Toward a circular transition in port waste streams

The case of worn-out mooring lines at the Port of Norrköping

Master's thesis in Industrial Ecology

ANNA TINGFALK
LINNÉA ERIKSSON

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

Toward a circular transition in port waste streams

The case of worn-out mooring lines at the Port of Norrköping

ANNA TINGFALK
LINNÉA ERIKSSON

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026

Toward a circular transition in port waste streams
The case of worn-out mooring lines at the Port of Norrköping
ANNA TINGFALK
LINNÉA ERIKSSON

Supervisor: Brener Felipe Melo Lima Gomes, Department of Environmental Systems Analysis
Supervisor: Vendela Santén, RISE Maritime Department
Supervisor: Anna Skotte, RISE Maritime Department
Examiner: Anna Nyström Claesson, Department of Environmental Systems Analysis

Master's Thesis 2026
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Mooring lines in port operations at Fiskebäck Harbour, Gothenburg. Photograph by the authors.

Gothenburg, Sweden 2026

Toward a circular transition in port waste streams
The case of worn-out mooring lines at the Port of Norrköping
ANNA TINGFALK
LINNÉA ERIKSSON
Department of Technology Management and Economics
Chalmers University of Technology

Abstract

Ports are key nodes in material flows and logistics networks, yet the management of complex waste streams within port environments remains largely linear and understudied. This study examines the end-of-life (EoL) management of worn mooring lines at the Port of Norrköping, Sweden, with the aim of identifying barriers, opportunities, and value-chain changes required to support more circular management. Through qualitative data collection that included interviews, email correspondence and a site visit, a total of 25 actors actively contributed to the study, with their expertise and insights on the area.

The results of the value-chain mapping show that worn-out mooring lines are currently managed linearly, mixed with other complex materials and directed toward incineration. Key challenges to circularity include mixed polymer compositions, physical size, contamination from use, insufficient sorting at source, and low material volumes that limit the economic viability of dedicated circular pathways. Responsibilities for EoL management are fragmented across the value-chain, with no single actor assuming system-wide responsibility.

Circular management is enabled through collaboration, particularly with upstream actors. The EoL waste management is currently treated as a local problem, but it demands a systemic perspective for a circular transition. In the current linear handling between multiple stakeholders, critical information about moorings is lost. Material characteristics and knowledge must be preserved and carried throughout the entire lifecycle. The system requires a fundamental shift in perspective, moving away from a linear material-focused approach toward a product-oriented and systemic view to achieve higher levels of circularity.

The study concludes that advancing circularity for mooring line waste requires coordinated action across the value-chain, with particular engagement from upstream actors such as rope manufacturers, regulators, and logistics service suppliers. Ports can play an important facilitating role by improving waste categorisation and fostering stakeholder collaboration.

Keywords: Circular economy, Mooring lines, End-of-life management, Port waste streams, Value-chain, Stakeholder analysis, Recycling

Acknowledgements

We would like to express our gratitude to our supervisors, Brener Felipe Melo Lima Gomes at Chalmers University of Technology, Vendela Santén and Anna Skotte at RISE Marintime Department, for their guidance, feedback, and support throughout this work. We would also like to thank our examiner Anna Nyström Claesson for her valuable input during the process.

We are grateful to the Port of Norrköping and all stakeholders who generously contributed their time and knowledge through interviews and email correspondence. Your insights were essential to this study.

Anna Tingfalk and Linnéa Eriksson, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that were used throughout the thesis, listed in alphabetical order:

CE	Circular Economy
CBAM	Carbon Border Adjustment Mechanism
CEAP	Circular Economy Action Plan
CVORR	Complex Value Optimisation for Resource Recovery
DPP	Digital Product Passport
ESPR	Ecodesign for Sustainable Products Regulation
EoL	End-of-life
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse gas
HDPE	High Density Polyethylene
HMPE	High Modulus Polyethylene
IMO	International Maritime Organisation
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
MEG	Mooring Equipment Guidelines
OCIMF	The Oil Companies International Marine Forum
PCO	Product Chain Organisation
PE	Polyethylene
PEX	Cross-linked polyethylene
PP	Polypropylene
TA	Thematic analysis

Contents

List of Figures

List of Tables

1

Introduction

Ports are central nodes in global trade and logistics networks, handling vast volumes of goods, materials, and resources. In Europe alone, 74% of all goods entering or leaving the continent pass through seaports (European Commission, ndb). The scale of material flows concentrated at these sites positions ports as strategic locations for advancing Circular Economy (CE) strategies and reducing resource losses along supply chains.

The EU launched the Circular Ports project, an Interreg-funded initiative running from 2025 to 2028 that advances the transition from linear to circular systems in port environments across the Baltic Sea region (Interreg Baltic Sea Region, 2025). The project brings together port authorities, enterprises, waste management actors, and local public authorities to identify synergies, develop circular business practices, and encourage systemic change in port communities. Among the participating ports, the Port of Norrköping has identified complex materials, as a particularly challenging waste fraction. The port has mapped its waste streams in its sustainability report (Norrköpings Hamn AB, 2024), where this fraction includes various synthetic products, such as mooring lines, slings and plastic bands.

Worn-out mooring lines constitute a particularly challenging waste stream due to their material complexity, frequent contamination, and embeddedness in a broad and fragmented value-chain (Kirchherr et al., 2018). These products are often composed of multiple polymer types and are affected by operational wear, environmental exposure, and contamination during use, all of which complicate sorting, recovery, and recycling (Gadaleta et al., 2024). Their management extends beyond the port itself, involving multiple actors across production, use, collection, treatment, and potential valorisation stages. Despite this complexity, mooring line waste remains unexplored in academic literature, and no established framework exists for managing it in a circular manner.

This study examines the current end of life (EoL) management of worn mooring lines at the Port of Norrköping, with the aim of identifying barriers, opportunities, and value-chain changes required to support more circular management. The study takes a systems perspective, engaging different stakeholders across the value-chain and developing exploratory scenarios for alternative management pathways. In doing so, it aims to contribute to a more systemic understanding of how ports can move beyond conventional waste management practices toward more circular and collaborative resource management.

1.1 Aim

The aim of this study is to identify opportunities, challenges, value-chain changes, and the roles of stakeholders to support more circular management of worn-out mooring lines at the Port of Norrköping.

1.2 Research questions

To address the aim of the study, three research questions have been formulated. Together they move from mapping the current system, to evaluating alternative pathways, to understanding what stakeholder cooperation is needed to enable change:

i How are worn-out mooring lines currently managed at EoL at the Port of Norrköping, and what are the opportunities and challenges for more circular management?

ii What alternative circular pathways can be identified for worn-out mooring lines, and what value-chain changes would be required to enable them?

iii How do stakeholder positions shape the governance of worn-out mooring lines, and what changes are needed to enable higher circularity?

1.3 Limitations

This study is limited to worn-out mooring lines within the complex materials fraction at the Port of Norrköping. Other materials in this fraction, such as slings, plastic bands and tarpaulins, are only considered to the extent that they affect the handling of mooring lines. Mooring line waste as a distinct fraction in port environments has not previously been studied, and a significant part of the empirical work was therefore devoted to mapping the current system rather than conducting quantitative assessments such as life cycle assessment (LCA). The study therefore relies exclusively on qualitative stakeholder data, gathered during the spring of 2026.

2

Sustainable transition, circularity and port environments

2.1 The Green Deal transition and EU strategies

Ports and their operations are shaped by regulatory frameworks at multiple levels. The EU's Green Deal is driving systemic change in how materials and products are managed across industries in the EU, while the maritime sector has long been subject to dedicated waste management regulations governing how operational waste is handled at port. Together, these frameworks form the regulatory context within which this study is situated.

2.1.1 EU strategies and applications

The European Green Deal provides the EU's overarching framework for reaching climate neutrality by 2050 (European Commission, nda), operationalised through the European Climate Law which embeds this target in legislation across all member states. To meet this target, the EU has committed to reducing greenhouse gas (GHG) emissions of at least 55% by 2030 and 90% by 2040, relative to 1990 levels. The 2030 target is pursued through the Fit for 55 package, a set of interconnected instruments including a reformed Emissions Trading System (ETS), revised renewable energy and energy efficiency directives, and a Carbon Border Adjustment Mechanism (CBAM) (Council of the European Union, nd). Rather than targeting a single sector, the Fit for 55 package covers a broad range of areas including energy and fuels, land use and forestry, buildings and road and maritime transport. The cross-sectoral scope reflects the Green Deal's holistic approach, targeting structural economic transformation rather than fragmented, sector-by-sector emission reductions, generating regulatory pressure across the EU market and its operating actors.

The EU's traditional linear economy, in which resources are extracted, used, and discarded, has driven significant pressures on natural systems and material supply chains (Council of the European Union, 2024). In response, the Circular Economy Action Plan (CEAP) was adopted by the European Commission in 2020 as a cornerstone of the European Green Deal (European Commission, 2020), representing a strategic shift toward circular economy (CE). CEAP shifts the focus to the upstream phases of a product's lifecycle, targeting goals for product design, material selection, and production processes, with the explicit aim of making sustainable products the norm across the single market (European Commission, 2015). To achieve this, the framework introduces ecodesign requirements covering durability, repairability, recyclability, extended producer responsibility schemes that shift EoL accountability onto manufacturers, and instruments to develop functioning secondary materials markets (European Commission, 2020).

Central to the CEAP's implementation is the Ecodesign for Sustainable Products Regulation (ESPR), which extends the scope of the earlier Ecodesign Directive beyond energy-related products to include a broad range of goods sold on the EU market (European Commission, 2024). Under the ESPR, the European Commission is empowered to set product-specific performance requirements targeting material categories identified as priorities due to their high resource intensity or significant environmental impact, including textiles, electronics, furniture, construction materials, and plastics (European Commission, 2024).

A key instrument introduced under this framework is the Digital Product Passport (DPP), designed to make product-level data accessible throughout the value chain (Publications Office of the European Union, 2024). The DPP requires manufacturers to disclose information on material composition, recycled content, repairability, and EoL handling, enabling downstream actors such as recyclers, businesses, and consumers to make more informed decisions (Publications Office of the European Union, 2024). In the linear economy, information has not travelled with the product, leaving downstream actors unable to distinguish recyclable from non-recyclable material at EoL, or to verify the chemical composition, technical lifetime, and quality of components, factors that have historically prohibited material reuse. By embedding traceability and transparency requirements directly into product regulation, the CEAP aims to close the information gaps that have restricted the development of circular material flows and secondary raw material markets (European Commission, 2020).

2.1.2 Waste management regulation

Waste management in the maritime and port sector is governed by a layered regulatory framework spanning over international, European, and national levels. At the international level, the International Maritime Organization (IMO) governs the management of ship-generated waste through MARPOL Annex V (the International Convention for the Prevention of Pollution from Ships), which establishes the fundamental requirements for the prevention of pollution by garbage from ships. The regulation applies to all ships operating in the marine environment (International Maritime Organization, 2011). In Annex V, garbage is broadly defined to include all kinds of food, domestic and operational waste, all plastics, cargo residues, incinerator ashes, cooking oil, fishing gear, and animal carcasses generated during normal ship operations. Operational waste is specifically defined as all solid waste not covered by other MARPOL Annexes that is collected onboard during normal maintenance or operations of a ship (Van den Dries, 2023).

MARPOL Annex V also mandates flag states to ensure the provision of adequate port reception facilities to vessels (International Maritime Organization, 2011). At the European level, Directive 2019/883 on port reception facilities directly implements and strengthens these requirements for EU member states, introducing mandatory pre-arrival waste notification submitted by vessels, waste reception and handling plans, and a no special fee principle designed to incentivise vessels to deliver waste ashore (European Parliament and Council of the European Union, 2018). More broadly, the EU Waste Framework Directive (2008/98/EC, amended by 2018/851/EU) establishes a waste hierarchy relevant across all sectors, including ports, requiring that waste should be prevented, reused, or recycled before disposal is considered (European Parliament and Council of the European Union, 2008, 2018).

In Sweden, these frameworks are transposed through the Environmental Code and operationalised through two key regulations from the Swedish Transport Agency. TSFS 2010:96 governs vessels' obligations regarding waste delivery to port reception facilities before departure. TSFS 2023:15 requires Swedish ports to provide adequate reception facilities and to collect waste separately in accordance with the Swedish Waste Ordinance, which transposes the EU Waste Framework Directive into national law.

2.2 System perspective and application frameworks

The three analytical frameworks used in this study are life cycle thinking (LCT), value-chain perspective and circular economy (CE). LCT provides the conceptual basis for understanding and visualising product systems across their full lifetime. The value-chain perspective maps the actors and relationships governing how products move through each stage, from raw material extraction to EoL. CE R-strategies identify where circular activities are possible and how much value each preserves.

2.2.1 Life cycle thinking (LCT)

LCT provides understanding for where environmental burdens arise in the life-cycle by visualising the system. Rather than evaluating a product, process, or service at a single stage, LCT adopts a systems perspective that follows material flows and impacts across the full sequence of stages a product undergoes throughout its lifetime (International Organization for Standardization, 2006; Baumann and Tillman, 2004). This is necessary because optimising one stage in isolation risks shifting burdens elsewhere in the lifecycle chain, producing outcomes that appear locally beneficial but are neutral or harmful when considered across the whole system (Lindén et al., 2019).

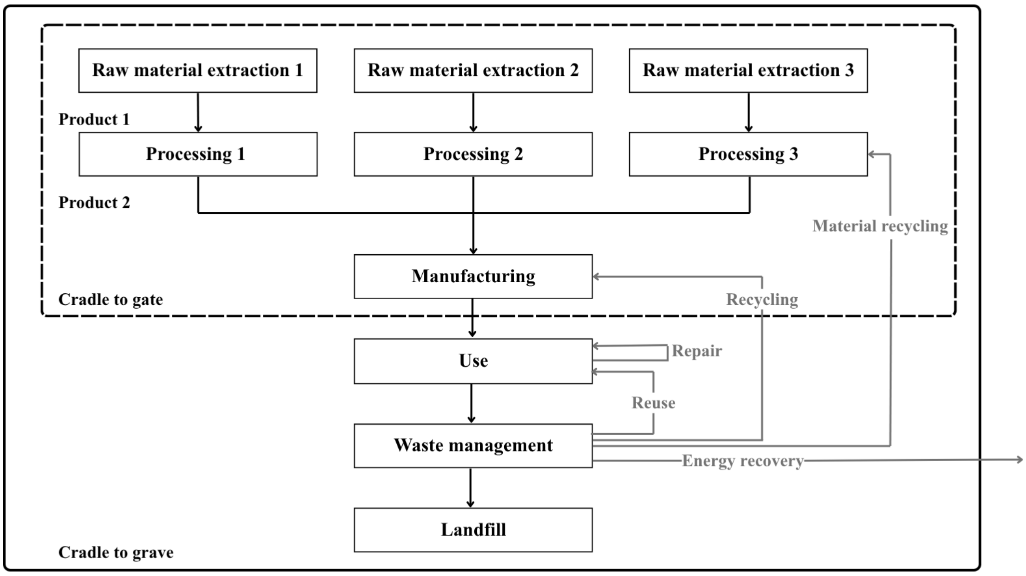


Figure 2.1: The life cycle model, developed based on Baumann and Tillman (2004).

LCT is visualised through flowcharts, where each stage of the life cycle is represented as a node connected by flows of materials and products within explicitly defined system boundaries (Figure 2.1). The model distinguishes between three system scopes. Cradle-to-gate covers impacts from raw material extraction up to the point the product leaves the factory. Cradle-to-grave extends this to include the use phase and final disposal, representing a linear system in which materials are not recovered and value is permanently lost. Cradle-to-cradle closes the loop by recovering materials at EoL and reintroducing them into production rather than discarding them, representing a circular system. Together, these distinctions make visible where flows are lost, diverted, or accumulate in ways that would not be apparent from examining any single stage in isolation (Baumann and Tillman, 2004).

2.2.2 Value-chain perspective

The value-chain describes the full sequence of activities through which a product passes from raw material extraction to delivery to the end user, with each stage involving different actors, processes, and decisions (Porter, 1985). Beyond a sequence of physical transformations, it is also a network of actors and relationships through which value is created, exchanged, and captured (De Martino, 2021). A sustainability-oriented perspective extends this view beyond efficiency and customer satisfaction to assess the economic, social, and environmental consequences of decisions made within the chain for actors both inside and outside it (De Martino, 2021).

The Product Chain Organisation (PCO) study builds on this by integrating the product life cycle view of LCT with the actor-focused perspective of the value-chain (Baumann, 2012) (Figure 2.2). The method proceeds in two steps. First, a basic life cycle flow model of the studied product is established, tracing the material from raw material extraction through production, use, and waste treatment. This technical backbone defines the scope of the study and determines which stages and actors are included. Second, an organisational study is conducted along this backbone, mapping the companies, institutions, and other actors that enable the product to move between stages. Without these actors, no material flow occurs; the PCO foregrounds this dependency rather than treating flows as abstract technical processes (Baumann, 2012).

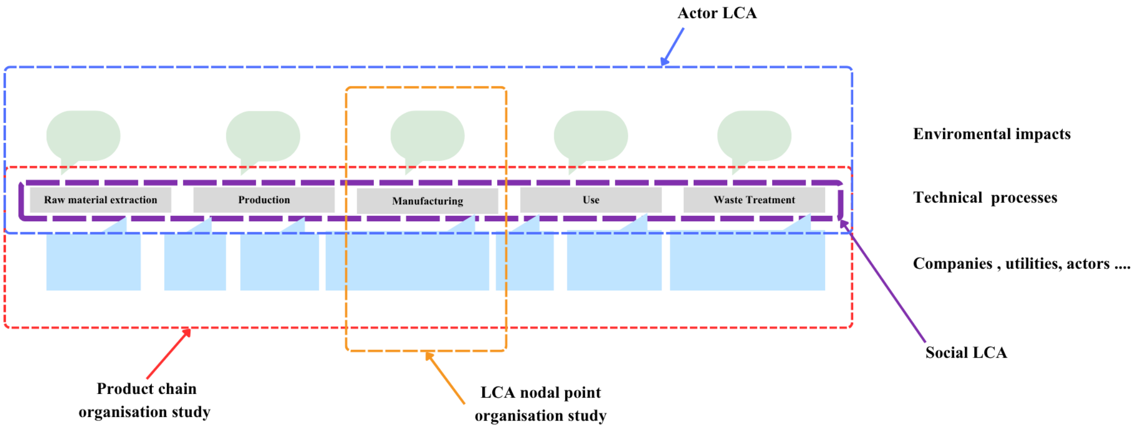


Figure 2.2: Visualisation of the technical processes and actors included in a PCO study, adapted from Baumann (2012).

Where a value-chain analysis focuses on where value is created and captured, a PCO study focuses on how the chain is organised and what that organisation enables or forecloses in terms of environmental outcomes. This includes where ownership and responsibility shift between actors, how decisions made at one stage constrain what is possible at another, and where information or coordination is absent. The approach draws on actor-network theory, which treats both physical materials and human actors as equally relevant to understanding how a system functions (Baumann, 2012).

A key distinction when studying value-chains is between upstream and downstream perspectives. Upstream refers to activities that precede a focal actor, such as raw material extraction, production, and manufacturing, while downstream refers to the stages that follow, such as distribution, use, and EoL treatment (Porter, 1985; Singer and Donoso, 2008). This distinction matters because environmental burdens and economic leverage are rarely evenly distributed across the chain. A focal actor may have direct control over its own operations, while the majority of environmental and economic consequences lie upstream in how a product is designed, or downstream in how it is used and disposed of (Lindén et al., 2019). Singer and Donoso (2008) highlights that decisions at one stage do not exist in isolation: a choice to focus efforts upstream or downstream will shape, and be shaped by, decisions made across all other stages.

2.2.3 Circular economy (CE) strategies

The 10R framework was developed as a tool to operationalise CE strategies across product value-chains (Potting et al., 2017). Rather than classifying activities as either circular or not circular, the framework organises strategies along a hierarchy from the most to the least circular, allowing practitioners to assess where in a system circular interventions are possible and how much value each intervention preserves (Table 2.1). In this study, the framework is applied from a value-chain perspective to map where circular interventions are feasible.

Level of Circularity

High

Goal	**Strategy**	**Description**
Smart product use and manufacture	R0 – Refuse	Make product redundant by abandoning its function or offering the same function with a radically different product.
	R1 – Rethink	Make product use more intense (e.g., product-sharing, multi-functional product).
	R2 – Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.
Extend lifespan of product and its part	R3 – Reuse	Reuse of a functional discarded product by another consumer.
	R4 – Repair	Repair and maintenance of a defective product to restore its original function.
	R5 – Refurbish	Restore an old product to bring it up to date.
	R6 – Remanufacture	Use product or parts in a new product with its original function.
	R7 – Repurpose	Use product or parts in a new product with a different function.
Useful application of materials	R8 – Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality.
	R9 – Recover	Incinerate materials to recover energy.

