sigma\ C_{rec} * (F_{2,4} + F_{1,4} + F_{3,4a} + F_{3,4b})$
$F_{4,7}$	Waste FGs to landfill (t/yr)	MoP in collected waste FGs landfilled at the WMFs.	WMFs survey	$\Sigma\ C_{landfill} * (F_{2,4} + F_{1,4} + F_{3,4a} + F_{3,4b})$
$S_1 + DS_1$	Stock change of total FGs owned by commercial fishers (t)	MoP in the stocks of FGs owned by the Norwegian fishing fleet.	Fishers survey	$C_{turnover} * F_{0,1}$
$S_3 + DS_3$	Stock of ALDFG in the ocean (t)	MoP accumulating annually in the ocean as ALDFG.	Mass balance	$F_{1,3} - (F_{3,4a} + F_{3,4b})$

company that require major repair each year. In addition, the survey also determined the fraction of the total mass of FGs replaced during major repairs.

Face-to-face and telephonic interviews were conducted along Norway's six major ports. Answers from 114 commercial fishing companies were recorded and statistically analyzed to estimate the transfer coefficients of FGs flowing and stocked in the system. The formulae developed to estimate transfer coefficients and other methodological details adapted for fishers' survey are detailed in Deshpande et al. (2019).

In Norway, dedicated efforts are made to retrieve derelict FG from the ocean and beaches. Several voluntary actions are conducted throughout the year to collect and remove accumulated marine debris from the coastline (Falk-Andersson et al., 2019). One key stakeholder fighting against marine litter is Hold Norge Rent (HNR). HNR started as a project in 2012 to clean up Norwegian beaches, and went on to become an independent organization aiming to prevent environmental pollution by organizing volunteer clean-ups of trash and hazardous waste in nature (Jacob, 2016). Data on FG waste collected in beach clean-up activities from 2015 to 2017 in Norway was obtained through telephone interviews with the experts from these operations.

Information on FGs retrieved during ocean clean-up operations was obtained from the annual FG retrieval organized by the Norwegian Directorate of Fisheries and the Fishing for Litter (FFL) project. In Norway, commercial fishing vessels (size ≥ 28 meters) are required to report incidents that involve the loss of FGs and parts to the Coast Guard Central. This reporting includes specifications and geographical coordinates about the lost gear, and facilitates the Directorate of Fisheries' retrieval operations (Langedal, 2011). Under the FFL initiative, fishing vessels can deliver (free-of-charge) marine litter caught during regular fishing activity to collection points spread in specific harbors along the Norwegian coasts (Johnsen, 2017). The MoP from FGs collected through these schemes in the 2015 to 2017 period was gathered from the organizations' annual reports and interviews with the respective project managers.

In WMFs, waste is segregated and sent for landfilling, to incineration plants or to recycling facilities. For our questionnaire, we shortlisted 13 WMFs based on their proximity to harbors and ports. Then, the typical annual load of waste FGs received by the WMFs and the fractions of it sent for landfilling, incineration or recycling, was recorded. The questionnaires and responses from fishers, data from WMFs and other stakeholders, as well as statistical analysis and assumptions, are available in the supplementary material. Following data collection, a preliminary MFA model was built. In the second round of interviews, a preliminary MFA model was presented to all relevant stakeholders for validation. Finally, validated results and uncertainties were incorporated into the final MFA model presented in this study.

2.4. Uncertainty Analysis

Quantifying data uncertainty is a vital cog in justifying MFA results. As MFA demands the gathering, computing and harmonizing of physical flows and stocks from various sources with different data qualities, its results are inherently uncertain (Laner et al., 2014). In this study, standard statistical mean and the standard deviation were used to estimate the uncertainty of input variables. Further, uniform distributions are typically selected when it is possible to specify only a range of probable values. The probability distributions of the parameters and input data were used to estimate the probability distribution of the model outputs by applying Monte Carlo simulations (MCSs). The resulting histograms characterize the respective uncertainty associated with individual model outputs. The estimated output values of model flows, and the associated uncertainty through MCS iterations, were then further validated through STAN software to present the final values and uncertainties after data reconciliation (S3, supplementary data).