Low

Table 2.1: The 10R strategies for CE. (Potting et al., 2017).

Another way of visualising the 10R framework is a classification along a scale from circular to linear practices (Figure 2.3), and extends the original framework by including a 10th category representing landfill disposal (Svedberg, 2026). The scale distinguishes between strategies that maintain circularity (R0–R7) and those that reflect a linear, take-make-dispose approach (R8–R10), where resources are ultimately lost through downcycling, energy recovery, or landfill.

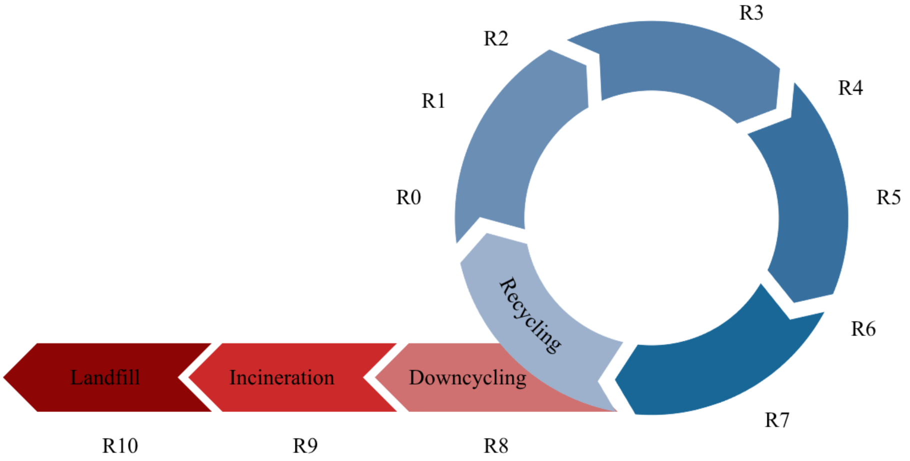


Figure 2.3: Visualisation of the expanded 10R framework, illustrating the circular (R0–R7) to linear (R8–R10) strategies.

The strategies are grouped into three categories reflecting different points of intervention in the product life cycle (Potting et al., 2017; Morseletto, 2020) (Table 2.1). The first group (R0–R2) targets the design and manufacture phase, aiming to reduce the need for products or materials altogether. The second group (R3–R7) focuses on keeping products and components in use through various forms of life extension. The third group (R8–R9) addresses materials at EoL, where recycling and energy recovery represent the last resort before value is permanently lost. Mapped onto the life cycle model (Figure 2.1), R0–R2 intervene in the cradle-to-gate phase, R3–R7 extend the use phase, and R8–R9 operate at the end of a cradle-to-grave system, with higher R-levels representing a shift toward cradle-to-cradle thinking.

2.3 Stakeholder theory, managing issues and scenario construction

This section introduces frameworks for identifying the actors relevant to worn-out mooring line waste management and understanding how their power and interests are distributed across the system. In addition, it considers the kind of collaboration between actors that is needed to enable more circular solutions to take shape.

2.3.1 Wicked problems and fragmented responsibility

Many sustainability-related challenges can be characterised as complex or "wicked" problems (Pearce and Ejderyan, 2020). Such problems are both highly complex and ill-structured, meaning that goals may be unclear, multiple solution paths exist, and different stakeholders may have competing perspectives on the issue (Pearce and Ejderyan, 2020).

Because these problems require the cooperation and buy-in from diverse groups, and because no single actor possesses sufficient knowledge or mandate to address them alone, stakeholder participation and the integration of different knowledge bases are considered essential for developing effective solutions (Pearce and Ejderyan, 2020).

However, stakeholder participation is not always required to the same extent in all situations. Hurlbert and Gupta (2015) argue that the appropriate level of participation depends on the nature of the problem at hand. For structured problems, where there is broad agreement on knowledge and values, decisions can often be handled through more technocratic processes with limited stakeholder involvement. In contrast, unstructured problems, where uncertainty and conflicting perspectives exist, require greater stakeholder participation, dialogue, and social learning to develop effective solutions (Hurlbert and Gupta, 2015). Social learning is understood here as a collective process of acquiring and sharing knowledge through social interaction, leading to cognitive and relational change among the actors involved (Ernst, 2019).

2.3.2 Stakeholder analysis and characteristics

Given that wicked problems require the involvement of multiple actors, identifying and understanding the role of those actors becomes a critical first step. Stakeholder analysis provides a structured way to do this, and has become increasingly popular across a wide range of fields, including business management, development, and natural resource management (Reed et al., 2009).

A commonly used tool for this is the power-interest grid, which maps stakeholders along two dimensions: their power to influence outcomes and their interest in the issue (Ackermann and Eden, 2011) (Figure 2.4). The emphasis on the two dimensions should be assessed separately, since stakeholders with significant interest are not necessarily powerful, and vice versa (Ackermann and Eden, 2011). The four resulting quadrants capture distinct stakeholder positions: *players* have both high power and high interest, meaning they are significant stakeholders who deserve sustained management attention; *subjects* have high interest but limited power, meaning they are engaged with the issue but have less influence over its outcomes; *context setters* hold significant power but low interest, meaning they can influence the broader context within which strategies operate without being directly engaged in the issue; and the *crowd* exhibits neither high interest nor power, meaning they can be seen as potential rather than actual stakeholders. By identifying which quadrant each actor occupies, it becomes possible to prioritise engagement, encourage productive coalitions, and consider how actors might be moved between quadrants to enable systemic change (Ackermann and Eden, 2011).

Reed et al. (2009) propose that stakeholder analysis consists of three core steps: identifying stakeholders, differentiating between and categorising them, and investigating the relationships between them. By systematically working through these steps, it becomes possible to determine whose perspectives need to be considered, where conflicts or synergies may arise, and how different actors can be effectively engaged. While all stakeholders need to be considered, not all necessarily need to participate actively. Instead, key stakeholders should be identified and engaged based on their relevance to the issue at hand (Reed et al., 2009).

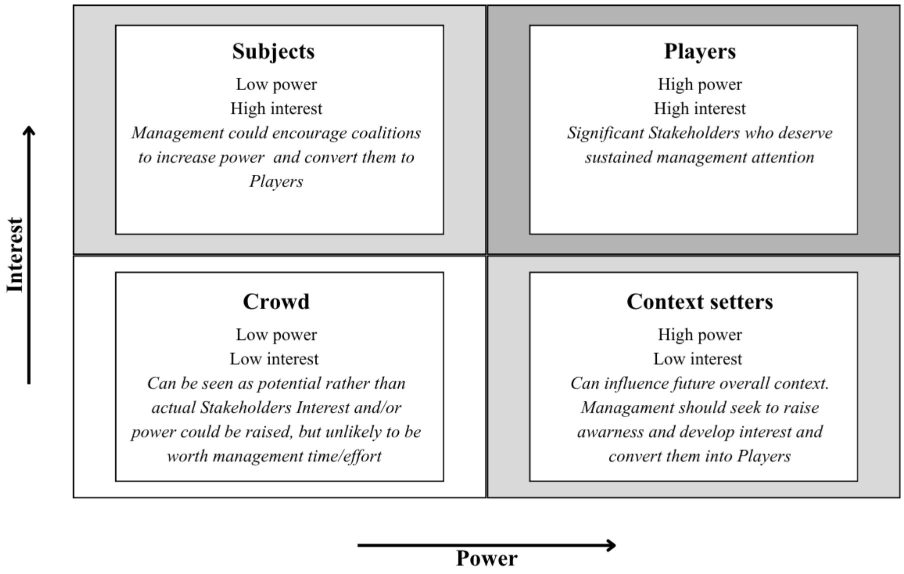


Figure 2.4: Power-interest grid, adapted from Ackermann and Eden (2011).

2.3.3 Scenario construction

Scenarios can serve fundamentally different purposes depending on the questions they are designed to answer. Börjeson et al. (2006) propose a typology that organises scenarios according to the user's underlying need: to know what will happen, what can happen, or how a specific target can be reached. These needs correspond to three main scenario types: predictive, exploratory, and normative, each with distinct characteristics (Figure 2.5).

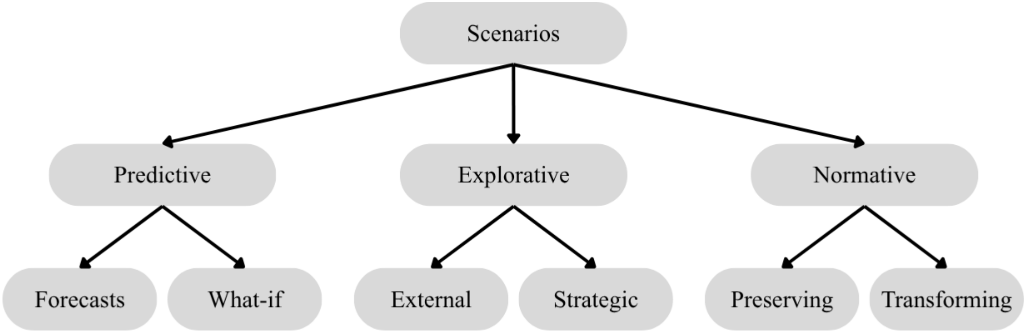


Figure 2.5: Types of scenarios based on underlying needs, adapted from Börjeson et al. (2006).

Predictive scenarios estimate what is likely to happen based on existing trends. Normative scenarios work backwards from a desired future state, asking what conditions would need to be in place for that outcome to be realised. Exploratory scenarios occupy the middle ground, asking what can happen across a range of plausible futures without committing to a single prediction or target (Börjeson et al., 2006). These are further divided into external scenarios, which focus on developments outside any single actor's control, and strategic scenarios, which examine how different decisions by an actor might play out.

In the context of waste and resource management, scenarios provide a structured way to compare alternative pathways for how materials could be handled, and to evaluate what technical, economic, and organisational conditions would need to be in place for each pathway to become viable (Iacovidou et al., 2017). Rather than prescribing a single solution, exploratory scenarios allow decision-makers to assess trade-offs across multiple plausible futures, making them particularly useful when systems are complex, actors are many, and outcomes are uncertain.

In this study, exploratory scenarios are used to examine alternative EoL pathways for mooring line waste, allowing both near-term improvements and longer-term systemic changes to be assessed within the same analytical framework. This is particularly relevant given that circular transitions require changes at multiple levels of the value-chain, from waste treatment to product design and supply chain organisation (Bocken et al., 2016). The scenarios are evaluated in terms of both technical feasibility and the level of material value preserved at each R-level, drawing on the CVORR framework (Iacovidou et al., 2017). This means each scenario is assessed not only on what treatment routes are available, but also on which actors would need to capture, share, or act on information about material composition, volumes, and condition to make each pathway viable. Each scenario is further linked to the corresponding level of circularity through the 10R framework, making trade-offs between value preservation and practical feasibility explicit across circularity levels.

2.4 Case study - Port of Norrköping and moorin lines

This study is conducted in collaboration with the Port of Norrköping, with the aim of addressing waste management challenges associated with complex materials, with a particular focus on mooring lines, as part of the Circular Ports project and the port's broader effort to increase circularity in its waste streams.

2.4.1 Port of Norrköping and complex material

The Port of Norrköping is one of Sweden's largest ports, handling approximately four million tonnes of goods annually and receiving around 1,000 vessel calls per year (Norrköpings Hamn AB, 2026). As part of its sustainability commitment, the port participates in the Circular Ports project, an Interreg Baltic Sea Region initiative engaging ports to become more circular by exploring waste reduction alternatives (Interreg Baltic Sea Region, 2025). Through this work, the port has identified complex materials, including mooring lines, slings, and plastic bands, as a particularly challenging waste fraction. According to the port's environmental reports, this fraction is classified under EWC code 17 09 04 and encompasses plastic straps, ropes, and similar materials (Norrköpings Hamn AB, 2024). The total volume of the fraction has varied over time (Table 2.2). However, quantitative data are only available for 2020, 2024, and 2025, as these are the years covered by the retrieved environmental reports and internal documents (Norrköpings Hamn AB, 2024, 2020). All materials are currently collected together in a single skip and directed primarily toward incineration.

Year	**Weight (tons)**
2020	84.54
2024	12.6
2025	27.4

Table 2.2: The annual total complex material fraction at the Port of Norrköping.

2.4.2 Mooring lines

Mooring lines are the ropes, chains, or wires used to secure a vessel to a fixed structure such as a pier, quay, or buoy, preventing it from drifting due to wind, currents, or waves (Wärtsilä, nd). They are an essential component of port operations and are used each time a vessel berths or departs. The Oil Companies International Marine Forum (OCIMF) has established recommended minimum requirements for the design, performance, and safety of mooring systems through the Mooring Equipment Guidelines, fourth edition (MEG4), published in 2018 (Oil Companies International Marine Forum, 2018). Although primarily directed at tankers and gas carriers, MEG4 provides guidance across the maritime industry on the purchasing, inspection, condition monitoring, and retirement of mooring lines. Lines that have lost more than 25 % of their original breaking strength are considered unfit for mooring use and should be retired (Oil Companies International Marine Forum, 2018).

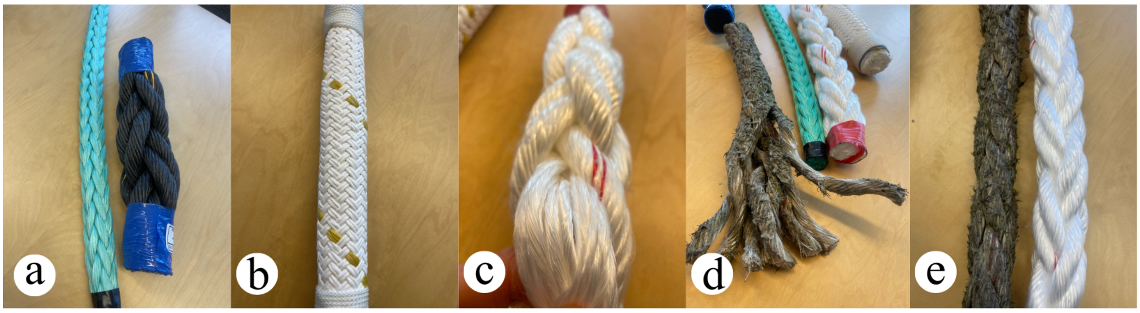
Mooring lines are usually manufactured from synthetic polymer fibres, primarily polypropylene (PP), polyester, polyamide (nylon), and high modulus polyethylene (HMPE), each with distinct mechanical and chemical properties suited to different operational requirements (Duracordix, 2025) (Table 2.3).

Material	**Melting point [°C]**	**Density [g/cm^3]**
PP	≈165[1]	0.91[1]
HDPE	130–135[2]	0.93–0.97[2]
Polyester	≈260[1]	1.38[1]
HMPE	≈145[1]	0.97[1]
Nylon	≈220[1]	1.14[1]

[1] Based on Duracordix (2025).
[2] Based on Conniff (2026).

Table 2.3: Melting points and densities of polymers commonly associated with synthetic mooring lines.

The differences in melting point and density between polymer types are significant for EoL management: PP and HMPE melt at relatively low temperatures while polyester and nylon require higher temperatures, meaning that mixed-polymer fractions cannot be processed together without degrading material quality (Rasilainen et al., 2026). Because no single material satisfies all performance requirements simultaneously, many lines are produced as composite constructions combining two or more polymers (Duracordix, 2025) (Figure 2.6). During the use phase, mooring lines are subjected to extensive wear, UV degradation, and contamination from oil, sand, and biological matter, all of which reduce material quality and complicate recovery (Duracordix, 2025). Their physical dimensions create further practical challenges, as some lines measure 15 to 20 centimetres in diameter and require specialised equipment to handle. These characteristics mean that worn mooring lines are often incompatible with standard waste treatment infrastructure, causing operational disruptions and limiting options for material recovery, and thereby creating the waste management challenge that this study addresses.



(a) HMPE rope (left) and PP rope (right), (b) braided rope with coating of unknown composition, (c) composite rope with polyester outer layer and PP core, (d) cross-section of rope in (c) showing fiber structure and contamination from use, (e) new (left) and worn (right) rope of same type as (c), illustrating degree of contamination over time.

Figure 2.6: Mooring lines at Logistic Service Supplier A (Authors own pictures).

3

Method

This study adopted an exploratory qualitative case-study design to examine the management of worn-out mooring lines at the Port of Norrköping through stakeholder engagement, value-chain mapping, thematic analysis and exploratory scenario development (Figure 3.1). The workflow was structured into two main phases: data collection (Step 1) and data analysis (Steps 2–5). Each phase built systematically on the previous, ensuring that the analytical framework remained grounded in empirical data.

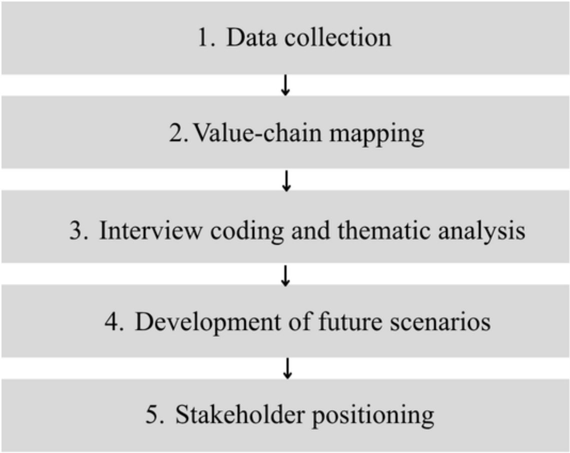


Figure 3.1: The workflow of the study.

3.1 Data Collection

Data was collected in two steps: primary stakeholder engagement through interviews, email correspondence, and a site visit; and complementary data sourced from relevant literature and supporting documents.

3.1.1 Stakeholder engagement

Qualitative data on stakeholders' roles, interests, and perspectives were collected through semi-structured interviews, email correspondence, and site visits. Stakeholders across the marine and port industry were contacted via email and invited to contribute to the study. A total of 25 stakeholders participated, of whom 12 contributed through interviews and 13 through email correspondence. One interview was conducted at the stakeholder's main office, which simultaneously served as a site visit, providing photographs and firsthand observations that deepened the study's contextual understanding of mooring lines.

The stakeholder selection followed a purposive and iterative approach unfolding in two phases. In the first phase, an initial set of stakeholders was identified through a theoretical mapping of the value-chain, meaning that relevant actor categories were identified based on their expected roles in the production, use, and EoL management of mooring lines, drawing on existing literature and project documentation. This ensured that the starting sample spanned the full breadth of the system, from material producers to end-users, though specific organisations within each category were not yet identified. The study then began with an interview with the Port of Norrköping, who described the waste fraction and identified the first set of relevant actors. In the second phase, the sample was expanded through snowball sampling, by which interviewees and project partners identified additional relevant actors, allowing the sample to grow in response to empirical insights rather than remaining fixed to the initial theoretical mapping. Throughout both phases, selection was guided by stakeholders' roles in the value-chain, their influence on material flows, and their relevance to the research questions. The goal was not statistical representation, but a diverse range of perspectives.

Table 3.1 presents the stakeholders engaged throughout the study, along with the data collection method or contact channel used for each. All stakeholders, with the exception of the Port of Norrköping, were anonymised and assigned a unique ID used consistently throughout the report, in order to protect the privacy of individuals and organisations involved and to encourage open and honest responses during data collection.

Stakeholder type	Geographical location	ID	Contact
Port of Norrköping	Norrköping, Sweden	-	Interviews and Email
Port	Sweden	B	Interview and Email
Port	Estonia	C	Email
Port	Denmark	D	Email
Port	Sweden	E	Email
Collaboration Partner	Sweden	A	Interview
Logistics Service Supplier	Sweden	A	Interview and Site visit
Incineration Plant	Sweden	A	Email
Incineration Plant	Sweden	B	Email
Incineration Plant	Sweden	C	Email
Incineration Plant	Sweden	D	*
Circular Solution Company	Norway	A	Interview
Circular Solution Company	Sweden	B	Interview
Circular Solution Company	Sweden	C	Interview
Circular Solution Company	Sweden	D	Interview
Circular Solution Company	Sweden	E	Interview
Circular Solution Company	Denmark	F	*
Waste Handling Organisation	Sweden	A	Interview
Waste Handling Organisation	Sweden	B	Email
Waste Handling Organisation	Sweden	C	*
Shipping Company	Sweden	A	Email
Shipping Company	Sweden	B	Email
Shipping Company	Sweden	C	Email
Shipping Company	Sweden	D	Email
Shipping Company	Sweden	E	Email
Rope Manufacturer	Sweden	A	Interview
Researcher	Sweden	A	Interview

* Stakeholders identified but not actively engaged in study.

Table 3.1: Anonymised stakeholders in study and the form of contact.

A total of 12 interviews were conducted with representatives from the identified stakeholder groups to collect qualitative data on the study area. To this end, semi-structured interviews were designed following the framework proposed by Longhurst (2003). The interviews addressed the handling of the waste fraction, the stakeholders' roles, and their perspectives and expertise on the management of the complex material fraction, with a particular focus on worn-out mooring lines at the Port of Norrköping. This format allowed consistency across interviews while providing flexibility to explore emerging topics during discussions. All stakeholders, except shipping companies, were asked the same set of eight core questions (Table 3.2), thereby ensuring comparability across respondent groups.

Core questions	
No.	**Question**
Q1	Can you briefly describe your role and your organization's relation to mooring lines or slings?
Q2	How do you currently interact with mooring lines and slings throughout their life cycle?
Q3	What challenges do you perceive in the current handling of worn-out mooring lines and slings?
Q4	Which stakeholders do you cooperate with that are connected to the complex materials value-chain?
Q5	What barriers do you perceive limit the circularity of the material today?
Q6	What opportunities do you see for EoL alternatives for the material?
Q7	What conditions would need to be fulfilled for you to engage in a circular solution?
Q8	From your perspective, what would be the most important next step toward a more circular management of mooring lines?

Table 3.2: Core interview questions used in stakeholder interviews.

Additional interview questions were tailored to each stakeholder group based on their specific roles, responsibilities, and areas of expertise, in line with the facilitation techniques described by Hemmati (2002). This enabled a more in-depth exploration of topics as they emerged during each interview. Most interviews were conducted digitally via Microsoft Teams and lasted between 30 and 60 minutes. With participants consent, all interviews were audio-recorded and subsequently transcribed using the AI-based transcription tool Klang, with timestamps included to facilitate traceability back to the original recordings. As all interviews were conducted in Swedish, the transcriptions were translated into English. The transcriptions were reviewed and corrected where necessary to ensure accuracy and reliability.

Email correspondence was used as a complementary data collection method when interviews were not feasible due to availability constraints. The approach ensured that all stakeholder perspectives were represented and provided additional insight into current practices for handling mooring lines. As the primary stakeholders during the use phase, shipping companies were asked a separate set of questions (Table 3.3), specifically designed to examine how mooring lines were managed onboard and which practices were followed when they reached EoL.

Operational questions	
No.	**Question**
Q1	Where do you procure mooring lines?
Q2	What material of mooring lines do you primarily use?
Q3	How long are mooring lines typically used, and when do you replace them?
Q4	What actions do you take on board to extend the lifespan of mooring lines?
Q5	How do you determine when a mooring line can no longer be used for mooring?
Q6	What do you usually do with mooring lines once they are taken out of use?
Q7	If mooring lines are left at the port, do they need to be cut or divided into smaller parts beforehand?
Q8	Do you have any agreements with waste management or recycling companies handling EoL mooring lines?
Q9	If yes, how does the process work in practice (e.g., where is the material delivered, which company receives it, and are any preparations required)?
Q10	Do you know what typically happens to the mooring lines after they are handed over (e.g., incineration, recycling, or other treatment)?
Q11	Do you experience any challenges in handling EoL mooring lines today?

Table 3.3: Emailed operational questions regarding the use-phase handling of mooring lines.

3.1.2 Literature and other documents

Relevant scientific literature was reviewed throughout the study to support the findings, theoretical framework and analysis (Table 3.4). The selection was guided by relevance to the research questions rather than a systematic search process. For instance, policy documents and directives were retrieved from the EU Commission and IMO, while peer-reviewed articles were identified through Scopus and Google Scholar. Results from these databases were filtered to include peer-reviewed research and review articles published in English, with titles and abstracts screened for relevance prior to selection and usage.

Complementary data and documents were also retrieved from internal sources to assess the scope and context of the problem. These included documents from the Port of Norrköping, RISE, and the Interreg Circular Ports Project, such as waste flow excel datasets, environmental data, and other project reports. The available material was limited and primarily served to build an initial understanding of waste management practices at the Port of Norrköping.

Subject area	**Document type**	**Database**	**Search terms**
EU regulatory frameworks	Policy documents, directives	EU Commission, IMO	*The Green Deal, Fit for 55, CEAP, ESPR, DPP*
Waste management regulations	Policy documents, directives	EU Commission, Scopus	*MARPOL Annex V, Waste framework directive, Environmental code, Waste hierarchy, Producer responsibility*
Circular economy	Peer-reviewed articles, Grey literature	Scopus, Google Scholar	*Circular economy, Resource recovery, Sustainability, CE strategies*
System thinking	Peer-reviewed articles	Scopus, Google Scholar	*Systems thinking, LCT, LCA, LCM, PCO, Value-chain, Industrial ecology*
Scenario creation	Peer-reviewed articles	Scopus, Google Scholar	*Explorative scenarios, Future scenarios, Scenario development*
Stakeholder theory	Peer-reviewed articles	Scopus, Google Scholar	*Stakeholder analysis, Wicked problems, Power–interest, Social learning*
Port of Norrköping	Grey literature, Environmental reports	Google	*Waste policy, Port operations, Swedish ports*
Mooring lines	Peer-reviewed articles, Industry reports, Grey literature	Scopus, Google	*Mooring lines, Marine applications, Polymer, Plastics, Synthetic, Material performance, Material durability, EoL treatment, Chemical recycling, Mechanical recycling*

Table 3.4: Literature search strategy by subject area.

3.2 Data Management

The data analysis followed an iterative process in which the understanding of the problem evolved continuously alongside the empirical work, guided by the collaborative problem framing framework of Pearce and Ejderyan (2020) and Stokols et al. (2010). As the value-chain was traced and interviews progressed, the study's framing shifted from an initial single-actor perspective toward a more systemic, multi-stakeholder understanding. This evolving problem understanding informed each subsequent step of the analysis: the value-chain mapping, the coding and thematic analysis, the development of scenarios, and the stakeholder positioning.

3.2.1 Complex material value-chain mapping

The value-chain of the complex material waste fraction was mapped using the PCO framework (Baumann, 2012), which structures the analysis around both the technical processes and the actors involved at each stage of the life cycle. Following this framework, the mapping traces how the material moves between actors, where ownership and responsibility shift, and how decisions made at one stage constrain or enable what is possible further along the chain.

The mapping process was iterative and stakeholder-driven, following a life cycle perspective (Baumann and Tillman, 2004). Beginning with the Port of Norrköping, each actor was asked to describe how the material was managed once it left their organisation, and to identify the next actor in the chain and the processes the material underwent there. This approach allowed the value-chain to be traced step by step, from the point at which the material became waste at the port through to its final treatment destination, with knowledge assembled gradually through conversations with multiple stakeholders, each contributing their part of the picture.

The mapping distinguishes between two value-chains, reflecting a shift in handling practices identified through the interviews: the original value-chain, capturing how the material was managed before operational disruptions occurred, and the current value-chain, capturing how the material fraction is handled today.

3.2.2 Coding and thematic analysis

The qualitative data collected through interviews, email correspondence, and site visits were analysed using thematic analysis (TA), following the six-phase framework proposed by (Ahmed et al., 2025). This approach was chosen for its structured yet flexible nature, enabling systematic identification of patterns across diverse stakeholder perspectives while allowing for iterative refinement throughout the process.

Phase 1 - Familiarisation with the data. All interview recordings were transcribed, and email responses were compiled into a unified document. The material was read and re-read to establish an initial understanding of recurring ideas and patterns across the dataset (Ahmed et al., 2025).

Phase 2 - Generating initial codes. The data were organised in a spreadsheet matrix structured around the core interview questions, enabling systematic comparison across stakeholder groups. An inductive coding approach was applied, whereby relevant text segments were labelled with descriptive codes. The coding categories were structured around four dimensions linked to the research questions: key concepts, challenges, stakeholder perspectives, and circular ideas. Coding was carried out continuously after each interview was added to the matrix, so that emerging patterns could be identified and refined throughout the data collection process.

Phase 3 - Searching for themes. Codes were grouped into broader patterns, with analytical observations and emerging themes systematically documented to ensure traceability between the raw data and the developing analysis (Ahmed et al., 2025).

Phase 4 - Reviewing themes. The candidate themes were reviewed by comparing responses to the same questions across stakeholder groups side by side, noting similarities, contradictions, and perspectives unique to specific groups. An issue occurring once was recorded as a single mention, defined as an explicit reference to a challenge, opportunity, or characteristic related to the research topic, while recurring references to distinct aspects were counted as multiple mentions.

Phase 5 - Defining and naming themes. Themes were refined and named to reflect the analytical content rather than merely describing the data (Ahmed et al., 2025).

Phase 6 - Writing the report. The transition from raw data to results followed a structured process of coding, categorisation, and thematic synthesis, forming the analytical foundation for the three main areas of results: the identified challenges, the stakeholder positions and opportunities, and the value-chain mapping.

3.2.3 Scenarios for alternative management

Two exploratory value-chain scenarios were developed as analytical tools to examine alternative ways of managing the mooring line waste stream. Rather than representing implementation-ready models, the scenarios serve as structured thought experiments to assess the plausibility and potential of different circular management pathways under current conditions (Börjeson et al., 2006). The scenarios differ in scope and perspective: the first focuses exclusively on downstream waste management activities, while the second takes a broader circular perspective by integrating both upstream and downstream interventions. Both are of an exploratory external character (Börjeson et al., 2006), meaning they aim to examine a range of plausible future conditions for EoL treatment rather than to prescribe specific actions.

The scenarios were structured following the Complex Value Optimisation for Resource Recovery (CVORR) framework (Iacovidou et al., 2017), which organises the assessment of resource recovery systems into three phases: system synthesis, system analysis, and system refinement. The starting point for scenario development was the identified value-chain, as mapped in Section 4.1. Potential circular interventions were identified through an iterative, bottom-up process (Leite et al., 2000), drawing on opportunities and ideas expressed by stakeholders during interviews, email correspondence and complemented by insights from the literature and project documentation. Interview data reflected existing practices and real-world conditions, while the literature provided higher-level circular strategies not yet implemented in practice. These activities were subsequently categorised according to the 10R framework (Potting et al., 2017), which ranks strategies from the most to least resource-preserving. Each identified activity was manually assigned to the R-level that best reflected its degree of circularity based on its position in the value-chain and the extent to which it preserved material value. The identified activities were compiled into a table and assessed in terms of technical readiness, scalability, and associated advantages and disadvantages (Appendix Table A.2).

The first scenario was developed from a downstream value-chain perspective, focusing on how mooring line waste was managed after the use phase. This perspective was chosen because the interviews revealed that the primary challenges and decision points were concentrated at the EoL stage, where responsibilities for collection, sorting, and treatment were unclear and fragmented. The scenario therefore examines how existing downstream actors and processes could be reorganised or strengthened to improve material recovery.

The second scenario took a broader, circular perspective by integrating both upstream and downstream activities. This scope was motivated by insights from stakeholders operating across multiple stages of the value-chain, who identified opportunities for intervention beyond the EoL stage, such as design for disassembly and producer responsibility. The scenario incorporates principles from industrial ecology and cradle-to-cradle thinking (Iacovidou et al., 2017), and applies stakeholder theory by grouping relevant actors according to their roles and analysing potential collaborations that could enable a more systemic transition toward circular management.

3.2.4 Stakeholder process

Following the stakeholder engagement described in Section 3.1.1, a stakeholder characterisation was conducted using the power-interest matrix (Ackermann and Eden, 2011), in order to assess how different actors related to the issue and to identify whose engagement would be most critical in moving toward a circular management of mooring line waste.

Each stakeholder was individually classified along the two dimensions of power and interest, positioning them in one of four quadrants (Ackermann and Eden, 2011), (Figure 2.4). The classification was conducted jointly by both authors through an iterative discussion process until consensus was reached, in order to minimise individual bias in the interpretation. Placements were based on two sources of evidence: empirical data gathered through the interviews, in which stakeholders themselves described their roles, responsibilities, and degree of engagement with the waste fraction; and the authors' analytical interpretation of structural factors, such as regulatory authority, contractual relationships, and position in the value-chain. Where interview data provided direct evidence of a stakeholder's level of interest or formal power, this was treated as the primary basis for classification. Where such evidence was absent, placements reflect the authors' interpretive judgement.

4

Results

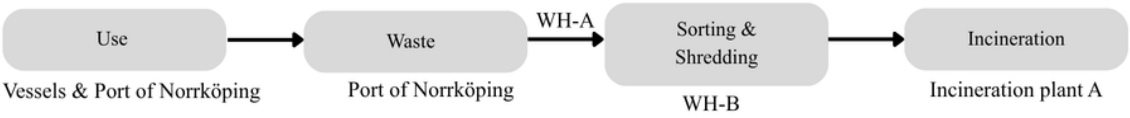
The empirical findings of the study were structured around three areas of investigation. First, the downstream value-chain of mooring line waste at the Port of Norrköping was mapped across two states: an original configuration and the current one. Second, the opportunities identified by the stakeholders for more circular activities were presented, followed by the challenges they saw in the current management. Finally, two exploratory scenarios were developed to illustrate alternative pathways for the EoL management of mooring lines.

4.1 Value-chain mapping

The waste management value-chain was mapped for mooring lines and other complex materials classified as waste at the Port of Norrköping, tracing each material through to its final treatment destination. The mapping covers both the original and the current processes, reflecting how the handling of these materials has changed over time.

4.1.1 The original waste management of mooring lines

In the original system, the downstream value-chain stages of the complex materials involved conventional waste handling through a linear system (Figure 4.1). The complex material fraction consisted of mooring lines, slings, plastic bands and tarpaulins, collected in a skip and transported by Waste Handling Organisation A for sorting and shredding at Waste Handling Organisation B. The material was then sent to Incineration Plant A for incineration, generating heat as the end product.



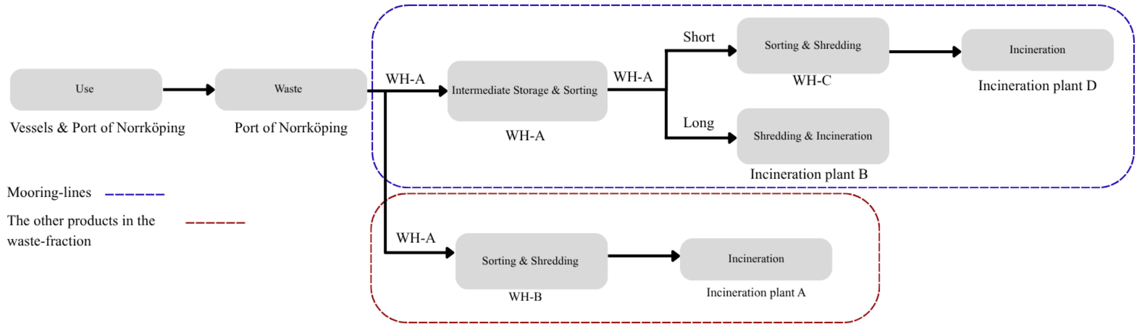
WH= Waste handling organisation.

Figure 4.1: Original downstream value-chain processes and involved stakeholders

The linear system, as previously described worked well until operational issues occurred at the incineration process. Due to the length and structural complexity of mooring lines they tended to get entangled in the machinery, leading to blockages in the fuel preparation stage or disruptions in the boiler feeding system (Incineration Plant A, personal communication, 4 March 2026). Consequently, Incineration Plant A formally added the material to its deviation list of non-conforming waste fractions, which was communicated to all of their contracted customers. The plant also acknowledged that any such materials received in error were separated and placed into dedicated landfill skips.

4.1.2 The current waste management of mooring lines

At the time of the study, the disruption of the original value-chain had led to a more complex system involving a broader set of actors and two separate processing routes depending on the physical characteristics of the materials in the complex material fraction (Figure 4.2). The waste management process began the same way as before: mooring lines arriving at the Port of Norrköping as waste were collected by Waste Handling Organisation A for intermediate storage and initial sorting, during which they were separated from the remaining complex material fraction (Waste Handling Organisation A, personal communication, 11 March 2026). From this point, the process diverged depending on size: smaller mooring lines were transported to Waste Handling Organisation C for sorting and shredding, then forwarded to Incineration Plant D for incineration; larger, heavier mooring lines required more individualised handling and were instead sent directly to Incineration Plant B, where they were shredded and incinerated on site. Incineration Plant B was selected because its advanced cutting technology was capable of handling large and complex mooring lines, while the smaller mooring lines were routed through Waste Handling Organisation C to Incineration Plant D, which was chosen due to its shorter transport distance (Waste Handling Organisation A, personal communication, 11 March 2026).



WH= Waste handling organisation.

Figure 4.2: Current downstream value-chain processes and involved stakeholders

Unlike the mooring lines, the remaining materials in the complex material fraction continued to follow the original system. They were transported by Waste Handling Organisation A to Waste Handling Organisation B, where they were sorted and shredded before being sent to Incineration Plant A for incineration. Waste Handling Organisation B did not handle mooring lines due to limitations in their cutting equipment, which could not process long ropes without causing operational disruptions.

The transition from the original to the current system illustrated that the initial value-chain was not stable. The disruption arose from an operational incompatibility at the incineration process, where existing equipment was unable to accommodate all material types, forcing the mooring lines to be redirected to alternative incineration plants. This led to a restructured system with additional actors and separate processing routes based on the physical characteristics of the materials.

4.2 Opportunities for circularity by stakeholders

Different opportunities for more circular management of mooring line waste were identified through the stakeholder engagement. These were grouped into three categories according to the 10R framewok: low-level strategies such as possible recycling pathways, mid-level strategies connected to reuse and repurposing, and high-level strategies centred on systems thinking and design for recyclability (Potting et al., 2017) (Table 4.1). The mid- and high-level strategies were further supplemented by circular activities identified through email correspondence and the literature review, as examples of such strategies currently applied in practice were more limited and isolated at higher levels of circularity.

Identified opportunities	**No. of stakeholders**
Low-level circularity (R8–R9)	
Mechanical recycling (R8)	7
Chemical recycling (R8)	3
Mid-level circularity (R3–R7)	
Re-purpose ropes for parts (R7)	2
Re-purpose for design applications (R7)	2
Reuse in same application (R3)	1
Other identified circular activities	
High-level circularity (R0–R2)	
Reverse logistics & Design for Recycling (R1)	2
Other identified circular activities	

Table 4.1: Identified circular alternatives and number of stakeholders expressing each opportunity

4.2.1 Low level (R8-R9)

The low-level opportunities identified were associated with two recycling (R8) pathways. Mechanical recycling was the most frequently mentioned pathway across the interviews and was considered the most viable near-term opportunity, primarily for single-polymer ropes composed of PP and PE, which could be shredded, melted, and extruded into recycled plastic granulates for use in new products (Logistic Service Supplier A, personal communication, 17 March, 2026). Relatively pure polymers such as PP could be integrated into existing plastic recycling systems in Sweden, where the granulates could be used to manufacture components for the automotive industry, provided the material arrived sorted, in sufficient volumes and free of contamination (Circular Solution Company C, personal communication, 19 March, 2026).

For ropes of mixed or uncertain polymer composition unsuitable for mechanical recycling, chemical recycling was identified as a potential alternative pathway. Emerging waste-to-methanol and gasification infrastructure were highlighted as viable routes for handling mixed and contaminated plastic fractions, though these technologies were considered more costly and less technologically mature than mechanical recycling (Researcher A, personal communication, 4 April, 2026). Chemical recycling was seen as a useful addition to mechanical recycling, able to address waste fractions that fall outside the scope of mechanical processing. Nonetheless another stakeholder acknowledged that the pathway remains dependent on thorough pre-treatment and is similarly affected by contamination and material heterogeneity (Circular Solution Company E, personal communication, 17 April, 2026).

Other parallels were drawn to already established cable recycling systems, where the physical characteristics of the material, such as length and size, pose similar handling challenges to those of mooring line waste. On this basis, chemical recycling was suggested as a potentially applicable pathway, as such systems already process polymers like cross-linked polyethylene (PEX), which could indicate transferable treatment approaches for rope waste streams (Circular Solution Company D, personal communication, 21 April, 2026).