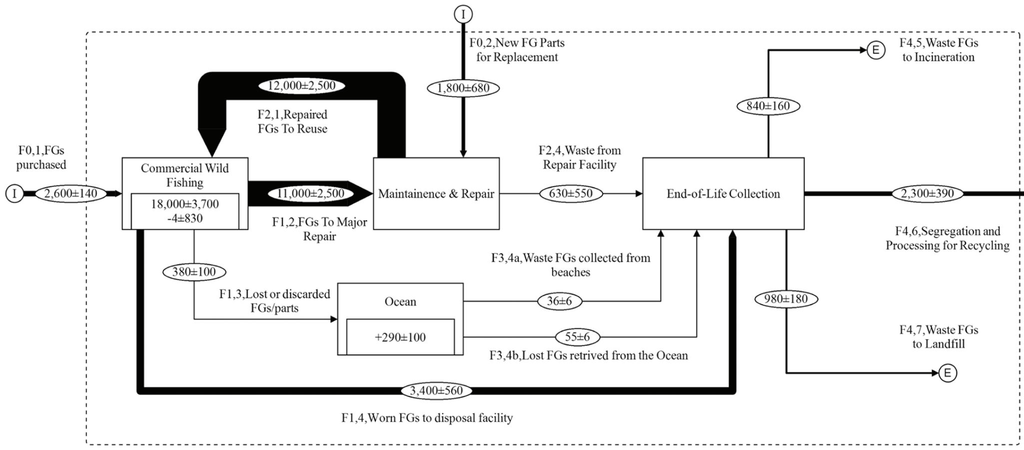

Fig. 3. MFA of plastic (PP, PE, and Nylon) from six fishing gears used by the commercial fishing fleet of Norway in 2016 (tons/yr).

3. Results

Fig. 3 presents the MFA of plastics from six types of FGs used annually by commercial fishers in Norway. Flows and stocks evolving in the system are calculated through the purchase, use and end-of-life phases of FGs.

3.1. Purchase phase

The total MoP in the form of newly purchased FGs ($F_{0,1}$) in 2016 is estimated to be 2626 ± 143 tons per year. Additionally, 1755 ± 681 tons of MoP is purchased as FG parts for replacement during major repairs ($F_{0,2}$). The weight of metal components in FGs, such as trawls, purse seines, Danish seines, and traps/pots, are excluded from the model calculations. The fishing fleet typically purchases the selected FGs to equalize their stock of owned FGs. Responses from 114 fishing companies were used to calculate the turnover coefficient of selected FGs. Such results in the estimated stock of FGs of 18413 ± 3676 tons MoP owned by the Norwegian fishing fleet.

3.2. Use phase

3.2.1. Repair Patterns

The responses from 114 fishers and typical repair-replace patterns for the six gears are presented in Fig. 4. Results indicate that repair of large and expensive gears such as trawls and purse seines is frequent, with more than 80% of total trawls and more than 50% of total purse seines subject to major repair every year. On the other hand, only one-third of the total owned inexpensive FGs, such as gillnets, traps/pots, and longlines, undergo major repairs.

Replacement of gear parts is a frequent process at repair facilities as parts of trawls, purse-, and Danish seines get lost and damaged during operation. The fishers' survey responses highlighted that FG types that undergo major repairs require the replacement of parts that make up 15% to 25% of the total mass of the gear. For instance, fishers informed us that during the deployment of trawls, they sometimes lose or damage the net extremity known as the 'cod-end.' Resultantly, they must replace the part, which represents 15% to 20% of the total weight of the gear, more often than any other parts of the trawl.

3.2.2. Deployment losses

Fishers reported the associated risk of damaging FGs and of losing part of or the entire gear upon deployment in the ocean. Survey responses showed that not all the commercial FG types are equally prone

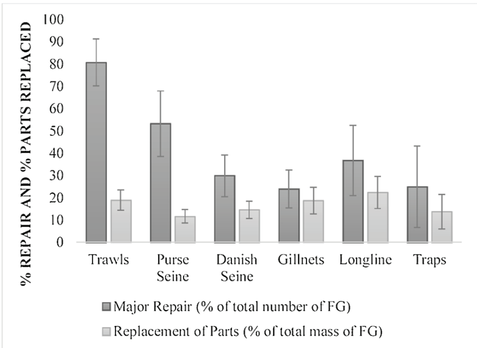

Fig. 4. Annual repair and replacement patterns of six commercial FGs used in Norway.

to get lost in the ocean. There are significant differences in their probabilistic loss rates. Additionally, it is important to note that the rate of FG losses estimated in this study only includes FGs that are lost upon deployment either accidentally or due to operational damage; deliberate abandonment of FGs are not considered in this study.

Responses from fishers within this study **(**Fig. 5) provide the annual loss rates of the six FGs and their parts occurring in Norwegian waters upon deployment.

It is evident that longlines and pots have higher chances of loss upon deployment. Indeed, around 4% to 7% of total longlines and traps/pots owned by the Norwegian fishing fleet ends-up in the ocean every year. Contrarily, purse seines and Danish seines are proven to be robust and safe gears that are rarely lost upon deployment. Gillnets are the primary source of derelict gears. Although only 1% to 2% of total gillnets are reportedly lost upon deployment, the amount of gillnets used by commercial fishers exceeds most other gears. Thus, lost gillnets also pose a significant threat to the marine ecosystem.

3.2.3. Typical disposal patterns of fishing gears

If not lost during operation or able to be repaired effectively or economically, fishers must dispose of FGs at their end-of-life. These EOL FGs are disposed either at port reception facilities or the nearest WMFs. Fishers' responses provided the operational life-span variability of the studied FGs. Sophisticated and expensive gears like purse seines and

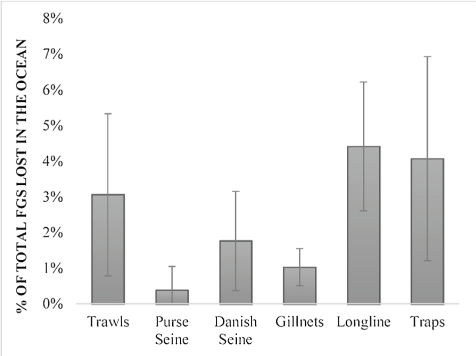

Fig. 5. Annual rates at which commercial fishers lost their FGs upon deployment.

Danish seines last the longest because of their fishing principal (slow deployment in the open sea) that minimizes wear and tear. FGs like gillnets and longlines, on the other hand, are cheap and display an operational life between 1-3 years implying frequent disposal. Consequently, almost one-third of gillnets and longlines, and one-fourth of trawls are disposed of by the fishing companies every year (Fig. 6).

3.3. End-of-Life Phase

3.3.1. Collection of gears from beaches and the ocean

Marine litter accumulated on the coastline is cleaned throughout the year through clean-up efforts. Analysis of the collected litter reveals that plastic from FGs constitutes up to 30% of the total marine litter found on the beaches in Norway (Jacob, 2016, Hartviksen, 2017). Personal interviews with managers of beach clean-up operations informed the estimation of the average weight-range of waste FGs collected during clean-up operations. The fraction of waste MoP removed from registered beach clean-up operations in Norway accounts for 36 tons per year ($F_{3,4a}$). This waste fraction is sent to the nearest WMFs for further management.

The amount of plastic collected through listed ocean clean-up operations was calculated from raw data, excluding metal and other non-plastic components of the FGs. An estimated 55 tons MoP is retrieved from Norwegian waters annually from the two ocean operations, annual gear retrieval surveys by the Norwegian Directorate of Fisheries and recovery of waste FGs through FFL ($F_{3,4b}$). It is impossible to know the source of these FGs and the year in which they entered the ocean.

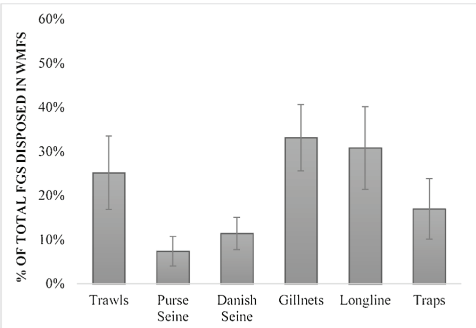

Fig. 6. Annual rates at which commercial fishers dispose of their gears to the WMFs.

3.3.2. Handling of FGs by WMFs

All the flows of waste FGs from fishers, repair facilities, and collected from land and water ends-up in the nearest WMFs. Responses from 13 WMFs were recorded, from which patterns of handling waste FGs were derived. Around 55% of the total FGs collected by WMFs are segregated and sent to recyclers for further processing, whereas 21% are sent for incineration and 24% are landfilled in Norway. It is essential to note that although 55% of the collected FG waste is sent for recycling, the fraction of waste generated during the recycling process and the recycling inefficiencies are excluded. Both the chemical and mechanical recycling of PP, PE, and Nylon take place out of Norway, and therefore, are considered out of scope for this study.