4.2.2 Mid level (R3-R7)

Reuse and re-purposing were identified as opportunities by several stakeholders. Ropes in sufficient structural condition could be untwisted and the recovered fibres redirected into new rope products, while ropes no longer suitable for high-performance applications could be resold to industries with lower certification requirements, representing a re-purposing for parts (R7) (Circular Solution Company A, personal communication, 4 March, 2026). Reuse possibilities also included incorporating rope material into composite products such as construction beams, or directly reusing ropes for other purposes (R3) (Circular Solution Company B, personal communication, 10 March, 2026). Niche re-purposing through art and design applications (R7) was also highlighted, with the creation of benches serving as one such example; projects of this kind were further noted as a means of drawing attention to marine plastic waste (Circular Solution Company B, personal communication, 10 March 2026; Collaboration Partner A, personal communication, 25 February 2026).

Other identified circular activities were found among the shipping organisations, aimed at extending the serviceable life of mooring lines (Appendix A.2). Repair and reconditioning (R4) included reversing lines to redistribute wear, shortening, splicing new eyes, and removing damaged sections (Shipping Organisation A, personal communication, 11 March 2026; Shipping Organisation C, personal communication, 15 April 2026; Shipping Organisation D, personal communication, 15 April 2026). Replacement and maintenance of protective sleeves and coatings (R4) was also reported as a activity of extending rope durability (Shipping Organisation B, personal communication, 15 March 2026; Shipping Organisation D, personal communication, 15 April 2026). Condition-based inspection routines were likewise applied, ranging from monthly visual assessments to the usage of tracking systems, though it was noted that visual inspection alone may not reliably capture the loss of internal strength (Shipping Organisation B, personal communication, 15 March 2026; Shipping Organisation D, personal communication, 15 April 2026; Shipping Organisation E, personal communication, 15 April 2026). Collaboration between Shipping Organisation B and Logistic Service Supplier A on a hybrid rope construction (*Reline*) incorporating recovered material (R6) was also identified, and was regarded as a scalable transition solution, although the quality consistency was highlighted as a remaining challenge (Shipping Organisation B, personal communication, 15 March 2026).

4.2.3 High level (R0–R2)

Reverse logistics and take-back systems (R1) were described as near-term solutions for improving collection and handling of discarded ropes, integrated into existing transport flows where worn mooring lines were collected during the return transport of new products. Such systems were already being implemented within the sector, reducing the need for separate waste collection logistics while creating a direct connection between users and circular solution providers (Logistic Service Supplier A, personal communication, 17 March, 2026). Mooring line service models including collection, inspection, and return coordination were also identified as a means of ensuring EoL handling and material recovery, though coordinated reverse logistics and unclear responsibility allocation were noted as challenges (Circular Solution Company A, personal communication, 4 March, 2026).

Design-for-recycling (R1) was identified as a principle for future mooring line development and manufacturing. Current rope constructions were described as difficult to recycle due to mixed polymer compositions and complex multi-layered structures (Logistic Service Supplier A, personal communication, 17 March, 2026). Future rope designs using more standardised material compositions and fewer polymer combinations were suggested as a way to simplify recycling, though such design changes were noted to involve trade-offs related to cost, safety, operational requirements, and onboard inspection practices.

Additional circular activities were also identified at the design phase (Appendix A.2). The use of recycled rather than virgin material in new rope constructions (R2) was noted as a means of reducing resource extraction, but still with potential quality implications raised as a concern (Logistic Service Supplier A, personal communication, 17 March, 2026). Another connection to circularity was identified in relation to MEG4, which sets dimension requirements for mooring lines based on safety criteria. Using ropes that meet but do not exceed these requirements was seen as a way to avoid unnecessary material use (R2), though the MEG4 guidelines themselves do not address this circular potential, and realising it would require deliberate standards adaptation (Oil Companies International Marine Forum, 2018). Condition monitoring and inspection systems were mentioned as a way of optimising replacement timing and extending rope service life (R2), with sensors and data infrastructure identified as prerequisites for wider implementation (Shipping Organisation B, personal communication, 15 March 2026; Shipping Organisation D, personal communication, 15 April 2026; Shipping Organisation E, personal communication, 15 April 2026). Digital product passports and NFC-chips (R1) were highlighted as tools for storing and transferring information on material composition and treatment history along the rope lifecycle, thereby supporting more informed decisions on reuse, repair, and recycling at EoL. Limited data availability and lack of industry-wide adoption were identified by the shipping organisations as current limitations to their practical effectiveness (Shipping Organisation B, personal communication, 15 March 2026; Shipping Organisation D, personal communication, 15 April 2026; Shipping Organisation E, personal communication, 15 April 2026).

4.3 Management challenges by stakeholders

The interviews and stakeholder engagement process identified several challenges in the current management of mooring line waste. Some were raised by multiple stakeholders, as they span several phases of the material life cycle, for example the size and length of mooring lines. The identified challenges are summarized in (Table 4.2). The following elaboration presents these challenges grouped into three categories: material challenges, technical challenges, and economic challenges.

Identified Challenges	**No. of stakeholders**
Material challenges	
Size and length	10
Mixed polymer materials	8
Material quality (Contamination and degradation)	6
Technical challenges	
Sorting at source	7
Stable material flow (Volume of waste fraction)	6
Separation technologies	3
Economic challenges	
Economic feasibility of circular options	8

Table 4.2: Most common challenges among stakeholders, grouped by category

4.3.1 Material challenges

Size and length of the mooring lines were identified as significant practical barriers to effective waste management by ten stakeholders across the value-chain, such as ports, waste handling organisations, incineration plants and collaboration partners and research actors. The key difficulty was that mooring lines varied greatly in size, making it impractical to handle them in a standardised way. A single mooring line could fill an entire skip or represent only a small part of a mixed material fraction, and was enough for the entire load to be classified as complex material, even if it represented only 5% of the total weight (Waste Handling Organisation A, personal communication, 11 March, 2026). The largest lines, measuring 15 to 20 centimetres in diameter, could not be handled by hand and required cranes or lifting trucks (Port of Norrköping, personal communication, 24 February, 2026) (Figure 4.3). This inconsistency made it difficult to accommodate the material within standard waste contracts and handling routines, sometimes resulting in unexpected costs. Overall, the physical properties of mooring lines such as their length, size, and volume constituted a shared practical challenge for multiple stakeholders across the value-chain, as the high variability in these dimensions complicated the establishment of standardised handling practices.

The size challenge of the mooring lines also prompted downstream actors to introduce handling constraints of their own. Port B required vessels to cut their mooring lines into segments of 0.5 to 1 metre before depositing them. Incineration Plants A, B, and C raised the same concern, noting that material not reduced in size caused operational disruptions. For Incineration Plant A specifically, fraction sizes exceeding 100 mm posed serious operational risks, ultimately making locally conventional incineration unavailable for mooring line waste.

Figure 4.3: Large size mooring at Port of Norrköping

Beyond size, the material complexity of mooring lines themselves was considered a key barrier to circularity among downstream stakeholders. Logistic Service Supplier A noted that while some ropes consist of a single polymer such as HMPE or PP, many ropes were designed to meet specific performance requirements, such as high strength and elasticity, and therefore consist of multiple polymer types integrated in different structural configurations (Logistic Service Supplier A, personal communication, 17 March, 2026). Circular Solution Company C specified that mixed polymers such as PP combined with polyester or polyamide were difficult or impossible to recycle in their process (Circular Solution Company C, personal communication, 19 March, 2026).

Mixed polymer compositions were identified as a key material challenge, particularly by circular solution companies. Effective recycling require relatively pure and well-sorted material streams, as different polymers had distinct melting temperatures and material properties (Circular Solution Company C, personal communication, 19 March 2026; Circular Solution Company D, personal communication, 21 April 2026). When mixed polymers were processed together, material quality decrease, limiting the potential for high-value recycling and often resulting in downcycling. The most recyclable ropes were made from a single identifiable polymer, identifying and separating these from the broader waste stream remained a practical challenge throughout the value-chain (Logistic Service Supplier A, personal communication, 17 March 2026).

Contamination and material degradation were also identified as significant material challenges. During use, mooring lines were subjected to extensive wear and exposure to oil, UV radiation, biological matter such as shells and algae, and abrasive materials such as sand, leading to both physical degradation and chemical contamination of the fibers (Figure 4.4). Consequently, used mooring lines require cleaning before any recycling process could begin, and fiber degradation reduces the quality of the recovered material even after cleaning (Logistic Service Supplier A, personal communication). Contamination could also extend beyond visible soiling, as ropes could contain metal parts, tapes, and additives with restricted substances, which posed the risks of damage to processing equipment (Circular Solution Company C, personal communication, 19 March, 2026).

Figure 4.4: Worn-out mooring lines (Authors own pictures).

4.3.2 Technical challenges

Sorting at source was identified as a key technical challenge. At the Port of Norrköping, both vessel crews and port workers deposited waste into a shared complex material skip, producing a mixed fraction of synthetic materials (Figure 4.5). Waste Handling Organisation A identified this as a primary barrier to effective waste management.

(a) Mooring lines, (b) mixed materials including slings and plastic bands, (c) plastic strappings and tarpaulins.

Figure 4.5: Complex material fraction at Port of Norrköping

The consequences of poor source separation extended across the value-chain. Mechanical recycling depended on well-sorted, single-polymer inputs, meaning unsorted mixed fractions effectively closed off this pathway (Circular Solution Company A, personal communication, 4 March 2026; Circular Solution Company C, personal communication, 19 March 2026). Circular Solution Company A characterised current practice as convenience disposal and argued that a fundamental change of mindset was needed among vessel crews and operators: sorting material correctly at the point it became waste, rather than depositing it unsorted into a shared skip, could substantially reduce the problem of mixed fractions (Circular Solution Company A, personal communication, 4 March 2026).

Insufficient source separation also made it difficult to establish stable and reliable material flows. At the Port of Norrköping, mooring lines were not collected as a separate waste fraction, making it impossible to reliably quantify how much material was generated, from which vessel types, or at what frequency. Although the complex material fraction grew between 2024 and 2025, the proportion attributable to mooring lines specifically remained unknown. Beyond the data gap, volumes were small in absolute terms. Viable supply chains required stable and sufficient input, and mooring line waste was described as a very specific and relatively small flow (Circular Solution Company A, personal communication, 4 March 2026; Circular Solution Company D, personal communication, 21 April 2026). Large-scale recycling operations typically required inputs of around 1,000 tonnes or more to be economically viable (Circular Solution Company D, personal communication, 21 April 2026), far exceeding what a single port generated.

Polymer separation presented a further processing challenge, raised by three stakeholders with direct experience handling mooring line waste. The fiber-level integration of different materials made it difficult to isolate individual polymer streams without degrading them (Logistic Service Supplier A, personal communication, 17 March, 2026). The separation process itself remained largely manual and labour-intensive, with limited technology available to handle different components efficiently at scale (Circular Solution Company B, personal communication, 10 March, 2026).

4.3.3 Economic challenges to circular waste management

The main perspectives among stakeholders were that the cost of sorting, transporting, and processing mooring line waste exceeded the value recovered from the material. A reason for this was that virgin polymer prices remained lower than recycled alternatives, making it difficult to justify the additional cost of circular handling as long as this price gap persisted (Logistic Service Supplier A, personal communication, 17 March, 2026). Economic incentives and clear business models were considered necessary conditions for circular systems to become attractive in practice (Circular Solution Company A, personal communication, 4 March 2026; Circular Solution Company B, personal communication, 10 March 2026). One proposed model involved sharing the waste handling fee paid by the vessel between actors to create viability at both ends of the value-chain (Circular Solution Company A, personal communication, 4 March, 2026), while virgin plastic was considered too cheap and the market not yet ready for recycled material (Circular Solution Company B, personal communication, 10 March, 2026).

For a circular solution to function, a commercial receiver capable of using the material in an economically sustainable way was considered essential. The solution needed to be financially viable not only for the sender but also for the receiving end of the value-chain (Collaboration Partner A, personal communication, 25 February, 2026). As one researcher summarised: "there are always solutions, it just depends on who is willing to pay" (Researcher A, personal communication, 13 April 2026, translated from Swedish).

A concrete example of this economic barrier was that a shredder capable of handling mooring lines had previously been tested with fairly good results, but the operating costs were too high and the process too time-intensive to justify continued use. The equipment was no longer used, and materials that could not be processed were instead sent to landfill (Incineration Plant C, personal communication, 16 March, 2026).

4.4 Scenario value-chains for mooring line management

Two exploratory scenarios were developed to illustrate alternative pathways for the EoL management of mooring lines. The first scenario focused on downstream EoL options within the existing port waste system. The second adopted an upstream perspective, centred on stakeholder collaboration across the maritime supply chain.

4.4.1 Downstream EoL options

The first scenario was built around separating mooring lines from the broader complex material fraction at the point of collection, rather than mixing them with other waste. This separation would determine which downstream treatment route each mooring line entered, based on its material composition and condition (Figure 4.6).

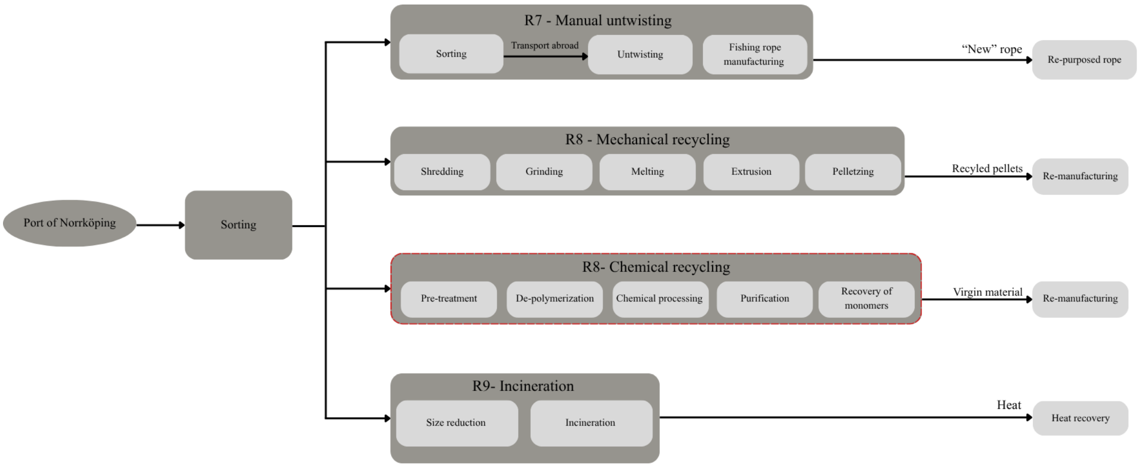


Figure 4.6: Downstream EoL possible value-chain routes

Mooring lines reaching EoL at the port would be collected as a distinct waste category by a contracted waste handling organisation, explicitly named as a separate fraction under the port's waste management contract. The lines would then be transferred to an intermediate storage facility, where they would be assessed and sorted by polymer type before being directed to one of four downstream treatment routes, drawing on the circular opportunities found in Section 4.2.

Ropes in sufficient structural condition would be directed to a repurposing (R7) route through manual untwisting and fiber recovery, redirecting the material into new rope products or applications with lower performance requirements. Ropes of identifiable single-polymer composition, particularly PP and PE, would be directed to mechanical recycling (R8), where they would undergo shredding, grinding, melting, and extrusion into recycled plastic granulates for re-manufacturing. Ropes of mixed or uncertain polymer composition that were not suitable for mechanical recycling would be directed to chemical recycling (R8), recovering monomers that could re-enter plastic production as near-virgin material. Material that could not be directed to any of the above routes due to excessive contamination, degradation, or unidentifiable composition would be sent to incineration with energy recovery (R9).

4.4.2 Upstream system collaboration

The second scenario was constructed around actors already engaged with mooring lines throughout their life cycle, such as logistics service suppliers and circular solution companies. Rather than focusing on mooring lines only once they entered the waste stream, the scenario was built on the premise that these actors, operating within the maritime supply chain and maintaining direct relationships with vessels and shipping organisations, were better positioned than waste management actors to coordinate a circular system.

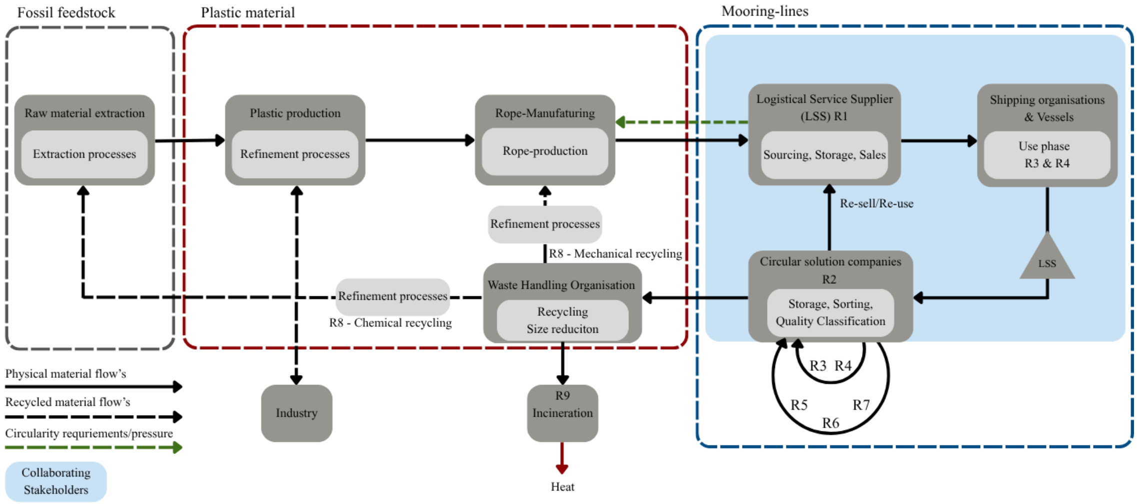


Figure 4.7: Circular system of mooring lines

As illustrated in Figure 4.7, the scenario was based on collaboration and information sharing among logistics service suppliers, circular solution companies, shipping organisations, and rope retailers. A logistics service supplier would supply mooring lines to vessels and collect worn ropes on the return leg of the same transport, as already demonstrated in existing take-back arrangements within the sector. Once collected, the ropes would be transferred to a circular solution company for storage, sorting, and quality assessment. Depending on condition, ropes would then be directed to life-extending strategies at R-levels R3 to R7, while lower-quality material would be channelled to recycling or recovery at R8–R9.

5

Analysis

The three research questions addressed in this chapter were not independent. They describe the waste of worn-out mooring lines at three different levels: how the system currently works (i), what alternative pathways exist (ii), and which stakeholders who would need to act to enable them (iii). The analysis moved across all three, and the overarching argument was built on the empirical findings, which suggested that the current system was linear by default rather than by necessity, and that changing it required coordinated action upstream, not just better waste handling downstream.

5.1 Mooring line EoL management and circular opportunities at the Port of Norrköping

This chapter examined the EoL handling of mooring lines at the Port of Norrköping and evaluated the opportunities and challenges for more circular management. By assessing the stakeholder engagement and the 10R framework, the analysis showed that although circular activities existed across the value-chain, their implementation was limited by structural barriers such as upstream design lock-ins, contamination, labour-intensive processing, the absence of incentives for sorting, and the well-established incineration pathway. These constraints explained why circular options remained largely theoretical under current conditions.

5.1.1 The current waste management at Port of Norrköping and difference between other ports

The transition from the original to the current mooring line value-chain (Figure 4.1; Figure 4.2) was not the result of a planned effort to improve how the material was handled. It emerged as a reactive response to a specific operational problem: mooring lines caused blockages and damage at incineration plants. The immediate disruption was addressed by rerouting the material to facilities with compatible equipment, but the underlying system problem remained undefined. The questions that would be necessary for a circular transition, what should actually happen to mooring lines, who was responsible, and how they should be managed across the whole value-chain, were never asked. The fragmented responsibilities and inconsistent practices seen in the current value-chain were a direct result of this reactive logic, and they made improvements very difficult.

The regulatory framework added another layer of complexity. Both the Swedish Environmental Code operationalised through TSFS 2010:96 and TSFS 2023:15, and MARPOL Annex V required ports to accept and handle all waste from vessels. However, neither framework classified mooring lines as a specific waste type or defined how they should be separated, tracked, or treated. This meant ports were legally obliged to manage the material, but without a shared standard for what it was or how it should be handled. This became visible when comparing practices across ports: some reported receiving mooring line waste only once or twice a year, while others had no record of receiving it at all (Table A.9). The absence of mooring lines from port waste registers reflected not necessarily low volumes, but the absence of a common framework that would make them visible and trackable as a distinct stream.

Once mooring lines were handed over at the port, they were formally classified as waste and from that point treated as such. This classification marked the moment at which any potential value the material still held was lost, not because the material itself had changed, but because the system provided no mechanism to treat it as anything other than something to be disposed of. As Circular Solution Company A described, the current system operated on a logic of convenience disposal, where vessel crews and port operators deposited material into shared skips because the system provided no reason to do otherwise (Circular Solution Company A, personal communication, 4 March, 2026). No actor in the chain had a reason or a mandate to question this, so each party handled the material in whatever way was most practical for them. The outcome was a system with no common direction and no clear path toward higher levels of circularity, precisely the kind of situation where problems persist and reinforce themselves rather than get resolved (Hurlbert and Gupta, 2015; Pearce and Ejderyan, 2020).