4. Discussion

4.1. Stock of plastics from FGs in the ocean

Despite stricter controls of fishing practices, our MFA shows that an estimated 380 ± 104 tons MoP is lost in the ocean annually by the Norwegian fishing fleet, which actively contributes to the marine littering and ghost fishing problematic. Considering the direct proportion between registered fishing vessels (Fiskeridirektoratet, 2017), amount of fishing activity and rate of FG loss upon deployment, a backcasting was conducted to estimate the fishing fleet's ALDFG contribution since 2007 (Fig. 7). Although dedicated efforts are made to retrieve ALDFGs from the ocean territory in Norway, an estimated annual influx of 308 tons remains unrecovered, piling up the stock in the ocean. Such retrospective estimation shows that approximately 4000 tons of plastic accumulated in the ocean since 2007 from Norwegian commercial fishing alone. Table S12 of SI presents the analysis steps followed for backcasting.

Buhl-Mortensen and Buhl-Mortensen (2017) conducted elaborate seabed mapping using 1778 video transects of Nordic oceans. They concluded the dominance of waste FGs in all marine landscapes across Norway, confirming the alarming quantities of accumulated FGs reported in this study. However, the estimate presented in Fig. 7 is still only partial as loads of ALDFG from international commercial fishing vessels fishing in Norwegian territory, leisure fishing boats and deliberate abandonment of FGs are not considered in current MFA study.

A 40-day long gear retrieval survey from the Directorate of Fisheries is an attempt to recover accumulated ALDFGs from fishing vessels throughout the year. A vessel equipped with recovery and FG location technology spans the length of the Norwegian coastline each summer. In 2016, the cleaning operation recovered around 20 tons of plastic FGs, 20-25 tons of metal wires, and several tons of marine animals entangled in fishing gears (Langedal, 2017), confirming the detrimental threats of the lost FGs fraction of overall marine litter. Cheap and abundantly deployed FG types such as gillnets, longlines, and associated ropes are the most significantly recovered fractions of ALDFG. Trawls and Danish seines are challenging to find and retrieve due to the presence of metal parts. These gear types sink into the ocean's depth, making them difficult to retrieve. Many of the sunken gears get entangled on coral reefs and rocky surfaces. Forcefully retrieving such FGs is usually avoided because it is likely to damage coral reefs or the marine ecosystem. Some of the lost FGs drift with the ocean currents to the coastline transferring the ALDFG load from the ocean to land. The lack of technology to locate lost FGs, coupled with adverse weather conditions, FGs drifting with ocean currents and the associated costs of retrieval operations significantly limit further improvements of ALDFG recovery. It is therefore essential to find a suitable alternative to manage and mitigate the accumulation of ALDFG in the ocean compartment alongside recovery and clean-up operations.

4.2. Sustainable management of FG resources

The mass flows estimation provided in the MFA analysis is raising

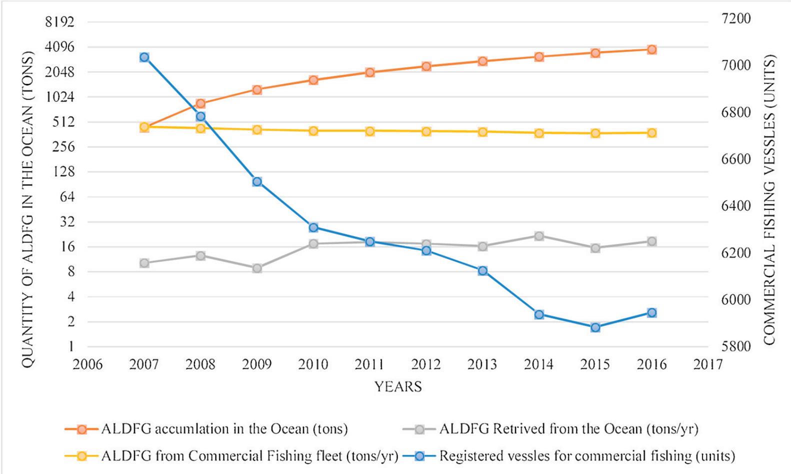

Fig. 7. Back-casting annual flow of plastic from lost FGs and accumulating in the ocean from 2007-2016.

awareness about the extent of plastics pollution from commercial fishing. More importantly, it also allows us to identify strategies for sustainable management of FG resources. Such strategies can prevent the detrimental effects of ALDFGs, and also generate circular economy opportunities through closing the FGs plastic loop. Table **S13** in the **SI** gives an overview of strategies considered relevant for the Norwegian commercial fishing sector modified after Deshpande and Aspen (2018). The proposed strategies are presented in relation to their application within FG lifecycle phases.

4.2.1. Pre-use phase

Gear marking or gear identification is considered a key strategy for responsible fishing and for controlling the ALDFG problem. This can enable fishers to minimize risks of losing FGs upon deployment, as well as aid authorities in improving collection and management of waste FGs. The Fisheries Department of the Food and Agricultural Organization (FAO) published a systemic guideline encouraging member states to incorporate gear marking in their policies. According to these guidelines, gear marking aids in providing an understanding of the location, scale and nature of FG in the water (FAO, 2016). Some of the proposed marking identifiers include electronic tagging, coded wire tags, barcoding, color-coded ropes, metal stamps or metal/steel tags incorporated into the FG. Information on gear location and ownership aids in estimating the position of the FG and in tracing the owners responsible for lost FGs.

Furthermore, the Norwegian government is considering Extended Producer Responsibility (EPR) as a strategy to minimize and prevent plastic pollution from FGs at a regional scale. Under the EPR, companies who produce, import or distribute FGs (the entire value chain up to the user of the equipment) will be responsible for the collection of the gear after use and for ensuring that it is properly recycled (Sundt et al., 2018). A feasibility assessment of the EPR scheme was conducted by the Norwegian Directorate of the Environment in 2018. It highlighted the need for in-depth understanding of the FG system's life cycle (flows and stocks) to aid in the selection of relevant mechanisms for the implementation of such regulation. This study may act as background evidence to support EPR policies before their implementation in Norway. A take back mechanism, a reward scheme for end-users to promote the collection of EOL FGs, is an example of an effective way to realize EPR at the regional scale. Introducing an Environmental Tax on the sale of fishing equipment is another proven strategy to internalize the costs of EOL collection and waste treatment in market prices. Stakeholder perception and market readiness must be assessed before implementing such strategy on a regional scale.

4.2.2. Post-use handling and collection of FGs

Currently, in Norway, marine litter caught during fishing can be handed in at the calling port. The costs associated with the reception of ship-generated waste are covered through the collection of a fee from all ships, irrespective of whether the ship-generated waste is delivered to the reception facility (EU DIRECTIVE, 2002). A dedicated EU Directive 2000/59/EC mandates all EEA member states to ensure availability of a Port Reception Facility (PRF) and a waste handling and management plan on all ports. PRFs are defined as 'any facility, which is fixed, floating or mobile and capable of receiving ship-generated waste or cargo residues'.

According to the recent judgment by the EFTA Court (2016), Norway has failed to fulfill the obligations under the EU directive, as only 1514 of 4443 registered ports and landing sites had showcased the availability of waste reception and a handling plan. A large number of landing sites without any dedicated waste management system led to the improper collection of fishing-related waste in the country. The absence of adequate facilities to collect ship-generated waste may result in illegal dumping, burning or stocking the waste on ports, and severely hinders the collection and treatment of waste FGs through adequate channels (EC, 2018a). Availability of PRFs is essential to ensure the reduction of marine plastic pollution from fishing and maritime activities. There is a need to develop a strategic plan to incorporate harmonized PRFs across Norway with the help of relevant stakeholders.

Strategies such as economic incentives and penalty schemes for fishing vessels may be considered to ensure the effective use of PRFs (Gilman, 2015). Additionally, stakeholder awareness campaigns may help to minimize the illegal dumping of marine litter on beaches and at sea. Additionally, training workshops for fishers to highlight best practices in handling FGs can prevent avoidable loss. Volunteering and deliberate clean-up campaigns are already proven mitigation measures for marine litter in Norway.

4.2.3. Closing the loop for plastics from FGs

To ensure the EOL management of plastics from FGs, it is essential to build the capacity and technology to extract value from waste based on circular economy principles. Currently, there exist numerous challenges in closing the loop for plastics from waste FGs. The EOL collection, segregation, capacity, and availability of recyclers are among the key concerns in realizing the economic benefits from material recovery.

In the Norwegian context, personal communication with waste managers revealed several challenges in handling waste FGs. One of the major challenges of WMFs is the lack of a best practice guide or harmonized technical expertise in cleaning and segregating waste FGs. Most EOL FGs are laden with rotten biomass, fish oil, and dirt. Since many WMFs lack the facility to clean such waste, the result is elevated rates of incineration or landfill within the waste fraction. Furthermore, an absence of industrial-scale recyclers' results in the exportation of the entire recyclable fraction out of Norway, thereby missing an opportunity to extract the optimum value out of locally produced waste FGs. Existing mechanical recycling technologies for PP and PE of waste FGs result in the formation of HDPE (high-density polyethylene) and LDPE (low-density polyethylene). These can be effectively used to replace virgin plastic polymers in products made by injection molding technology. Additionally, nylon polymers retain their properties through several recycling cycles, making nylon an economically attractive by-product to be recovered from waste FGs.