5.1.2 The circular opportunities and challenges for mooring lines

Mapping the identified opportunities against the 10R framework revealed that circularity was theoretically possible at multiple stages along the mooring line value-chain (Appendix Table A.2). However, the stakeholder engagement consistently showed that each opportunity was accompanied by challenges that constrained its feasibility under current conditions. A recurring pattern across interviews was that stakeholders described a viable circular route and, in the same response, explained why it did not work in practice. These contradictions pointed to a system in which the structural preconditions for circularity were absent at every level, not only at the point of waste treatment. Such situations, where problems persist across multiple levels without a shared framework for addressing them, are characteristic of unstructured problems that require systemic rather than technical solutions (Hurlbert and Gupta, 2015).

Upstream design decisions at the R0–R2 level, made long before a mooring line reached EoL, represented the greatest potential for systemic change (Appendix Table A.2). These activities addressed root causes rather than symptoms: if mooring lines were designed with recycling in mind from the start, the contamination, mixed polymer, and sortability problems that constrained all downstream pathways would be reduced. However, all R0 and R1 activities were assessed as concept or early stage with low scalability, reflecting the fact that they required broad organisational changes such as industry-wide adoption of design for recycling, new business models for take-back systems, and coordinated use of DPP (Publications Office of the European Union, 2024). Upstream design complexity has been identified as one of the most persistent barriers to CE implementation (Kirchherr et al., 2018), and existing actor behaviours can create lock-in that prevents more sustainable alternatives from taking hold (Bocken et al., 2016). In this case, the lock-in was visible as decisions made by design actors determined what was recyclable at EoL. However, these actors were not part of the system responsible for managing worn-out mooring lines once they were regarded as waste.

Life extension activities from reuse (R3) to repurposing (R7) preserved more material value than recycling and represented the second-best alternative within the 10R hierarchy (Potting et al., 2017). These activities were analytically important because they revealed an underutilised resource already present in the system: the lifecycle knowledge held by shipping organisations. All shipping organisations reported some form of active onboard maintenance including condition monitoring, re-splicing, and reversing lines. Shipping Organisation B noted specifically that replacement was based on assessed condition rather than time or appearance alone (Shipping Organisation B, personal communication, 25 March 2026). This lifecycle knowledge, if transferred to waste handlers and recyclers, could have supported more informed decisions about sorting and routing at EoL.

However, material condition at the point of EoL remained a significant constraint. During use, mooring lines accumulated oil, UV damage, biological matter, and abrasive contamination that degraded both structural integrity and fibre quality. As Logistic Service Supplier A noted, even ropes that appeared visually intact may have lost significant internal strength, making condition assessment difficult without dedicated inspection infrastructure (Logistic Service Supplier A, personal communication, 17 March 2026). Identifying which ropes were suitable for life extension required significant sorting effort, and the output varied between products and remained uncertain. Labour intensity compounded this challenge. As Circular Solution Company B described, manual untwisting and fibre recovery were time-consuming, and limited technology existed to handle different rope components efficiently at scale (Circular Solution Company B, personal communication, 10 March 2026). At the volumes generated by a single port, the effort was difficult to justify economically.

Material recovery through recycling (R8) was the most frequently discussed cluster of opportunities, including both mechanical and chemical pathways. For single-polymer fractions such as PP or PE, mechanical recycling is technically mature and well-established (Barbieri et al., 2024). The challenge was that the process was highly sensitive to material purity. As Circular Solution Companies C and D explained, when polymers such as PP, polyester, and polyamide were processed together, their different melting points and material properties produced output of such poor quality that no market existed for it (Circular Solution Company C, personal communication, 19 March 2026; Circular Solution Company D, personal communication, 21 April 2026). The opportunity of mechanical recycling was therefore real, but only for a narrow fraction of the material, and it still depended on ropes arriving sorted and identifiable to the EoL processes, which they currently did not.

Chemical recycling could handle broader and more contaminated input streams through processes such as gasification or waste-to-methanol conversion (Gadaleta et al., 2024), making it a potential route for materials that could not be mechanically recycled. However, as Circular Solution Company E noted, chemical recycling still required pre-treatment and sorting before accepting material, meaning contamination tolerance had limits (Circular Solution Company E, personal communication, 17 March 2026). Combined with substantially higher costs and technology that remained at a developing stage, chemical recycling expanded the range of treatable fractions without removing the sorting problem that blocked access to the entire R8 cluster.

Both recycling pathways shared a more fundamental barrier, they were constrained before any treatment decision was made. As Circular Solution Company A described, the current system operated on a logic of convenience disposal, where vessel crews and port operators deposited material into shared skips because the system provided no reason to do otherwise (Circular Solution Company A, personal communication, 4 March 2026).

Incineration with energy recovery (R9) was currently the dominant treatment route and in many cases the only available one. As Potting et al. (2017) note, activities at this level of the R-scale preserve significantly less value than those higher up. The dominance of R9 was not a deliberate choice but the result of a system where the conditions needed to support higher R-levels had not been put in place.

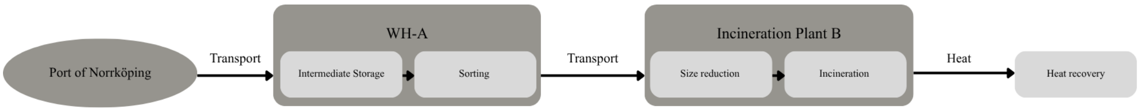
Taken together, the three tiers of the 10R framework reflected not only a technical progression but a conceptual one. For mooring lines, the available pathways depended fundamentally on how the material was perceived. When a worn line was seen as waste, the only option was currently incineration. But when it was seen as a product with remaining value, reuse and repurposing became relevant. When it was seen as part of a larger system, with known composition, traceable history, and coordinated actors, upstream design changes at R0–R2 became possible. As Potting et al. (2017) note, activities higher on the R-scale preserve more value because they retain more of what was originally invested in a product. The current system operated almost entirely at the lowest level, meaning moving toward higher R-levels therefore required not only new technology or infrastructure, but a change in how mooring lines were understood by the actors who handled them.

5.2 Alternative pathways and value-chain changes for circular mooring line management

This section examined three alternative pathways for managing worn mooring line waste. The first was a linear improvement that consolidated the current system without increasing circularity, but which created the data foundation that more circular alternatives depended on. The second was a downstream scenario that examined circular EoL treatment routes within the existing port waste system. The third adopted an upstream perspective, focusing on how circularity could be enabled through stakeholder collaboration across the supply chain rather than through waste handling alone. The section then returned to the Port of Norrköping to identify the institutional and operational changes needed to support either circular pathway.

5.2.1 Linear improvements

Before examining circular alternatives, it was worth considering what an improved but still linear system would look like, since the data it would generate was a precondition for any circular transition. Instead of dividing mooring lines between different facilities according to their size, as occurred in the current system, all mooring lines would follow a single dedicated route through Waste Handling Organisation A for intermediate storage and sorting, before being shredded and incinerated at Incineration Plant B (Figure 5.1). This simplification addressed several of the practical challenges identified through the stakeholder engagement, particularly those related to size handling and inconsistent material flows, while creating a more stable and measurable waste stream. Routing all mooring lines through a single defined pathway would generate a more consistent and traceable material flow, making volumes, frequencies, and rope size distributions more visible than in the current system. Such data, which were currently unavailable, constituted a necessary foundation for future improvements and for any potential transition toward more circular management.



WH= Waste handling organisation.

Figure 5.1: Proposed linear improvement of value-chain

However, this hypothetical value-chain did not enhance the circularity of the material. Incineration with heat recovery remained an R9 strategy, representing the lowest level of circularity within the 10R framework (Potting et al., 2017). As such, the simplified route did not alter the final material outcome, and the treatment system continued to reflect the logic of a linear economy. The value-chain should therefore be understood as an adaptive stabilisation or linear improvement of a complex value-chain, rather than as a transition toward circularity.

5.2.2 Evaluation downstream scenario

The downstream scenario was built around a single enabling condition: that mooring lines were collected as a distinct and identifiable fraction at the port. Without this precondition, none of the sorting and routing logic that underpinned the scenario could function. The analytical purpose of the scenario was therefore not to prescribe a solution, but to trace which treatment routes became feasible depending on how well that condition was met, and what the implications were for each route.

Mechanical recycling (R8) represented the most viable starting point for a downstream circular transition. The process was technically mature for single-polymer fractions (Barbieri et al., 2024), and several circular solution companies expressed concrete willingness to engage with the material under the right conditions. The central question was therefore not whether mechanical recycling was feasible in principle, but whether the downstream sorting and collection logic could create the material stream it required. The scenario showed that if mooring lines were collected as a distinct fraction and sorted by polymer type at an intermediate storage facility, mechanical recycling became a realistic near-term circular route for the PP and PE portion of the waste stream. The implication was that the barrier was not technical but organisational: the sorting infrastructure needed to exist before the recycling pathway could be activated.

Chemical recycling (R8) served a different analytical function. Rather than competing with mechanical recycling, it acted as the route for material that sorting could not rescue, that is mixed-polymer and heavily contaminated fractions. The technology remained at a developing stage and costs were higher, meaning it was better understood as a medium-term complement that would become more relevant as sorting infrastructure matured. Its inclusion in the scenario was analytically important because it meant that even material which could not be mechanically recycled had a potential circular destination other than incineration, provided pretreatment steps were in place. Without chemical recycling as a complement, a significant share of the waste stream would default to incineration regardless of sorting effort.

Repurposing through manual untwisting (R7) preserved the most material value of the four routes, but was the most constrained in practice. The process was labour-intensive and output quality depended heavily on the condition of incoming material, with scalability assessed as low (Appendix Table A.2). It was therefore most realistic as a niche route for ropes in particularly good structural condition. Treating it as a primary route would risk overstating what the current material stream could support.

Incineration (R9) remained the fallback for material that could not be directed to any of the above routes due to contamination, degradation, or unidentifiable composition. Within this scenario it was understood as a residual route rather than a default. This represented a meaningful shift from the current system, where incineration was the starting point rather than the last resort, and where no sorting logic existed to direct material toward higher-value pathways first.

Taken together, the downstream scenario was most realistic as a tiered system where incoming material was assessed and sorted, with mechanical recycling as the primary circular route, chemical recycling as a secondary route for mixed fractions, repurposing reserved for the best-condition material, and incineration only for what remained. The analysis showed that the feasibility of each route was not primarily determined by technology, but by whether mooring lines arrived as a sorted and identifiable fraction. This was the core argument of the downstream scenario: circularity was not blocked by a lack of treatment options, but by the absence of the upstream sorting condition that all of those options depended on.

5.2.3 Evaluation upstream scenario

Where the downstream scenario focused on what happened after a mooring line became waste, the upstream scenario addressed why it arrived in the condition it did in the first place. The central argument of this scenario was that logistics service suppliers and circular solution companies were better positioned to coordinate a circular system than waste management actors, because they maintained direct and ongoing relationships with vessels and shipping organisations throughout the product life-cycle.

The practical foundation of this scenario was the take-back arrangement already demonstrated between Logistic Service Supplier A and Shipping Organisation A, where worn ropes were collected on the return leg of the same transport that delivered new ones (Logistic Service Supplier A, personal communication, 17 March 2026; Shipping Organisation A, personal communication, 11 March 2026). This showed that reverse logistics for mooring lines did not require a separate infrastructure to be built from scratch. It could be integrated into existing supply chain flows, which addressed one of the most commonly cited economic challenges in the stakeholder engagement: that the cost of separate collection and transport was difficult to justify at current volumes.

The scenario also changed what was possible upstream. Because logistic service suppliers interacted with rope manufacturers directly, they were in a position to apply pressure toward simpler polymer compositions that were more compatible with recycling. This was where the systemic value of the upstream scenario lay: the downstream scenario could not influence what a mooring line was made of, but the upstream scenario could. As Bocken et al. (2016) argued, circular transitions required changes at the design and supply chain level, not only at the waste treatment level, and the upstream scenario was the only one of the two that reached that far.

The challenge was that this scenario depended on a level of coordination among actors who currently operated independently. Circular solution companies needed stable and sufficient material volumes to invest in sorting and quality assessment infrastructure. Logistic service suppliers needed commercial incentives to prioritise return logistics. Shipping organisations needed clear and simple procedures that did not add burden to vessel operations. None of these conditions were in place across the system as a whole, even if isolated examples existed. The scenario therefore represented a longer-term pathway that required deliberate stakeholder alignment rather than changes that any single actor could implement alone.

What the two scenarios shared was a dependence on the same foundational step: mooring lines had to be recognised as a distinct and trackable material fraction. Without that, neither the sorting logic of the downstream scenario nor the volume aggregation needed for the upstream scenario could function. The scenarios were therefore not alternatives in the sense that one replaced the other. The downstream scenario offered a more immediate and port-level entry point, while the upstream scenario offered the systemic conditions under which the downstream circular routes became economically viable at scale.

5.2.4 The role of Port of Norrköping

Across all three pathways discussed above, the Port of Norrköping played a role, though the nature of that role differed in each case (Table 5.1). In the linear improvement, the port's contribution was to begin treating mooring lines as a named and separate waste fraction, which was the minimum change needed to generate reliable data on volumes and material flows. Without this step, even the linear improvement could not function as intended. For either of the circular scenarios to become an operational reality, a broader set of coordinated changes had to be assessed.

In the first scenario, the port was the central point of intervention. The most immediate and actionable change involved separating mooring lines from the broader category of complex waste fractions, formalising them as a named waste category in the port's waste management contracts, and beginning systematic data collection on volumes received, vessel type, and collection frequency. Without these steps, the sorting and routing logic that underpinned the first scenario could not function, as the material remained invisible and untrackable within the broader complex material fraction. A further institutional step concerned how vessels were informed about waste sorting expectations upon arrival. Introducing mooring lines as a distinct fraction within the port's ship-generated waste policy would formalise the expectation that mooring lines were to be handed over separately and make the port's role in receiving them explicit. This addition would place mooring lines alongside other recognised waste streams that vessels were expected to declare and deposit. Lowering waste handling fees for shipping organisations that sorted their waste well could further incentivise compliance and improve the quality of the incoming material stream.

In the second scenario, the port's operational role was less central, as mooring lines would ideally be collected and managed within existing supply chain flows before reaching the port as waste. Nevertheless, the port could play a facilitating role by offering infrastructure that supported the broader circular system. One concrete model would be the installation of a dedicated collection skip at the port, into which mooring lines from arriving vessels were deposited and accumulated until a sufficient volume justified transport to a processing or sorting facility. This mirrored models used in other sectors, such as fishing gear collection at harbours, and could be operated on a periodic pick-up basis without requiring continuous staffing. In this sense, the port functioned less as a waste manager and more as a logistics node within a larger reverse logistics or circular system, well-suited to this role given that ports were natural aggregation points that received materials from multiple vessels at regular intervals and already operated within established waste handling and documentation frameworks.

	Linear improvement	**Scenario 1 (Downstream)**	**Scenario 2 (Upstream)**
Main intervention	Single dedicated incineration route for all mooring lines	Separate collection and sorting by polymer type at port	Take-back logistics integrated into existing supply chain flows
Main actors	Port of Norrköping, Waste Handling Organisation A, Incineration Plant B	Port of Norrköping, Waste Handling Organisations, Circular Solution Companies	Logistic Service Suppliers, Circular Solution Companies, Shipping Organisations
Key enabling conditions	Mooring lines named as distinct waste fraction	Mooring lines collected as separate fraction; sorting infrastructure in place	Stable material volumes; commercial incentives for return logistics
Main challenges	No sorting or data collection currently in place	Absence of source separation; mixed and contaminated material	Actor coordination; no shared business model
Circularity level	R9	R7–R8 (primary), R9 (residual)	R1–R9
Time horizon	Short-term	Short to medium-term	Medium to long-term

Table 5.1: Comparison of the three pathways for mooring line waste management at the Port of Norrköping.

5.3 Stakeholder positions and required changes toward higher circularity

The analysis showed that power-interest positions and stakeholder engagement were unevenly distributed, with key upstream and regulatory actors holding significant influence yet remaining weakly involved, while operational actors faced fragmented responsibilities. These misalignments formed the basis for understanding which stakeholders must take on new roles and what coordination is required to support a circular EoL handling system.

5.3.1 Distribution of power and interest among stakeholders

The power-interest grid (Figure 5.2) was used to characterise stakeholder positions based on their ability to influence the system and their expressed level of engagement with the issue, as described in Section 3.2.4. This characterisation made it possible to identify where structural misalignments existed between influence and engagement, and to assess which actors would need to change their roles to enable a circular EoL system.

The Port of Norrköping, waste handling organisations, and circular solution companies were positioned as *players*, reflecting both high power and high interest. The port controlled the point at which mooring lines entered the waste stream and determined how the material was sorted, classified, and contracted for further handling. Waste handling organisations held operational control over material flows once the material left the port. Circular solution companies demonstrated clear interest in engaging with the material and expressed concrete ideas for EoL alternatives and specific conditions under which they could engage.

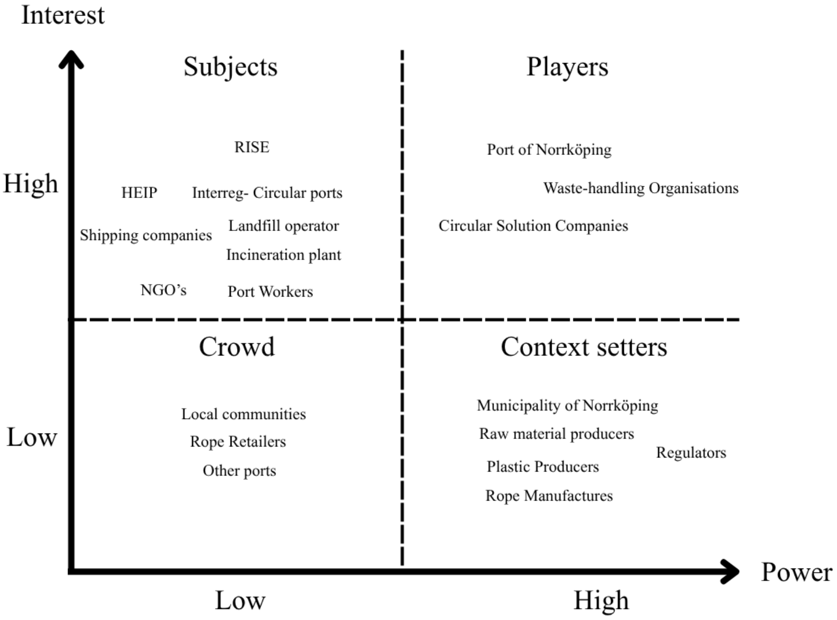


Figure 5.2: The power-interest grid with stakeholders

Shipping organisations, RISE, collaboration partners, and the Interreg Circular Ports project were positioned as *subjects*. These stakeholders showed high interest in the issue but had limited power to change the system on their own. Shipping companies were the primary generators of mooring line waste and several expressed awareness of the challenges of circular practices. RISE, collaboration partners, and the Circular Ports project played important supporting roles but lacked direct operational control over material flows.

Regulators, rope manufacturers, and logistic service suppliers were positioned as *context setters*, stakeholders with high structural power but low expressed interest in the specific issue at the Port of Norrköping. Rope manufacturers controlled decisions about polymer composition and product design that directly determined how recyclable a mooring line was at EoL, yet this group was not actively engaged with EoL management in the study.

Regulators held the authority to introduce requirements, such as mandatory waste classification or recycled content targets, that could shift the economic conditions for circular solutions, but were not included as active participants in the study. Their positioning as context setters therefore reflected their structural role in the system rather than expressed views gathered through interviews.

Rope retailers and other ports were positioned in the *crowd* quadrant, indicating relatively low power and low interest in relation to the mooring line waste stream at the Port of Norrköping. The ports contacted outside Sweden all expressed that they did not have a problem with this type of waste or that they barely received it.

5.3.2 Stakeholder collaboration needed for higher circularity

The power-interest grid presented in Section 5.3.1 captured the current stakeholder configuration. Its analytical value, however, lay not only in describing where actors were positioned, but in revealing the structural misalignments that prevent circularity from emerging. The key insight was not that actors needed to move between quadrants, but that collaboration across quadrants could generate the pressure and enabling conditions needed for system-level change.

Several actors outside the players quadrant held important unrealised potential. Shipping organisations, positioned as subjects, retained latent influence through their control over material condition and sorting practices at the point of port arrival. If shipping organisations aligned with regulators, who held formal authority over waste classification and product requirements, their combined pressure could compel players such as waste handling organisations and the Port of Norrköping to adapt their handling practices. Similarly, rope manufacturers and logistic service suppliers, positioned as context setters, shaped the upstream conditions that determined what was recyclable at EoL. If these actors engaged more actively with circular solution companies, they could influence material design and logistics infrastructure in ways that made downstream circular handling viable.

A more circular system therefore depended on collaboration across quadrants rather than on individual actors gaining more power or interest. Context setters held the structural leverage to create enabling conditions through design changes, regulatory frameworks, and logistical coordination. Subjects such as shipping organisations and the port could reinforce this by improving source separation and material traceability. Together, such cross-quadrant collaboration could shift the conditions under which players operated, making circular handling the path of least resistance rather than an additional burden.

5.3.3 Barriers to collective action

The fragmentation identified in the stakeholder analysis was not only structural but also cognitive. As Argyris and Schön (1996) argued, actors tend to operate according to a *theory in use*, an implicit model of how things work that frequently diverges from broader system logic. The Port of Norrköping framed the issue around physical characteristics and economic burden, waste handling organisations around sorting and operational flow, incineration plants around machinery disruption, and shipping organisations around convenience at the point of disposal. However, no actor assumed responsibility for what happened beyond their own node in the chain.

This fragmentation was most visibly expressed in the shared complex material skip, into which mooring lines, slings, plastic bands, and tarpaulins were deposited together. For shipping organisations, placing everything into one skip was the path of least resistance, and there was no incentive, instruction, or infrastructure that would suggest otherwise. Yet this single act cascaded through the entire downstream value-chain, preventing recycling options, disrupting operational flow, and complicating incineration. The shared skip could therefore be interpreted as more than a practical waste solution. It also reflected a prevailing system logic in which mooring lines were treated as part of an undifferentiated residual waste stream rather than as a potentially recoverable material.

The system was not linear because no alternative existed, but because it was designed for linearity and the economic and organisational conditions required to support a different approach were not yet in place. As Researcher A observed: *"there are always solutions, it just depends on who is willing to pay"* (Researcher A, personal communication, 13 April 2026, translated from Swedish). The question of who bore the cost and who benefited remained unresolved, and the system as structured provided little incentive for the collective action and collaboration that a circular transition would require.

6

Discussion

This chapter reflects on the choices made throughout the study and their implications for the findings, discusses the study's contributions to theory and practice, and situates the results within a broader regulatory and environmental context.

6.1 Strength and weaknesses

This section reflects on the choices made throughout the study and discusses how they affect the credibility, limitations, and transferability of the findings.

6.1.1 Data collection

The study engaged 25 stakeholders across the mooring line value-chain through interviews, email correspondence, and site visits. The iterative, snowball-driven selection ensured that the sample expanded in response to empirical insights rather than remaining fixed to an initial theoretical stakeholder mapping. However, the number of interviews and stakeholder engagement varied across stakeholder categories. Shipping companies, as the primary generators of mooring line waste, were primarily reached by email, meaning their perspectives are less thoroughly captured than those of downstream stakeholders, such as circular solution companies which were all interviewed. As a result, the findings may underrepresent the upstream perspective, and the challenges and practices of the primary waste generators are based on self-reported views rather than observed or verified behaviour.

Responses reflected how each stakeholder expressed their views rather than objectively verified practices, meaning that actual waste handling procedures may differ from what was reported. This limits the study's ability to draw firm conclusions about current practices across the value-chain. Furthermore, the absence of quantitative data on material volumes introduces uncertainty into the assessment of the scale and feasibility of alternative management pathways, as it is not possible to determine whether identified circular strategies would be viable at the volumes actually generated.

The material composition of mooring lines was partly estimated based on general knowledge of typical product compositions, as direct compositional testing was outside the scope of the study. This introduces uncertainty into assessments of recycling feasibility, particularly for composite ropes of mixed or unknown polymer composition, and means that technical conclusions regarding recycling feasibility should be interpreted with caution.

6.1.2 Credibility and transferability

To strengthen credibility and transparency, all codes and themes were discussed and refined jointly by both authors, thereby reducing the risk of individual interpretive bias. The results were continuously checked against original interview transcriptions to ensure consistency between the original interview and analytical interpretation. The use of a structured thematic analysis, combined with a spreadsheet matrix for cross-stakeholder comparison, provided a systematic basis for identifying patterns across a diverse set of actors.

The findings are not statistically generalisable, but they may be analytically transferable to other ports handling difficult polymer-based waste fractions with low visibility, mixed compositions, and fragmented downstream routes. However, the exact configuration of actors, volumes, and feasible circular routes is likely to vary substantially across ports and national contexts.

6.1.3 Scenarios

The two scenarios are comparative rather than prescriptive in nature: rather than recommending a single course of action, they are designed as analytical tools to illuminate the trade-offs between a near-term downstream approach and a longer-term systemic circular transition, grounded in empirical stakeholder data rather than purely theoretical constructs. The scenarios should therefore be interpreted as directional frameworks for structured comparison, not as implementation-ready plans.

The downstream scenario (Scenario 1) is strongest as an analytical tool for assessing what is achievable within the existing port waste system under current conditions. Its primary contribution is not to prescribe a solution, but to make visible exactly where the current system lacks the conditions circularity requires.

The upstream scenario (Scenario 2) extends the analytical scope beyond waste management to examine what systemic conditions would need to change upstream for circular EoL management to become viable at scale. This distinction reflects a broader methodological point: downstream scenarios can identify what is blocked, but only an upstream perspective can address why those blockages exist in the first place. The take-back arrangement already demonstrated between Logistic Service Supplier A and Shipping Organisation A shows that this is not purely theoretical, but the scenario depends on a level of stakeholder coordination that goes beyond what any single actor can currently deliver.

Both scenarios carry significant uncertainties that limit the conclusions that can be drawn. The total volume of mooring line waste at the Port of Norrköping is incompletely known, as the complex material fraction is not separated by product type, and the aggregate volume across all Swedish ports remains untracked at a national level. Large-scale recycling operations typically require inputs of around 1,000 tonnes or more to be economically viable (Circular Solution Company D, personal communication, 21 April 2026), far exceeding what a single port generates, which means the economic viability of the proposed circular routes cannot be confirmed at this stage. Scenario 1 should therefore be understood not as a standalone solution, but as a first step toward making mooring lines visible as a distinct and trackable fraction, the data foundation without which neither scenario can be properly evaluated or scaled.

A further consideration is whether circularity for mooring line waste is achievable beyond niche cases if the Port of Norrköping is considered in isolation. The volumes generated by a single port may simply be too low and too heterogeneous to justify dedicated circular infrastructure. However, if multiple ports across the Baltic Sea region, for example through the Circular Ports project, were to aggregate their material flows, the combined volumes could reach a scale at which dedicated sorting and recycling infrastructure becomes economically viable. The heterogeneity and contamination of the material would nonetheless require extensive pre-treatment to secure sufficient material quality, which at current technology costs exceeds the value of the recovered material compared to virgin polymer alternatives. Developing more cost-effective processing technologies could represent one pathway toward enabling higher circularity at these volumes. It should also be noted that, since mooring lines are composed of synthetic polymers, value recovery could potentially be managed within existing plastic waste streams rather than through highly specific waste categories. Excessively narrow waste segregation requirements may increase the complexity of the management system and make practical implementation more difficult, suggesting that integration into broader polymer recycling flows may in some cases be more viable than treating mooring lines as a wholly separate fraction.

6.2 Contributions

This section outlines the study's contributions to both academic knowledge and practical waste management, addressing how the findings advance understanding of CE transitions in port environments.

6.2.1 Theoretical Contributions

This study contributes to CE literature by applying collaborative problem framing, stakeholder power-interest analysis, mental models theory, and the 10R hierarchy in a port waste management context that has received little prior academic attention. By mapping the downstream value-chain of mooring line waste and engaging stakeholders across the full system, the study made visible a waste stream previously absorbed into undifferentiated complex material fractions without dedicated analysis.

The application of mental models theory to explain the persistence of a linear system offers a contribution beyond the specific case. The finding that each actor defines the problem from their own position in the value-chain illustrates a mechanism of CE lock-in that is likely to apply in other fragmented waste stream contexts, reframing what appears to be a technical problem as a systemic one. This approach also revealed several structural conditions that block circularity, including fragmented responsibilities, absence of material traceability, and misalignment between actors with power to enable change and those bearing operational responsibility for the waste stream.

6.2.2 Practical Implications

This study demonstrates that treating mooring lines as a distinct and trackable waste fraction is a necessary first step toward any circular solution. For port operators, this implies introducing mooring lines as a named waste category in waste management contracts and beginning systematic data collection on volumes, frequencies, and material composition. Without this foundation, neither the economic case for recycling nor the logistical case for take-back systems can be established or evaluated.

For the Port of Norrköping, the most immediate practical implication is downstream: introducing mooring lines as a named waste category in waste contracts and beginning to track the fraction separately to generate reliable data on volumes and material composition. For shipping companies, it means implementing onboard sorting practices before port arrival. Upstream, the study points to the value of material certification and single-polymer product design by rope manufacturers and logistics service suppliers as interventions that would improve recyclability across the entire downstream value-chain.

The graduated scenario framework developed in this study, from linear optimisation through downstream circular transitions to a fully circular system, provides a transferable reference for other ports managing similar complex waste fractions with low material visibility and fragmented downstream routes. The framework illustrates that a circular transition does not require a complete solution from the outset, but can begin with incremental steps that generate the data and stakeholder trust needed for larger systemic change.

6.3 Broader implications

Beyond the specific case of the Port of Norrköping, the findings of this study have broader implications for how mooring line waste is governed and what environmental benefits a more circular system could enable.

6.3.1 Regulatory frameworks and governance

Mooring line waste management operates within a multilayered regulatory framework spanning international, European, and national levels, including MARPOL Annex V, Directive 2019/883 on port reception facilities, and Swedish national law, operationalised through TSFS 2010:96 and TSFS 2023:15. In principle, this framework should ensure that EoL materials from vessels are consistently deposited, recorded, and managed at port reception facilities. In practice, however, mooring lines are conspicuously absent from port waste registers, suggesting a significant divergence between regulatory intent and material reality.

This raises a fundamental question that the present study cannot fully resolve but that future work should address: is the absence of mooring lines from waste registers a failure of regulation, or a reflection of genuinely small and infrequent volumes? The answer matters because it points toward different solutions. If volumes are being mismanaged outside formal channels, regulatory intervention through clearer waste classification may be the most effective lever. If volumes are genuinely small, the problem is less a legislative gap and more a value-chain and coordination challenge, where the absence of dedicated infrastructure and shared responsibility across actors is the binding constraint. From the evidence gathered in this study, the latter appears more likely. The challenge at the Port of Norrköping emerged primarily as a rebound effect from incineration plants rejecting the material, rather than from active regulatory non-compliance. This suggests that coordination and collaboration across the value-chain may be a more productive starting point than regulatory reform alone.

6.3.2 Environmental implications

The current system also implied missed environmental benefits. As long as mooring lines are directed toward incineration, potential reductions in virgin polymer demand remain unrealised. However, the present lack of reliable data on volumes and composition means that these avoided impacts cannot yet be quantified in a robust way. This further strengthens the argument that stabilising and tracking the waste stream is a necessary first step toward both circular and environmental progress.

7

Conclusion

The findings show that waste management of mooring lines was not primarily a technical problem but a systematic one: responsibilities were fragmented, and the conditions for circularity were determined by actors outside the conversation. Mooring lines moved through a complex value chain with few circular alternatives in practice. While mechanical recycling was identified as the most viable future pathway, significant limitations remained. Enabling higher circularity required the material fraction to become visible and traceable, both at the point of waste classification and further upstream in the value chain. Rope manufacturers and regulators held the greatest power to enable circular solutions through product design and policy, yet remained disengaged from EoL management at the port. Closing this gap required shipping organisations to improve source separation, regulators to introduce requirements, and rope manufacturers to consider recyclability at the design stage. A circular transition could not be achieved by the port alone but depended on coordinated collaboration across the entire value chain.

Other conclusions from the study included:

- Without clearly assigned responsibility for the mooring line fraction, the system continued to respond reactively rather than enable circularity.
- The structural barrier were consistent across the R-scale: material arrived at EoL mixed, contaminated, and unidentifiable, which limited more circular pathways.
- Volumes at a single port were too low for a dedicated circular infrastructure; cross-port collaboration or broader partnerships were needed for economic viability.

Future studies

- Quantitative assessments of the environmental and economic impacts of the proposed circular pathways for mooring line waste.
- Investigation of the scalability of specific treatment strategies, including mechanical and chemical recycling, for marine rope waste streams.
- Examination of how regulatory instruments, such as MARPOL Annex V, could be strengthened to include mooring lines as a named and trackable waste fraction.
- Assessment of whether the challenges identified at the Port of Norrköping are present at other ports in Sweden and the Baltic Sea region, and what aggregated volumes of mooring line waste might look like at a national or regional scale.
- Exploration of how upstream interventions such as design for recycling and digital product passports could be implemented in practice for synthetic rope products.

Bibliography

Ackermann, F. and Eden, C. (2011). Strategic management of stakeholders: Theory and practice. *Long Range Planning*, 44(3):179–196.

Ahmed, S. K., Mohammed, R. A., Nashwan, A. J., Ibrahim, R. H., Abdalla, A. Q., Ameen, B. M. M., and Khdhir, R. M. (2025). Using thematic analysis in qualitative research. *Journal of Medicine, Surgery, and Public Health*, 6:100198.

Argyris, C. and Schön, D. A. (1996). *Organizational Learning II: Theory, Method and Practice*. Addison-Wesley, Reading, MA.

Barbieri, M., Terreni, E., Tollini, F., Storti, G., and Moscatelli, D. (2024). A novel process for recovery and exploitation of polyesters and polyamides from waste polymeric artifacts. *Invention Disclosure*, 4:100026.

Baumann, H. (2012). Using the life cycle approach for structuring organizational studies of product chains.

Baumann, H. and Tillman, A.-M. (2004). *LCA i ett nötskal*. Studentlitteratur, Lund, Sweden. Swedish translation of Chapter 1: LCA in a Nutshell.

Bocken, N. M. P., de Pauw, I., Bakker, C., and van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, 33(5):308–320. Accessed: 11 February 2026.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., and Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, 38(7):723–739.

Connect Knkt (n.d.). Mooring rope maintenance guide. Accessed: 18 May 2026.

Conniff, M. (2026). High-density polyethylene (hdpe): Definition, properties, and uses. Updated April 28, 2026; accessed 13 May 2026.

Council of the European Union (2024). The circular economy explained. Accessed: 25 May 2026.

Council of the European Union (n.d.). Fit for 55. Accessed: 12 May 2026.

De Martino, M. (2021). Value creation for sustainability in port: Perspectives of analysis and future research directions. *Sustainability*, 13(21):12268.

Duracordix (2025). Typer av förtöjningslinor för fartyg du bör känna till.

Ernst, A. (2019). Review of factors influencing social learning within participatory environmental governance. *Ecology and Society*, 24(1):3.

European Commission (2015). First circular economy action plan. Accessed: 11 February 2026.

European Commission (2020). Circular economy. Directorate-General for Environment. Accessed: 27 May 2026.

European Commission (2024). Implementing the ecodesign for sustainable products regulation. Green Forum, Directorate-General for Environment. Accessed: 27 May 2026.

European Commission (n.d.a). The european green deal. Accessed: 12 May 2026.

European Commission (n.d.b). Ports. Accessed: 10 June 2026.

European Parliament and Council of the European Union (2008). Directive 2008/98/EC on waste and repealing certain directives.

European Parliament and Council of the European Union (2018). Directive 2018/851/EU amending directive 2008/98/EC on waste.

Gadaleta, G., Notarnicola, M., and De Gisi, S. (2024). Impacts of techniques for plastic waste management. In *Reuse of Plastic Waste in Eco-efficient Concrete*, pages 37–62. Elsevier.

Hemmati, M. (2002). *Multi-Stakeholder Processes for Governance and Sustainability: Beyond Deadlock and Conflict*. Earthscan, London.

Hurlbert, M. and Gupta, J. (2015). The split ladder of participation: A diagnostic, strategic, and evaluation tool to assess when participation is necessary. *Environmental Science & Policy*, 50:100–113.

Iacovidou, E., Millward-Hopkins, J., Busch, J., Purnell, P., Velis, C. A., Hahladakis, J. N., Zwirner, O., and Brown, A. (2017). A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste. *Journal of Cleaner Production*, 168:1279–1288.

International Maritime Organization (2011). MARPOL consolidated edition 2011: Articles, protocols, annexes and unified interpretations of the international convention for the prevention of pollution from ships. Technical report, International Maritime Organization, London. Including Annex V: Regulations for the Prevention of Pollution by Garbage from Ships.

International Organization for Standardization (2006). ISO 14040:2006 environmental management – life cycle assessment – principles and framework. International standard.

Interreg Baltic Sea Region (2025). Circular ports – deploying circular economy in port environments. Accessed: 4 February 2026.

Iordan, C. M. and Strand, A. V. (2026). Recycling options and pathways for fiber mooring lines for offshore wind systems. Accessed: 18 May 2026.

Kirchherr, J., Reike, D., and Hekkert, M. (2018). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127:221–232.

Leite, J. C. S. d. P., Hadad, G. D., Doorn, J. H., and Kaplan, G. N. (2000). A scenario construction process. *Requirements Engineering*, 5(1):38–61.

Lindén, H., Rosén, M., and Baumann, H. (2019). Product chain collaboration for sustainability – a business case for life cycle management. *Business Strategy and the Environment*, 28(8):1619–1631.

Longhurst, R. (2003). Semi-structured interviews and focus groups. In Clifford, N. J. and Valentine, G., editors, *Key Methods in Geography*, pages 143–156. SAGE Publications.

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, 153:104553.

Norrköpings Hamn AB (2020). Miljörapport 2020. Miljörapport, Norrköpings Hamn AB, Norrköping, Sverige. Tillsynsmyndighet: Länsstyrelsen i Östergötland.

Norrköpings Hamn AB (2024). Miljörapport 2024. Environmental report, Norrköpings Hamn AB. Accessed: 13 February 2026.

Norrköpings Hamn AB (2026). Om oss.

Oil Companies International Marine Forum (2018). *Mooring Equipment Guidelines (MEG4).* Oil Companies International Marine Forum, 4 edition. Accessed 13 May 2026.

Pearce, B. J. and Ejderyan, O. (2020). Joint problem framing as reflexive practice: honing a transdisciplinary skill. *Sustainability Science*, 15:683–698.

Porter, M. E. (1985). *Competitive Advantage: Creating and Sustaining Superior Performance.* Free Press, New York.

Potting, J., Hekkert, M. P., Worrell, E., and Hanemaaijer, A. (2017). Circular economy: Measuring innovation in product chains. Policy Report 2544, PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands. Accessed: 11 February 2026.

Publications Office of the European Union (2024). Eu's digital product passport: Advancing transparency and sustainability. data.europa.eu. Accessed: 27 May 2026.

Rasilainen, I., Lahtela, V., and Kärki, T. (2026). Effect of processing temperature on the structure and mechanical properties of recycled plastic blends. *SPE Polymers*, 7(1):e70029.

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., and Stringer, L. C. (2009). Who's in and why? a typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, 90(5):1933–1949.

Scanunit AB (2026). Rope as a service. Accessed: 18 May 2026.

Singer, M. and Donoso, P. (2008). Upstream or downstream in the value chain? *Journal of Business Research*, 61(6):669–677.

Stokols, D., Hall, K. L., Moser, R. P., Feng, A., Misra, S., and Taylor, B. K. (2010). Cross-disciplinary team science initiatives: research, training, and translation. In Frodeman, R., Klein, J. T., and Mitcham, C., editors, *The Oxford Handbook of Interdisciplinarity*, chapter 32, pages 471–493. Oxford University Press, Oxford.

Svedberg, G. (2026). Circular plastics in life science: Potential, challenges and examples. Presentation at the National Centre for Sustainable Plastics at RISE – Circular Plastics 2026 Conference, Nolato AB.

Transportstyrelsen (2010). Transportstyrelsens föreskrifter och allmänna råd om åtgärder mot förorening från fartyg (tsfs 2010:96). Consolidated version.

Transportstyrelsen (2023). Transportstyrelsens föreskrifter och allmänna råd om mottagning av avfall från fartyg (tsfs 2023:15). Consolidated version.

Van den Dries, P. (2023). Guidance document on developing port waste management plans. Peer reviewed by the Food and Agriculture Organization of the United Nations (FAO).