Although both chemical and mechanical technologies are available for closing the material loop, industrial-scale recycling of FGs faces many economic and operational challenges. Personal communication with the recyclers revealed that the transport and segregation of waste FGs from source to gate pose a significant economic burden to recyclers. The presence of metal wires in ropes and other parts of FGs makes it difficult to cut them into transportable pieces. These metallic parts cause wear and tear to the mechanical recycling units forcing frequent maintenance and repairs. Design and composition of modern FGs and lack of technical expertise at the waste collection facilities cumulatively hamper the maximum material recovery from waste FGs.

Finally, to make recovery of plastic sustainable, there is a need to create a harmonized network and building capacity of downstream actors involved in the EOL collection and management of FGs. Additionally, research on the eco-design of FGs must be emphasized to explore alternative FG material that allows efficient and profitable recycling without hampering the effectiveness. In its recent strategy, the EU invites innovation and business solutions across the member states to facilitate the transition towards a circular economy with a particular focus on marine plastic waste from FGs (EC, 2018b). Taking this into account, Norwegian plastic industries are currently tapping into opportunities by replacing fractions of their virgin polymers with recycled polymers from waste FGs. The amount of waste FGs available for recycling estimated in this study provides a piece of vital information for realizing an eco-industrial network between recyclers and plastic industries in the region.

4.3. Delimitations and Data quality

This static MFA study aims to provide a snapshot of all the activities taking place in the system life cycle of FGs. Inconsistency in the purchase flow is attributed to the variety of plastic content in FG types that differs across producers. Additionally, this study only includes major FG suppliers, which means that small-scale suppliers of gear to commercial and leisure fishers were excluded. Expert judgment was used to minimize this uncertainty and underestimation. The most significant data inconsistencies come from estimating average per unit weight of commercial FGs. Fishers often customize trawls, purse seines and Danish seines depending upon their needs, causing significant weight variations for these gear types. Furthermore, the average weights of FG types and expert judgment are used to calculate the plastic quantities in FGs collected in ocean and beach clean-up surveys. Contacted experts include the managers of clean-up surveys, and associated inconsistencies in the data may arise from simplifying the weights of certain gear types.

The uncertainty in survey response can be attributed to responders being speculative while answering specific questions where they lack knowledge. In the present study, the aim was to capture the annual repair, loss and disposal patterns of FGs. In the survey, some questions required fishers to summarize the past 10 to 20 years of fishing practices, which could lead to memory bias and unavoidable subjectivity. Additionally, statistical variations in responses from fishers are due to differences in fishing practices, target species, fishing grounds (coastal or deep-water), fishing quotas, and experience, among others. The dependency of this MFA on survey results is attributed to an overall lack of data on fishing practices, which highlights the need for improved monitoring practices of the Norwegian fishing fleet.

5. Conclusion

In this study, we present a system-wide analysis of the common Fishing Gears (FGs) used for commercial fishing, i.e., trawls, seines (Danish and Purse), longlines, gillnets, and traps and model the flows of plastics polymers (PP, PE, and Nylon) used as building blocks of advanced FGs. The MFA model aids in generating scientific evidence on quantities of plastic entering the ocean as ALDFG and EOL FGs available for recycling in Norway. The study further uncovers the state of plastic waste management from commercial fishing practices in Norway. The static MFA shows that irrespective of local land and ocean clean-up efforts, an estimated 300 tons of plastic is accumulating annually as ALDFG in the ocean ecosystem from the commercial fishing alone. Furthermore, the model reports that in 2017, around 55% of collected waste FGs are sent for further recycling out of Norway due to the absence of industrial recycling. In the wake of the recent Chinese ban on import of waste, there is a need to establish alternative ways to handle EOL FGs to avoid the accumulation of waste in the system.

These findings are already becoming a critical science and technology input for the Environmental and the Fishery Authorities of Norway aiding the formulation of policies to monitor and minimize the plastic pollution from the commercial fishing sector. Additionally, the results are likely to create a future paradigm for monitoring and implementation of the new European strategy for plastics and on port reception facilities (2018/012 COD). Finally, the reported annual quantities of plastic waste collected in the end-of-life stage is considered vital evidence for regional recyclers and waste managers that aim at closing the material loop from FG resources in Norway.

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 material related to this article can be found, in the online version, at doi:10.1016/j.rcrx.2019.100024.

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Paper 4

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