Wärtsilä (n.d.). Mooring lines. Accessed 13 May 2026.

A

Appendix 1

A.1 Circular activities

The circular activities identified across the R-scale were categorised and visualised (Table A.2). The activities are assessed in relation to technical readiness, scalability, advantages, and limitations. The level of technical readiness and scalability use the classification of table A.1.1.

Technical Readiness Levels	
Concept	Early idea stage with no or very limited real-world testing; high uncertainty regarding feasibility and performance.
Early stage	Initial pilots or prototypes exist; concept validated in limited settings but not yet widely implemented.
Developing	Technology is being refined and partially implemented; performance and feasibility increasingly proven.
Mature / Operational	Fully developed and widely used in industry; proven reliability and performance.
Scalability Levels	
Very low	Applicable only in niche cases; difficult to expand due to economic, technical, or practical constraints.
Low	Limited scalability; can be applied in specific contexts but faces significant barriers to wider adoption.
Moderate	Scalable under certain conditions; requires adaptations, investment, or supporting systems.
High	Can be implemented broadly across the industry with manageable effort and infrastructure.
Very high	Easily scalable and already widely applied; minimal barriers to large-scale implementation.

Table A.1: Definition of technical readiness and scalability levels used in the assessment.

A.1.1 Overview of identified circular activities

Table A.2: Categorisation of circular strategies for mooring line waste, including technical readiness, scalability, advantages, limitations, and relevant actors.

R	Circular Activity	Technical Readiness	Scalability	Advantages	Limitations	Source or Actor
Design Phase (R0–R2)						
R0	Avoid use of synthetic mooring lines (Alternative materials or technical solutions)	Early stage	Low	Reduces mooring line waste	Limited feasibility due to different needs and routes of shipping organisations	Shipping Organisation D (Automatic mooring)
R1	ID numbers on certificates and mooring lines	Concept	High	Improves traceability and transparency	Requires system implementation	Idea - Logistic service supplier A (e.g. NFC chips)
R1	Digital product passport for mooring lines	Early stage	High	Enables lifecycle tracking and circular flows	Requires industry-wide adoption	(Publications Office of the European Union, 2024)
R1	Mooring line service at EoL (collection, inspection, logistics, and return coordination)	Early stage	High	Ensures EoL handling and material recovery pathways, also improves circular flow coordination	Requires coordinated reverse logistics, unclear responsibility allocation, and added operational complexity	Circular Solution Company A
R1	Mooring lines as a service	Early stage	High	Lifecycle responsibility, optimized usage	Requires new business models	(Scanunit AB, 2026)
R1	Take-back systems at EoL	Early stage	High	Enables recycling and reuse	Logistics and responsibility challenges	Logistic Service Supplier A
R1	Design for Recycling (DfR)	Early stage	High	Improves recyclability	Requires redesign and industry adoption	(Publications Office of the European Union, 2024)

Continued on next page

R	**Circular Activity**	**Technical Readiness**	**Scalability**	**Advantages**	**Limitations**	**Source or Actor**
R2	Use of recycled material instead of virgin material	Developing	High	Reduces resource extraction	Potential lower material quality	Re-line project - Logistic Service Supplier A
R2	Reduction of unnecessary rope size (MEG4 standards)	Developing	Moderate	Less material use, cost savings	Safety concerns, requires standards adaptation	(Oil Companies International Marine Forum, 2018)
R2	Condition monitoring/inspction for optimized replacement	Early stage	Moderate	Prevents premature disposal	Requires sensors and data systems	Shipping Organisation B, D & E
Use Phase (R3–R7)						
R3	Certified second-life use in lower-risk applications	Early stage	Low	Extends product life	Certification and safety challenges	Circular Solution Company A
R4	Cutting and re-splicing damaged sections	Mature	Low	Extends lifespan	Time-consuming, reduces rope length	Shipping Organisation C
R4	Replacement of protective sleeves/coatings	Mature	Low	Extends durability	Additional cost	Shipping Organisation B & D
R5	Cleaning mooring lines	Mature	Low	Extends usability	Limited effect on heavily worn ropes	(Connect Knkt, nd)
R6	Hybrid ropes (virgin + recovered material)	Early stage	Moderate	Scalable transition solution	Quality consistency challenges	Re-line project - Logistic Service Supplier A
R7	Manual untwisting for use in fishing ropes	Early stage	Low	Extends material use	Labor-intensive, often outsourced abroad	Circular Solution Company A
R7	Furniture and design applications	Early stage	Very low	High-value niche use, awareness	Not scalable	Shipping Organisation A & Logistic Service Supplier A
End-of-Life Phase (R8–R9)						
R8	Mechanical recycling	Mature	High	Established, cost-efficient	Downcycling, contamination sensitive	Circular Solution Company C & D

Continued on next page

R	**Circular Activity**	**Technical Readiness**	**Scalability**	**Advantages**	**Limitations**	**Source or Actor**
R8	Chemical recycling	Developing	Moderate	Near-virgin material quality	High cost, limited infrastructure	(Iordan and Strand, 2026) Discussed with Researcher A and Circular Solution Company D
R8	Closed-loop recycling into new ropes	Concept	Low	Circular model	Technically difficult	Project Re-line - Logistic Service Supplier A
R9	Incineration with energy recovery (size reduction required)	Operational	Very high	Reduces waste volume, energy recovery	GHG emissions, non-circular	Incineration plant A, B & C

A.2 Enlarged scenario figures

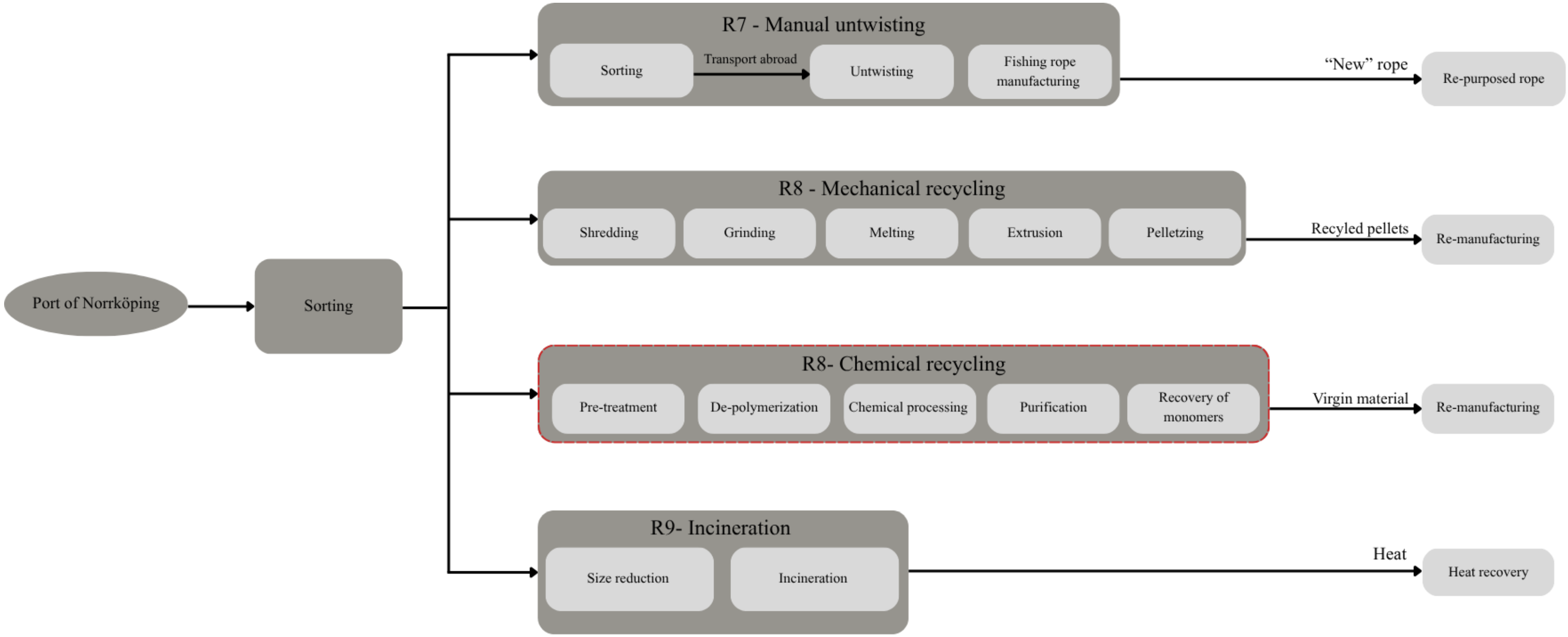


Figure A.1: Enlarged version of the downstream scenario presented in the results chapter.

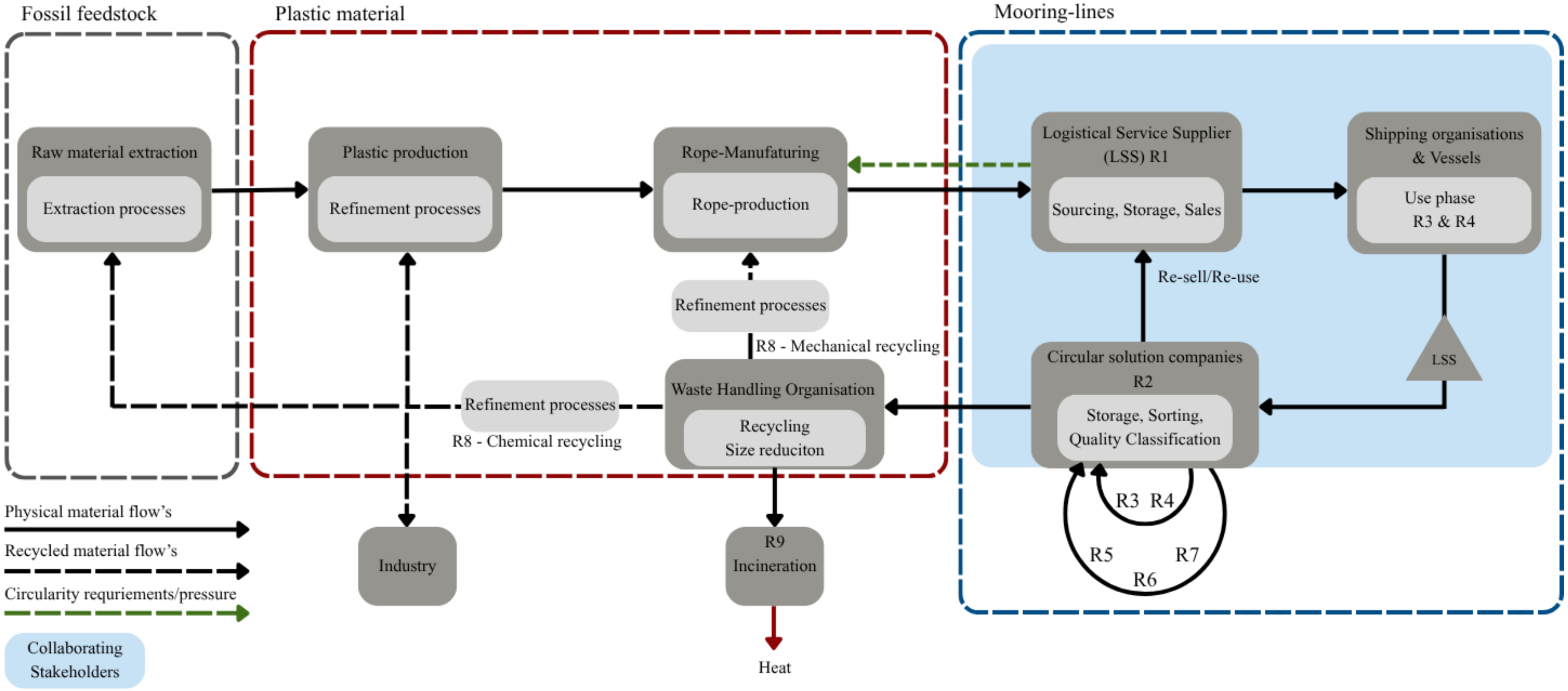


Figure A.2: Enlarged version of the upstream scenario of presented in the results chapter.

A.3 Stakeholder interview response summaries

This appendix presents summarized stakeholder responses from the semi-structured interviews conducted in the study. The responses have been translated from Swedish to English where relevant and condensed for readability while preserving the original meaning. Colour highlighting is used to reflect the thematic coding applied during analysis, where blue indicates key concepts and actors, red indicates challenges, orange indicates stakeholder perspectives, and green indicates circular activities and opportunities. The responses are presented question by question according to the interview guide. Question 1 and Question 4 have been excluded from this appendix due to anonymity considerations and limited analytical relevance.

A.3.1 Q2: How do you currently interact with mooring lines and slings during their life cycle?

Table A.3: Stakeholder responses to Q2.

ID	Response summary
Port A	The port mainly interacts with mooring lines and slings at the end of their life cycle. Slings are used in cargo operations involving ships, trucks, and trains, while mooring lines belong to the vessels and are used for mooring at the quay. Once these materials are worn-out, they are collected as waste, reported in advance by vessels, and handled by contracted waste management companies.
Collaboration A	He does not interact with mooring lines or slings operationally but was working with the port when they identidied their waste streams, including the complex material waste stream
Logistic service supplier A	The company supplies mooring lines to vessels and in some cases also takes back used ropes from customers through take-back arrangements, this is done in small case when they deliver new ropes (e.g. shipping organisation A). Returned ropes are stored, assessed, and then sent either to recyclers or to downcycling solutions, depending on the material type and condition.
Rope manufacturer A	The company produces and distribute ropes to boats and vessels. They manufacture ropes from different natural and synthetic fibers and sell them directly to customers or intermediaries. They do not provide repair or maintenance services for worn ropes due to safety concerns and quality guarantees.
Circular solution company A	Their main role is to collect used mooring lines from ships and redirect them into new value-chains instead of disposal. The company aims to use existing logistics systems that already deliver supplies to ships and use the return route to transport used ropes back to shore. Depending on the condition and material composition, the ropes can be reused, processed, or sent to recycling partners.
Circular solution company B	Interacts with smaller ropes mainly when they enter the waste stream. Materials arriving at the recycling center are stored, manually sorted, and separated into different fractions such as ropes, nets, metals, and floats. These fractions are then either sent to recycling companies, used in pilot tests or product development in a testbed, or occasionally reused in other design applications.
Circular solution company C	Mainly at the end-of-life stage. They have started a collaboration where ropes are collected from ports and sent to them for recycling. However, this is still in an early phase. They process the material by testing, shredding, filtering, melting, and converting it into plastic granulates used in new products.
Circular solution company D	They do not have a specific recycling process for mooring lines or slings. Similar complex materials are generally collected, sorted, and in some cases pre-processed, but mooring lines are most likely sent for incineration rather than material recycling.

Continued on next page

ID	Response summary
Circular solution company E	Their relation to mooring lines and slings is indirect, since they may assess such materials as waste, but they do not currently have an established recycling solution for them. They mainly interacts with mooring lines and slings at the end of their life cycle. If involved, they would assess the material, its composition, and the available volumes to see whether recycling could be possible instead of incineration. However, they do not currently process these materials in any regular way.
Research A	He do not interact directly with the material, since he is a researcher at chalmers.
Waste handling org A	They interact with mooring lines and similar materials at the EoL stage. They collect the material from the port, either through the mixed complex-material skip or through separate handling when mooring lines are identified. Smaller quantities are stored and consolidated until there is enough material for transport, while larger and longer ropes may require direct handling with crane trucks.
Port B	Mooring lines are disposed of as combustible waste and sent to incineration plant C. Due to their length, vessels are asked to cut the lines into shorter pieces beforehand to avoid operational disruptions. If lines arrive uncut on a pallet, port staff handle them separately. Overall, all material is treated as combustible waste.

A.3.2 Q3: What challenges do you perceive in the current handling of worn-out mooring lines and slings?

Table A.4: Stakeholder responses to Q3.

ID	Response summary
Port A	He explains that this type of material is difficult for district heating plants to handle, as they are designed for combustible waste used to produce heat and electricity. Materials such as mooring lines and slings can cause problems in the feeding system, where they may get stuck and disrupt operations. As a result, an agreement has been made with the operator that this type of material should not be sent to the plant as combustible waste.
Collaboration A	He perceives several challenges in the current handling of these materials. Sorting and handling require time and labour, which ports are generally unwilling to allocate as it is not part of their core business. The materials are bulky and difficult to manage, and incineration is currently the default option despite being costly and operationally risky. He also highlights that mooring lines can cause serious disruptions in waste-to-energy facilities by getting stuck in equipment.
Logistic service supplier A	A major challenge in handling worn-out mooring lines and slings is the complexity of the materials. Many ropes are made from combinations of polymers such as polypropylene and polyester, which are difficult to separate and therefore hard to recycle. In addition, used mooring lines are heavily contaminated with oil, sand, algae, and other residues, meaning they must be cleaned before any recycling process can begin. Even when cleaned, the degradation of fibers reduces the quality of the material. There is also a lack of demand for recycled mixed plastics, and virgin materials are still significantly cheaper, which reduces incentives for recycling. Technical limitations, such as different melting points of materials, further complicate the process.
Rope manufacturer A	One challenge is that damaged ropes are difficult and costly to repair, which often leads to them being discarded and replaced instead. Additionally, safety regulations and inspection requirements in sectors such as shipping contribute to more frequent replacement of mooring lines.
Circular solution company A	Ships often dispose of ropes in general waste skips because it is the easiest option. Circular solutions require additional sorting and handling on board, which demands a change in mindset. Another challenge is the complexity of the materials, as ropes are often made from mixed polymers that require different recycling processes.

Continued on next page

ID	Response summary
Circular solution company B	Handling marine rope waste is challenging due to contamination, sediment, and mixed materials. The separation process is often very manual and labor-intensive, as there is limited technology available to efficiently separate different components. Another challenge is the relatively small and inconsistent volumes, which makes it difficult to establish economically viable recycling processes.
Circular solution company C	One challenge is contamination. Mooring lines collected from ports are often dirty and may contain oil, metal parts, tapes, or additives such as pigments with restricted substances. Another challenge is material composition, as mixed polymers (e.g. PP combined with polyester or polyamide) are difficult or impossible to recycle in their process. Unexpected contaminants can also damage equipment.
Circular solution company D	The main challenges are the low volumes, the complexity of the materials, and the difficulty of separating different polymers. Long and fibrous products can also cause handling problems, meaning they may need to be cut, shredded, or otherwise pre-treated before further processing.
Circular solution company E	The main challenges are that the materials are complex, mixed, dirty, and difficult to handle. Mooring lines and slings often contain different polymers and are contaminated with sand and other substances, which makes sorting, washing, and recycling expensive and technically difficult. Their large size also creates practical handling problems.
Research A	The main challenges are that the materials are mixed, contaminated, physically difficult to process, and available only in small volumes. They often contain nylon, PP, PE, polyester, or combinations of these, and after marine use they have very low material value. A major practical issue is that long ropes get stuck in shredders, which means even incineration or chemical routes often require special pre-treatment equipment.
Waste handling org A	One major challenge is that mooring lines are difficult to handle because of their size and length. A single rope can cause an entire waste skip to be classified as complex waste, even if it only represents a small share of the total weight. Another challenge is that the material does not fit well into existing treatment systems, especially incineration, and the current sorting is not good enough to separate ropes clearly from other waste.
Port B	One challenge is that long mooring lines can cause operational problems during incineration, as they may get stuck in the waste treatment process. Therefore, ships are asked to cut the ropes into shorter pieces before disposal.

A.3.3 Q5: What barriers do you perceive limit the circularity of the material today?

Table A.5: Stakeholder responses to Q5.

ID	Response summary
Port A	Barriers to circularity include strict safety requirements, such as expiration dates on slings, which lead to disposal even when materials appear to be in good condition. The materials are often mixed and difficult to sort, and existing systems are primarily designed for incineration rather than reuse or recycling.
Collaboration A	Marine plastics are complex and lack standardisation, which makes recycling difficult. The material is often worn, contaminated, or technically “expired,” leading to uncertainty about quality and performance. Virgin plastic is cheap, which reduces demand for recycled alternatives. In addition, there is a lack of commercial actors willing to treat worn-out mooring lines as a valuable raw material, and incineration remains the easiest and cheapest option for many stakeholders.

Continued on next page

ID	**Response summary**
Logistic service supplier A	Important barriers are mixed polymer compositions, contamination, lack of economically viable separation methods, and low market demand for recycled mixed plastic. Virgin plastic is still cheaper, and some recycling systems are locked to specific rope brands or suppliers, not know information for all.
Rope manufacturer A	The difficulty of collecting used ropes, the complexity of separating different fiber types within a rope, and the technical and economic challenges of breaking down the material into reusable fibers. Recycled fibers often have lower performance, particularly in strength and durability, which limits their applicability.
Circular solution company A	The current waste management system often prioritizes convenience over material recovery, meaning ropes are thrown away instead of separated. Mixed material compositions and additives make recycling technically challenging. Existing industry standards and regulations can restrict the use of recycled materials in certain applications.
Circular solution company B	Contamination and mixed materials in the waste streams, the lack of efficient separation technologies, and the relatively low volumes of specific material fractions. Virgin plastic is often cheaper than recycled plastic, which makes it difficult to create a profitable market for recycled materials.
Circular solution company C	The lack of clean and well-sorted material. Mixed materials and contamination significantly reduce recyclability. Another barrier is insufficient knowledge about the material composition when it is collected, as well as inconsistent quality from suppliers. The need for high and stable material quality limits the use of complex waste streams.
Circular solution company D	Key barriers are insufficient volumes, poor profitability in plastic recycling, cheap virgin plastic, material complexity, contamination, and the lack of suitable recycling technology. Mixed polymers such as PE, PP, polyester, PVC, or fillers make recycling more difficult and reduce process yield.
Circular solution company E	The interviewee sees several barriers to circularity, especially low volumes, mixed materials, contamination, high processing costs, and weak market demand. He also stresses that recycling only works if someone is willing to pay for the process and if there is a customer for the recycled material.
Research A	He sees some opportunities mainly in recycling cleaner and more uniform materials, especially polypropylene (PP). There may also be potential in working with specialized companies that focus on these types of plastics, but the opportunities are still limited and difficult to scale commercially.
Waste handling org A	A key barrier is poor sorting, since mooring lines often end up mixed with other materials in the same skip. Another barrier is the lack of traceability and data, as they cannot easily determine how much of the complex waste fraction actually consists of ropes. Transport costs, low material density, long distances to possible recycling actors, and uncertainty around how the material can be reused or recycled also limit circularity.
Port B	The key challenge lies in how the material is classified as waste, including when it becomes waste, what the port is permitted to do with it, and who holds responsibility. This needs to be clarified. The material also varies in quality, with some lines being more contaminated than others, which may affect processing requirements.

A.3.4 Q6: What opportunities do you see for EoL alternatives for the material?

Table A.6: Stakeholder responses to Q6.

ID	**Response summary**
Port A	He suggests that the material could be used in different ways instead of being incinerated, for example through reuse or upcycling into products like furniture, such as braided seating from slings. He also mentions material recycling, particularly for mooring lines, which could be melted down and turned into new plastic products that still serve a practical function, even if the quality is lower.
Collaboration A	He suggests that certain fractions of the material could be suitable for downcycling into lower-performance applications if clear requirements were defined. Design- or art-based reuse could play a role in raising awareness, although he notes that such solutions are unlikely to handle large volumes. He also suggests looking into existing marine recycling initiatives and actors who already work with similar materials (like fishing gear).
Logistic service supplier A	Single-material ropes, especially PP ropes, have better recycling potential and can be mechanically recycled into pellets and new plastic products. Mixed-material ropes may still be downcycled into products such as filling material, cushions, or construction materials. There are also opportunities in redesigning products to make them easier to recycle and in expanding take-back systems from suppliers.
Rope manufacturer A	He suggests incineration to his cutomers but mentions that recycling could be possible, but the complexity of separating mixed fibers and maintaining material quality makes it difficult to implement in practice.
Circular solution company A	Different end-of-life pathways exist depending on the material composition. Some ropes can be mechanically recycled into plastic materials that can be used in other industries, such as automotive production. In other cases, ropes can be untwisted and the fibers reused to produce new ropes or products, particularly in markets where labor-intensive processes are feasible. There are also opportunities for direct reuse of ropes in applications where lower performance requirements are acceptable.
Circular solution company B	Opportunities for both recycling and reuse. Some plastic fractions can potentially be recycled if they are sufficiently clean and separated. Another opportunity is reuse, such as using ropes or nets directly for other purposes. There are also possibilities to incorporate mixed plastic fractions into composite products such as beams or construction materials.
Circular solution company C	There are opportunities to recycle mooring lines and similar materials into new plastic compounds, especially if they consist of relatively pure polymers such as PP. The company also sees potential in handling a wider range of plastic products, including slings and plastic bands, provided that the material is properly sorted and meets quality requirements.
Circular solution company D	There may be some opportunities in chemical recycling, particularly for more homogeneous plastic streams such as PE or PP, but this requires relatively clean and well-sorted input. Otherwise, the main realistic option today remains energy recovery, although pre-processing could potentially open up future recycling possibilities.
Circular solution company E	He sees some opportunities mainly in recycling cleaner and more uniform materials, especially polypropylene (PP). There may also be potential in working with specialized companies that focus on these types of plastics, but the opportunities are still limited and difficult to scale commercially.
Research A	He sees limited but real opportunities. The most realistic route for mixed, contaminated mooring lines is probably shredding followed by thermal or chemical conversion, especially gasification to syngas or methanol. He specifically mention the possibility of sending prepared material to emerging waste-to-methanol infrastructure, such as the Repsol-related development in Tarragona. He sees mechanical recycling as very limited and only relevant for rare, clean, homogeneous fractions.
Waste handling org A	They saw potential in finding more specialized and separate flows for mooring lines instead of mixing them into the general complex-material fraction. They also saw possible opportunities for reuse or recycling of certain materials, especially straps and bands that often appear to be in very good condition. If a dedicated actor were willing to receive the material, they could also manage the transport.
Port B	The port is open to alternative solutions such as sorting and separating mooring lines if a viable circular solution is identified.

A.3.5 Q7: What conditions would need to be fulfilled for you to engage in a circular solution?

Table A.7: Stakeholder responses to Q7.

ID	Response summary
Port A	For the port to engage in a circular solution, the solution must not compromise safety, must be practically feasible within existing operations, and should allow for improved sorting of materials. Collaboration with external actors who can develop viable reuse or recycling solutions is also necessary.
Collaboration A	He mantined that there must be a commercial receiver who can make use of the material in an economically sustainable way for a circular solution to be viable. Sorting would need to be simple or handled by an external actor, as ports are unlikely to take on additional operational tasks. Transport distances and costs must remain reasonable, and the solution must work at scale rather than only as a small pilot or design project.
Logistic service supplier A	There would need to be clear material information, functioning collection and take-back systems, and a recycling route that is technically and economically viable. Better documentation, such as material certificates linked to each rope, would also be important.
Rope manufacturer A	A functioning collection system for used ropes and more efficient technologies for separating and processing fibers would be required. The resulting recycled material would also need to meet market requirements for quality and performance.
Circular solution company A	Circular solutions require sufficient volumes and stable material flows to create viable supply chains. Ships must separate ropes from the general waste stream so they can be collected and handled properly. Economic incentives and clear business models, such as sharing the waste handling fees, are important to make circular systems attractive for all actors involved.
Circular solution company B	Sufficient volumes of relatively homogeneous material would be needed, along with financing and improved processing technologies. Clear logistics and stable supply chains would also be important to make the process economically viable.
Circular solution company C	The most important condition is proper sorting and material purity. They require that materials are delivered as specific, known polymers with minimal contamination. Suppliers must also ensure consistent quality and reliable material streams. If these conditions are met, the company is open to accepting and processing such materials.
Circular solution company D	For the company to engage in a circular solution, there would need to be larger and more consistent volumes, better sorting at the source, and clearer material composition. In addition, the solution would need to be economically viable, with functioning markets for the recycled material and technologies capable of handling the complexity.
Circular solution company E	For them to engage in a circular solution, the material would need to come in sufficient volumes, be better sorted, and contain less contamination. There would also need to be clear economic viability, meaning both a functioning market and customers willing to use and pay for the recycled output.
Research A	A circular solution would need to be technically robust, economically reasonable, and able to handle mixed and contaminated input without demanding perfect sorting. There would also need to be infrastructure for cutting/shredding the ropes, a downstream process that can accept the material, and stakeholders willing to pay for the extra handling. In short, the solution must work at scale, not just in theory or for pilot fractions.
Waste handling org A	They stated that they could participate in a circular solution if there were a clear receiving actor and a practical logistics setup. However, transport costs and responsibility for payment would need to be solved. Better source separation, clearer classification of the material, and a defined waste or product stream specifically for mooring lines would also make circular handling easier.

Continued on next page

ID	Response summary
Port B	Clear regulations, defined responsibilities, and an established process for handling the material as a resource rather than waste would be necessary.

A.3.6 Q8: From your perspective, what would be the most important next step toward a more circular management of mooring lines?

Table A.8: Stakeholder responses to Q8.

ID	Response summary
Port A	The most important next step is to better understand the material flows by documenting quantities, conditions, and material characteristics. Continuing dialogue with researchers and other stakeholders to explore alternative solutions.
Collaboration A	Mapping and “detective work” to understand material flows, volumes, quality, and current treatment routes. He views the current problems with incineration as an opportunity to push stakeholders to rethink existing practices. Use benchmarking against other ports and regions, applying a multi-criteria assessment to different material fractions, and focusing on those with the greatest potential for circular solutions.
Logistic service supplier A	A key next step is to identify which ropes are made from single materials and separate those from mixed-material ropes. He also emphasizes the need for better documentation of rope material composition and stronger collaboration with specialized recyclers such as Plastix.
Rope manufacturer A	Developing systems for collecting used ropes and improving technologies for material separation and fiber recovery would be important steps. These developments would need to make recycling processes technically feasible and economically viable.
Circular solution company A	Change the mindset around rope waste and integrate circular handling into normal maritime operations. This includes improving sorting practices on vessels, designing efficient logistics systems, and creating stable material flows that recycling partners can rely on. Adjustments to industry standards and regulations may also be needed to allow wider use of recycled materials.
Circular solution company B	Better understand the volumes, material composition, and physical characteristics of the ropes, such as length, thickness, and contamination levels. Establishing clearer collection systems and identifying suitable recycling processes or product applications for these materials would also be important.
Circular solution company C	Better understand the volumes, material composition, and physical characteristics of the ropes, such as length, thickness, and contamination levels. Establishing clearer collection systems and identifying suitable recycling processes or product applications for these materials would also be important.
Circular solution company D	The most important next step is to consider design for recycling and reduce material complexity already at the production stage. The interviewee suggests that using fewer or more compatible polymers could make future recycling more feasible, combined with improved sorting practices to separate materials earlier in the value-chain.
Circular solution company E	From his perspective, the most important next step is to map the materials more clearly and understand their composition and volumes. He also highlights the need to design mooring lines and slings in a way that makes them easier to recycle in the future, since many of today’s products are designed for strength and safety rather than circularity.

Continued on next page

ID	Response summary
Research A	The most important next step would be to structure the problem more clearly and compare realistic scenarios, especially around what happens after collection. Practically, he suggests that investing in suitable cutting/shredding capacity may be one of the most useful near-term actions, because it would open existing treatment routes and reduce landfill. He also stress the importance of challenging optimistic recycling claims and evaluating what happens to the residual fraction, not only the valuable parts of the plastic materials.
Waste handling org A	Improve sorting and create a separate waste stream for mooring lines instead of including them in the general complex-material category. This would make it easier to track quantities, understand the material flow, and connect the ropes to a more suitable treatment or recycling option. A clearer system for collection, classification, and destination would be necessary for circular management.
Port B	A better understanding of regulations and responsibilities, as well as collaboration with other stakeholders to develop viable reuse or recycling pathways.

A.4 Additional stakeholder input from email correspondence

Additional stakeholder input was collected through email correspondence with stakeholders who were either unavailable for interviews or where follow-up clarification was needed. The responses were summarized and translated from Swedish to English where relevant. These inputs are not structured according to the interview guide, as they were collected through separate email communication with stakeholders.

Table A.9: Summary of additional stakeholder input collected through email correspondence regarding the handling of mooring lines and related complex materials.

ID	Summary of input
Waste handling organisation B	The organisation states that it no longer accepts mooring ropes due to difficulties in handling them. However, it does accept larger fabric materials, which are crushed at its facility. It clarifies that matters related to this material are handled by Waste handling organisation A rather than Waste handling organisation B. It was later noted that some complex material, excluding mooring ropes, is still sent from the Port of Norrköping to Waste handling organisation B, where it is crushed and then sent for incineration at Incineration plant A, with no additional actors involved after Waste handling organisation B.
Port B	The port informs vessels that mooring lines may either be cut into pieces of approximately 0.5 metres and discarded as combustible waste, or taken whole by the workshop and disposed of as bulky waste. The port's own worn-out slings are discarded after annual external inspections. End-of-life mooring lines delivered by vessels are sent to landfill. No further handling beyond this is carried out.
Port C	No mooring lines have been handed over to the port as waste by vessels. Therefore, the port has not had the opportunity to direct them to recycling.

Continued on next page

ID	Summary of input
Port D	The port handles only very few slings and mooring lines, approximately once or twice per year, and these are discarded in the residual waste skip without further attention. The port suggested that extending the scope to include fishing nets and trawls could be relevant, and recommended contacting ports such as Port of Hanstholm, Skagen Havn, or Strandby Havn for this purpose.
Port E	The port does not handle this type of waste directly, as shipping organisations operating at the port have their own agreements with waste management providers.
Incineration plant A	The plant cannot accept or incinerate mooring ropes and slings, even though the material is combustible, because the fraction size above 100 mm causes serious operational disruptions in fuel preparation and boilers. As a result, the material is blacklisted. If it arrives at the plant, it is in practice sent to landfill via Waste handling organisation C, leading to increased costs for customers. For continued handling, either a new receiver with appropriate technology, such as a grate furnace, is required, or a functioning solution for cutting the material down to below 100 mm, which is currently lacking.
Incineration plant B	The plant handles only small volumes of mooring ropes, amounting to a few tonnes per year, and cannot disclose their sources. The ropes are typically longer than one metre and must be cut into smaller pieces before further treatment. Upon arrival, the waste is weighed, unloaded, and processed using a waste crusher to reduce its size. After processing, the material is incinerated in a grate furnace at the facility. The plant does not assess the condition of the ropes or their material composition. It also receives similar materials from the fishing industry. Due to the low volumes handled, the plant has limited insight into broader challenges or potential solutions for improving circularity or extending the lifespan of this type of material.
Incineration plant C	Complex materials are theoretically suitable for incineration but are currently sent to landfill due to operational challenges. The materials cannot be sent directly to incineration, as they require shredding first, and the available shredders are not designed for this type of material. Individual slings and straps can be processed if mixed with other combustible waste, but tangled bundles end up in landfill. A shredder capable of handling the material was tested previously but was not found to be economically viable.

A.5 Shipping organisation email responses

The following table presents responses collected from shipping organisations through email correspondence. The responses are presented question by question, have not been colour-coded, and have been translated from Swedish to English.

Table A.10: Shipping organisation responses collected through email correspondence.

Question	**Shipping organisation A**	**Shipping organisation B**	**Shipping organisation C**	**Shipping organisation D**	**Shipping organisation E**
Q1: Where do you procure mooring lines?	We purchase almost exclusively from Logistic service supplier A	We purchase mooring lines from several established suppliers, primarily Lankhorst, Logistic service supplier A, and TEHO, depending on the vessel, region, and specification.	Our most recent mooring lines have been purchased from Drahtseilwerk.	We purchase mooring lines from ScanUnit in Helsingborg.	Wilhelmsen. We use the Timm Master 12 SBA F45.
Q2: What material of mooring lines do you primarily use?	Plastic material of the same type of fiber, typically polypropylene (PP) and polyethylene (PE).	Historically, we have used a lot of 8-strand polyolefin/polyethylene. We are now moving more toward 12-strand constructions with reduced recoil (snap-back reduction) and various types of abrasion protection.	Nylon (DURA Winchline 68mm).	We have switched to wire rope, which is much better from a work environment perspective, as it weighs significantly less with the same breaking strength.	Mixed polyolefins/olefin plastic.
Q3: How long are mooring lines typically used, and when do you replace them?	It depends on usage and wear. For example, lines wear faster on vessels that use locks more frequently, such as in the Trollhätte Canal. Average use is approximately 3 years. They are used for a maximum of 5 years, after which they are replaced for regulatory and safety reasons.	The lifespan varies greatly depending on usage, load, and environment. Replacement is not based solely on time or appearance.	It depends. We replace them when they have become worn or when a strand has broken, for example.	Several years, as we only moor with lines at fixed berths designed for our vessels. Every two years we go to a shipyard, and this is the only time we moor outside our own area.	The most common reason for replacement is that they have been condemned due to damage. Otherwise, they are replaced on a 15-year interval.
Q4: What actions do you take on board to extend the lifespan of mooring lines?	If a line sustains damage that can be repaired, it is repaired. We do not automatically purchase new lines. The placement of mooring lines is always optimised to avoid unnecessary wear.	Regular inspections, Abrasion protection (sleeves etc.), Rotation of lines and Correct dimensioning relative to winch brake capacity	We reverse them, shorten them if possible, splice new eyes, cut away spikes, etc	We store them protected from weather. We reinforce wear points with sailcloth. We track usage time per line in our maintenance system.	We monitor them at every mooring. Otherwise, quarterly inspections are carried out. If the lines have not been reversed due to wear earlier, this is done after 7.5 years.
Q5: How do you determine when a mooring line can no longer be used for mooring?	They are inspected monthly. If damage has occurred that reduces the line to a length that is too short for continued use, they are discarded.	Primarily based on visual assessment and experience. The challenge is that lines can sometimes appear to be in good condition while having lost a significant proportion of their internal strength.	Based on how worn they have become.	Through visual inspection for broken strands, and consultation with ScanUnit as our supplier.	If it has become damaged, for example broken strands, painted over, or damage to the core rope that eliminates snap-back.
Q6: What do you usually do with mooring lines once they are taken out of use?	They are generally returned to the supplier.	In Sweden, end-of-life mooring lines are typically handled through Circular solution company D, which receives the material together with other waste. Material that cannot be recycled often goes to energy recovery (incineration). We do not currently have a fully established circular system where all mooring lines are collected and recycled, due to mixed materials in mooring lines, technical limitations in recycling, and logistics and collection infrastructure challenges.	We sort them as hard plastic at the port's recycling station in Värtahamnen.	They go to recycling via Circular solution company D.	We reuse them to make fenders for concrete locks. Otherwise, they are discarded.
Q7: If mooring lines are left at the port, do they need to be cut or divided into smaller parts beforehand?	N/A	N/A	No, we leave them as they are.	No, they are fairly short and do not weigh very much.	No, they are left whole.

Continued on next page

Question	**Shipping organisation A**	**Shipping organisation B**	**Shipping organisation C**	**Shipping organisation D**	**Shipping organisation E**
Q8: Do you have any agreements with waste management or recycling companies handling EoL mooring lines?	No, but our supplier accepts returns of end-of-life mooring lines in some cases.	No fully established agreement exists. However, together with Logistic service supplier A we have developed a new type of mooring line with better conditions for recycling, which we see as promising going forward.	Stockholm Ports procures waste management services from an external provider.	Yes, Circular solution company D.	No, they are handed over to a nominated waste collector at one of the ports we visit.
Q9: If yes, how does the process work in practice (e.g., where is the material delivered, which company receives it, and are any preparations required)?	The material is delivered to the supplier Logistic service supplier A, who receives it. No preparation is required before handover.	A possible future solution we are looking at includes separate collection of lines on board, pick-up via Circular solution company D or directly via supplier (e.g. Logistic service supplier A), and recycling within a more closed-loop system. This is not yet fully implemented.	At Stockholm Ports' environmental station in Värtahamnen at berth 513, Stena Recycling, No	On the quay, and we contact Circular solution company D, Circular solution company D, No	N/A
Q10: Do you know what typically happens to the mooring lines after they are handed over (e.g., incineration, recycling, or other treatment)?	Our supplier Logistic service supplier A has a recycling program where end-of-life mooring lines have been repurposed, including as backrests for benches at an outdoor theatre in Malmö/Nyhamnen.	Material that cannot be recycled often goes to energy recovery (incineration).	No.	Circular solution company D is a recognised company certified according to ISO 9001, 14001, and 45001.	Unknown. Depending on the damage, they may be reused by smaller vessels.
Q11: Do you experience any challenges in handling EoL mooring lines today?	The main challenge is the logistics of returning end-of-life lines using the same transport that delivers new ones. Arranging a separate transport for returns is not considered practical. This means the delivery must take place when the vessel is docked and has had the opportunity to prepare and replace the worn lines on board.	Difficulty assessing remaining strength, Limited traceability after use, Lack of standardised recycling flows, Material mix in current mooring lines	No.	No.	Not particularly. Some ports do not accept them, but it usually works out fine.

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY