Assessing Packaging Systems in Offshore Logistics

A comparative framework for evaluating GHG emissions from single-use and reusable packaging

ME54030 - ME-MME Thesis

A. A. Laghate

Delft University of Technology

Assessing Packaging Systems in Offshore Logistics

A comparative framework for evaluating GHG emissions from single-use and reusable packaging

by

A. A. Laghate

conducted at

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Daily Supervisor:	Dr. Ir. A. Napoleone
Supervisory Team :	Dr. Ir. F. Schulte
	Ir. M. O. Barnuevo
Project Supervisor (HMC):	Ir. D. Biegel
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Preface

This thesis marks the culmination of my time as a student at the Delft University of Technology. My three years at TU Delft have been a tumultuous experience, filled with the highest of highs, the lowest of lows, and everything in between. Through these experiences, I have learnt a great deal about myself and my capabilities. While the journey was not always easy or enjoyable, I am proud to have faced my challenges head on, pushed past my limits, and grown into a better version of myself.

While this journey was my own, it was only made possible with the help of many amazing people. First and foremost, I am eternally grateful to my parents for their unwavering faith in me. Their support, along with that of the rest of my family, was essential in helping cross reach the finish line. I am also immensely thankful to all of my friends, who helped in their own ways, and I am grateful to them for putting up with my frequent grumbles about every minor and major inconvenience. All of these fantastic people were instrumental to my success, and I hope to have given them a push in their own journeys as well.

I also want to give my sincerest thanks to Daniel Biegel and the rest of the Sustainability Department for giving me the opportunity to conduct my thesis at Heerema Marine Contractors. The whole team was incredibly supportive and made my time at HMC an absolute joy. Looking back, I will fondly remember all the fun banter, coffees, and team lunches. I would also like to thank Dr Alessia Napoleone for supervising me and guiding me through the thesis process.

As my time at TU Delft draws to a close, I am glad to have made the choice to study here. I feel lucky to have lived through incredible experiences and to be leaving with cherished memories. Learning is a lifelong process, and although the formal part of my education is complete, I hope to remain as curious as ever as I embark on the next phase of my life.

A. A. Laghate
Rotterdam, April 2026

Abstract

Packaging plays a necessary supporting role in offshore logistics, but it also contributes to material use, waste generation, and greenhouse-gas (GHG) emissions. Within the logistics operations of Heerema Marine Contractors (HMC), the environmental impact of packaging had not previously been quantified in a structured way, and the benefit of replacing the current single-use system with reusable alternatives was therefore unclear. This thesis develops and applies a comparative decision-support framework to assess packaging-related GHG emissions in offshore contractor logistics and to evaluate whether reusable packaging can reduce that impact. The study focuses specifically on packaging production, transportation, and end-of-life treatment, and is limited to GHG emissions expressed as CO_2eq.

The framework was applied to historical package-flow data extracted from the HMC ERP system for the period 2012–2025. Because packaging characteristics are not recorded systematically in the ERP, packaging configurations were reconstructed using package-assignment rules based on unit of measure, package weight, density assumptions, and transport-support logic. The resulting model combines package interpretation, transport reconstruction, end-of-life modelling, and yard-based validation to estimate the emissions of both the current single-use packaging system and a proposed reusable alternative. Validation showed that ERP package labels do not always reflect physical packaging practice and that some informal reuse already occurs in the current system, meaning that the baseline should be interpreted as a conservative approximation of a predominantly single-use system.

The results show that the current packaging system is dominated by wooden transport items, particularly pallets and dunnage. Across the full study period, the estimated total mass of single-use packaging was 1546 mt, with corresponding emissions of 1141 mt CO_2eq under cut-off accounting and 783 mt CO_2eq under system-expansion accounting. For the in-house subset used in the reusable comparison, the baseline reusable scenario yielded only a marginal net benefit of 4.3 mt CO_2eq under cut-off accounting, while under system expansion it performed worse than the single-use baseline by 101.5 mt CO_2eq. Sensitivity analysis further showed that the comparative outcome is influenced more strongly by reverse-logistics performance than by reusable transport-item lifetime. The thesis therefore concludes that packaging-related GHG emissions can be assessed systematically in a data-constrained offshore environment, but that reusable packaging should not be regarded as an inherently superior solution for HMC. Any potential benefit is limited, highly context-dependent, and sensitive to both accounting assumptions and operational conditions.

Summary

This thesis examines the greenhouse-gas (GHG) impact of packaging in the logistics operations of an offshore contractor and evaluates whether reusable packaging can reduce that impact in the case of Heerema Marine Contractors (HMC). The study addresses the following central research question: how can the greenhouse-gas impact of packaging in the logistics operations of an offshore contractor be assessed, and to what extent can a reusable packaging system reduce that impact? To answer this question, a comparative decision-support framework was developed and applied to historical logistics data from HMC.

The study focuses specifically on packaging-related GHG emissions and does not assess the environmental burden of the complete logistics system. The analysis is limited to emissions associated with packaging production, transportation, and end-of-life treatment. Primary packaging was excluded, as it is generally determined by suppliers and lies outside HMC's direct decision space. The empirical case is based on historical package-flow data extracted from the HMC ERP system for the period 2012–2025. Because packaging characteristics are not systematically recorded in the ERP system, the study reconstructs packaging configurations through package-assignment rules based on unit of measure, package weight, density assumptions, and transport-support logic. The resulting framework combines package interpretation, transport reconstruction, end-of-life modelling, and targeted yard validation in order to estimate the emissions of both the current single-use packaging system and a proposed reusable alternative.

Validation activities were undertaken to test the credibility of the main modelling assumptions. Yard observations confirmed that ERP package labels do not always reflect the physical packaging actually used in practice, and that support materials such as pallets, dunnage, and foil may be present even when not recorded explicitly. The validation also showed that some informal reuse already occurs within the current system, especially for wooden transport items, although this could not be quantified consistently enough for explicit inclusion in the model. The baseline therefore represents a conservative approximation of a predominantly single-use packaging system. Additional validation work was used to recalibrate carton and box density assumptions and to improve the representation of dunnage and foil consumption.

The baseline results show that the current packaging system is dominated by wooden transport items, particularly pallets and dunnage. Across the full study period, the estimated total mass of single-use packaging was 1546 mt, of which 444 mt originated from internal packages and 1102 mt from supplier-delivered purchase-order packages. This indicates that most packaging mass lies outside HMC's direct operational control. The corresponding emissions of the single-use system were estimated at 1141 mt CO_2eq under cut-off accounting and 783 mt CO_2eq under system-expansion accounting. In both cases, production and transportation dominate the positive burden, while the difference between the two totals is caused by the treatment of end-of-life emissions.

The comparative assessment of reusable packaging was restricted to the in-house subset of package flows within the company-controlled logistics boundary. Under the baseline reusable scenario, the reusable system yielded only a marginal net emissions benefit of 4.3 mt CO_2eq under cut-off accounting. Under system-expansion accounting, the result reversed and the reusable system performed worse than the single-use baseline by 101.5 mt CO_2eq. The comparative outcome was also highly uneven across destinations and packaging categories. Boxes performed poorly under both accounting approaches, pallets showed only limited benefit, and dunnage appeared to be the most promising category under cut-off accounting, although much of this advantage weakened or disappeared under system expansion.

Sensitivity analysis showed that the comparative result is much more strongly influenced by reverse-logistics performance than by RTI lifetime. The baseline cut-off result lies close to the break-even boundary, indicating that even where reusable packaging appears marginally beneficial, that benefit is not robust to modest changes in operational assumptions. This is particularly relevant in offshore logistics, where return flows are complex and reuse loops are difficult to control. Several of the most important uncertainties in the study, including informal reuse already occurring in the current system, possible overstatement of some dunnage use, and optimistic assumptions regarding reverse-logistics efficiency, are also more likely to reduce the apparent benefit of reusable packaging than to increase it.

The main conclusion of the thesis is therefore that reusable packaging should not be regarded as an inherently superior solution for HMC's logistics system. The study demonstrates that packaging-related GHG emissions can be assessed systematically in a data-constrained offshore environment, but it does not provide robust evidence that a broad transition to reusable packaging would reduce emissions under realistic HMC operating conditions. Instead, the results support a more selective and context-dependent interpretation, in which any future packaging intervention should be evaluated carefully by packaging type, destination, and operational feasibility. The principal contribution of the thesis is thus both practical and methodological: it provides HMC with a structured basis for evaluating packaging-related emissions, while also contributing a transferable framework for package-level comparative assessment in industrial logistics systems where packaging data is incomplete.

AI Statement

For this thesis report for the course ME-MME Thesis - ME54030, I have used Generative AI to:

- Review and refactor code in Python for pre-processing and calculation scripts
- Obtain inspiration for overall structure and layout of the report
- Check spellings and grammar, rewrite sentences to improve clarity and cohesiveness
- Generate tables and other latex formatting for the report

In all cases, I have reviewed and corrected the work and remain fully responsible for the content of the report.

Contents

List of Figures

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Nomenclature

Abbreviations

Abbreviation	Definition
ALCA	Attributional life cycle assessment
AHT	Anchor handling tug
CE	Circular economy
CLCA	Consequential life cycle assessment
CV	Crane vessel
DESNZ	Department for Energy Security and Net Zero
EC	European Commission
EOL	End-of-life
ERP	Enterprise resource planning
EU	European Union
GHG	Greenhouse gas
HMC	Heerema Marine Contractors
IMO	International Maritime Organization
LCA	Life cycle assessment
LE	Linear economy
MARPOL	International Convention for the Prevention of Pollution from Ships
RTI	Reusable transport item
SDG	Sustainable Development Goal
SSCV	Semi-submersible crane vessel
TIR	Transport, installation, and removal
TPC	Third-party equipment
UOM	Unit of measure
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PP	Polypropylene
BAG	Bag
BND	Bundle
BOX	Box
CRT	Carton
DRM	Drums / bottles / IBCs
EA	Each (individual item)
FOIL	Stretch wrap
PAL	Pallet
RACK	Gas rack
ROL	Roll

Sets and indices

Symbol	Definition	Unit
B	Set of density bands	–
I_p	Set of packaging items associated with package record p	–
P	Set of package records	–
R	Set of waste-treatment methods	–

Symbol	Definition	Unit
b	Density-band index	–
i	Packaging-item index	–
p	Package-record index	–
r	Waste-treatment-method index	–
z	EOL accounting approach index	–

Roman symbols

Symbol	Definition	Unit
B_p	Emissions benefit of reusable packaging relative to single-use packaging for package record p	kg CO_2-eq
B_{base}	Baseline emissions benefit used for normalization	kg CO_2-eq
B_{tot}	Total emissions benefit across all package records	kg CO_2-eq
d_b	Representative density value of density band b	kg m^{-3}
E_i^{prod}	Production emissions of packaging item i per use	kg CO_2-eq
E_p^{prod}	Production emissions of package record p	kg CO_2-eq
E_p^{eol}	End-of-life emissions of package record p	kg CO_2-eq
$E_p^{\text{trans,SU}}$	Transport emissions of the single-use system for package record p	kg CO_2-eq
$E_p^{\text{trans,RU}}$	Transport emissions of the reusable system for package record p	kg CO_2-eq
E_p^{SU}	Total emissions of the single-use packaging system for package record p	kg CO_2-eq
E_p^{RU}	Total emissions of the reusable packaging system for package record p	kg CO_2-eq
$E_p^{\text{RU,in}}$	Total emissions of the reusable system for an in-house package record p	kg CO_2-eq
$E_p^{\text{RU,po}}$	Total emissions of the reusable system for a purchase-order package record p	kg CO_2-eq
$E_p^{\text{prod,sup}}$	Production emissions of original supplier packaging for purchase-order record p	kg CO_2-eq
$E_p^{\text{eol,sup}}$	End-of-life emissions of original supplier packaging for purchase-order record p	kg CO_2-eq
$E_{\text{tot}}^{\text{SU}}$	Total single-use system emissions over all package records	kg CO_2-eq
$E_{\text{tot}}^{\text{RU}}$	Total reusable system emissions over all package records	kg CO_2-eq
$f_{p,b}$	Share of package p associated with density band b	–
k	Fill factor	–
L_i	Service life of packaging item i	cycles
m_i	Mass of packaging item i	kg
m_p^{pack}	Package-level packaging mass for package p	kg
M_p	Total packaging mass associated with package record p	kg
M^{pack}	Total packaging mass across the analytical dataset	kg
q_p	Quantity associated with package record p	–
R_p	Normalized benefit relative to the baseline scenario	%

Greek symbols

Symbol	Definition	Unit
α_i	Cradle-to-gate production emission factor of packaging item i	kg CO_2-eq kg^{-1}
β^z_{ir}	EOL emission factor of packaging item i under treatment method r and accounting approach z	kg CO_2-eq kg^{-1}
γ^z_{pi}	Effective EOL emission factor of packaging item i for package record p under accounting approach z	kg CO_2-eq kg^{-1}
λ	Reverse logistics multiplier	–
ϕ_{pr}	Fraction of waste from package record p assigned to treatment method r	–
ρ_p	Observed package density for package p	kg m^{-3}
$\hat{\rho}_p$	Predicted package density for package p	kg m^{-3}
τ_p	Route-specific transport emission factor for package record p	kg CO_2-eq kg^{-1}

Subscripts and superscripts

Symbol	Definition
base	Baseline scenario
eol	End-of-life
in	In-house package record
pack	Packaging
po	Purchase-order package record
prod	Production
sup	Supplier packaging
SU	Single-use packaging system
RU	Reusable packaging system
tot	Total over all package records
trans	Transportation
$\hat{(\cdot)}$	Estimated or predicted quantity

1

Introduction

1.1. Background

Anthropogenic climate change has been defined as the long-term change in climatic trends as a result of human activity and has been long theorized as early as the 19th century by Fourier[1]. In the 21st century, this theory is now well established and has been linked to several adverse impacts that have widespread effects around the world. Climate change has been linked to extreme weather events such as heatwaves and droughts leading to eutrophication. Melting icecaps have led to rising sea levels, making coastal environments more vulnerable to flooding during storms. These events have a drastic impact on society including reduction in food security, forced migration and conflicts due to population pressure leading to immense humanitarian and economic damage[2]. Global ecosystems are also being affected drastically due to climate change. Habitat loss and extinction of vulnerable species has led to the breakdown of food chains, in turn leading to widespread biodiversity loss. In its most extreme form, these effects can also lead to a complete collapse of ecosystems causing a mass extinction event[2][3].

Resource extraction has been the main driver of climate change since the industrial revolution. In the now famous study titled 'The Limits to Growth', Meadows et al.[4] concluded that expected population growth, combined with unsustainable resource exploitation and environmental destruction would lead to a catastrophic decline in human civilization without appropriate intervention. While the study has been very controversial and has sparked debate about its conclusions, it's core premise remains true. A 2019 study by the United Nations found that resource extraction of all types contributed to approximately 50% of global greenhouse-gas (GHG) emissions. Moreover due to rapid population growth, global resource use has increased three-fold since 1970 and has been growing by 2.6% per capita on average[5]. Therefore, changes are required to current economic models to sustainably manage our planet's finite resources before a potential collapse.

Circular Economy (CE) models have been proposed as an alternative to the conventional Linear Economy (LE) models that are in use today. CE models increase sustainability by reducing the demand for raw materials and by reducing waste generated thereby addressing the problem from both the input and output side[6][7][8]. A core idea in CE is value creation and destruction, with focus on preserving maximum value within the system. This can be clearly illustrated using a value hill diagram, also showing a comparison between circular and linear models. Conceptually during the life cycle of a product, value is added at each stage from raw material extraction, to production of finished product. The value is maximum when the product is being used by the consumer as shown in figure 1.1. In the conventional LE model, after the product has been used by the consumer, it is discarded and all of the value is lost. By contrast CE models attempt to retain value that would be otherwise lost at various post-use stages. Based on these principle, the '9-Rs' of CE have been derived namely, R0 Refuse, R1 Rethink, R2 Reduce, R3 Reuse, R4 Repair, R5 Refurbish, R6 Remanufacture, R7 Repurpose, R8 Recycle and R9 Recover. As a general indication, the closer the material remains to the original product, the more value is retained. E.g. For a car, repairing retains more value than refurbishment, which in-turn retains more value than scrapping the car and recycling the materials in it.

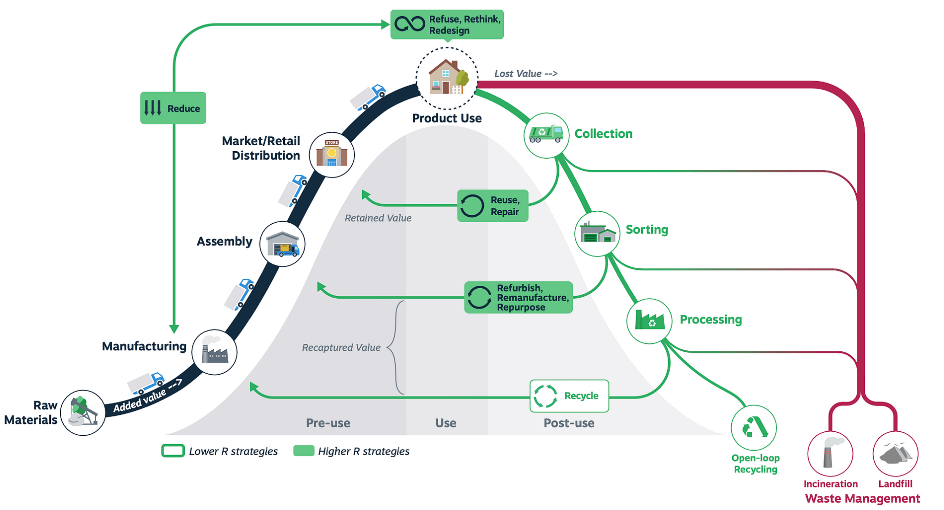

Figure 1.1: Value Hill Diagram[9]

Due to the potential environmental benefits and to increase resilience and self-sufficiency, the European Commission (EC) has adopted a new CE plan from 2020 as part of the 2019 European Green Deal, aiming for widespread adoption of sustainable products in the European Union (EU) and setting circularity targets for high impact sectors[10]. The Dutch government has also adopted the National Programme on Circular Economy with the goal of reducing 50% of resource use by 2030 and aiming for a fully circular economy by 2050[11].

1.2. Motivation

Heerema Marine Contractors (HMC) is an offshore contractor based in the Netherlands and the host company for this master's thesis. The company specializes in offshore construction projects, particularly the transport, installation, and removal (TIR) of offshore infrastructure. These activities are supported by a mixed fleet of four crane vessels, shown in Figure 1.2, of which three are semi-submersible crane vessels (SSCVs) and one is a conventional crane vessel (CV). In addition, HMC operates two ocean-going anchor handling tugs (AHTs) and various barges as part of its offshore fleet[12]. These vessels are highly specialized and capital-intensive assets with high fixed and operational costs. As a result, offshore contractors such as HMC organize work so as to maximize vessel utilization while operating under the regulatory and operational constraints associated with project execution.

These factors, coupled with tight project schedules, require a long and complex logistics chain to support vessel operations. Packages containing project equipment, crew provisions, spare parts, and operational supplies are transported globally, often months in advance, to ensure that required materials arrive at the correct location and time. In addition to routine vessel replenishment, logistics activities also support mobilization and demobilization in port, as well as repair and maintenance periods between projects. Because the goods being shipped vary widely in size, shape, and handling requirements, the associated packaging also takes many forms, including cartons, pallets, boxes, drums, bundles, and wrapped loads.

The extensive use of packaging in offshore logistics should be understood within the broader material footprint of offshore construction. Due to the scale of vessel operations, project equipment, and supporting infrastructure, offshore construction is highly material intensive. Consequently, substantial amounts of waste are generated during company operations. Maritime waste is classified according to standards developed by the International Maritime Organization (IMO), specifically under the MARPOL convention, which distinguishes nine waste categories from A to I. According to the HMC sustainability report, offshore operations generated a total of 10,690 m^3 of waste in 2024. The largest contributor was operational waste (5,544 m^3), followed by domestic waste (2,283 m^3) and plastic waste (2,091 m^3)[13]. Although the share attributable specifically to packaging is not separately reported, packaging disposal

Figure 1.2: Heerema crane vessel fleet. Clockwise from top left: Balder, Thialf, Sleipnir, and Aegir

forms part of this broader waste stream. Importantly, in a predominantly single-use system, this can lead not only to material waste but also to missed opportunities to retain packaging within the logistics chain through reuse.

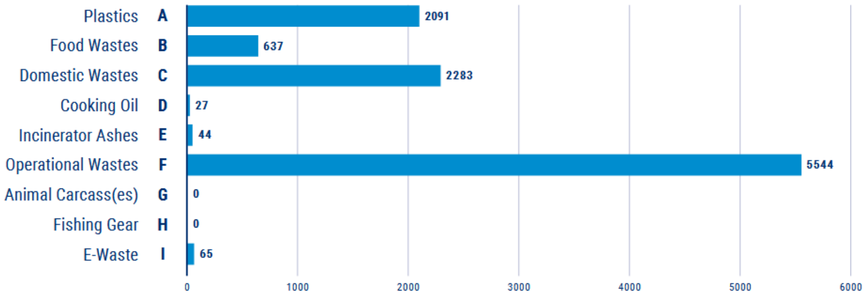

Figure 1.3: Waste breakdown by category in 2024[13]. Note: Operational waste includes waste related to project execution

As part of its long-term sustainability strategy, HMC has adopted a framework derived from the United Nations Sustainable Development Goals (SDGs)[14] and the IMO sustainability agenda. This strategy is organized around four pillars: Net-zero, Caring for People, Healthy Oceans, and Circular Heerema[13]. Within this framework, the Circular Heerema team seeks to retain maximum value within the company's operational footprint by minimizing raw-material inflows and waste outflows. Packaging is therefore a relevant intervention point, since it is both necessary for logistics and a potential contributor to waste. At the same time, the current packaging system has not been quantified in detail, and the environmental effect of introducing reusable alternatives is not yet known. This creates a clear need for a structured comparative assessment of the existing single-use packaging system and potential reusable alternatives in the context of offshore contractor logistics.

1.3. Research Definition

1.3.1. Problem Description

As part of HMC's circularity ambitions, the Circular Heerema team initiated this research to evaluate whether reusable packaging could reduce the emissions associated with packaging used in offshore logistics operations. The practical problem is that packaging is a necessary supporting element within the logistics system, but its current use and associated emissions have not previously been quantified in a structured way within the company.

In the logistics context considered in this study, packaging performs several operational functions. It is

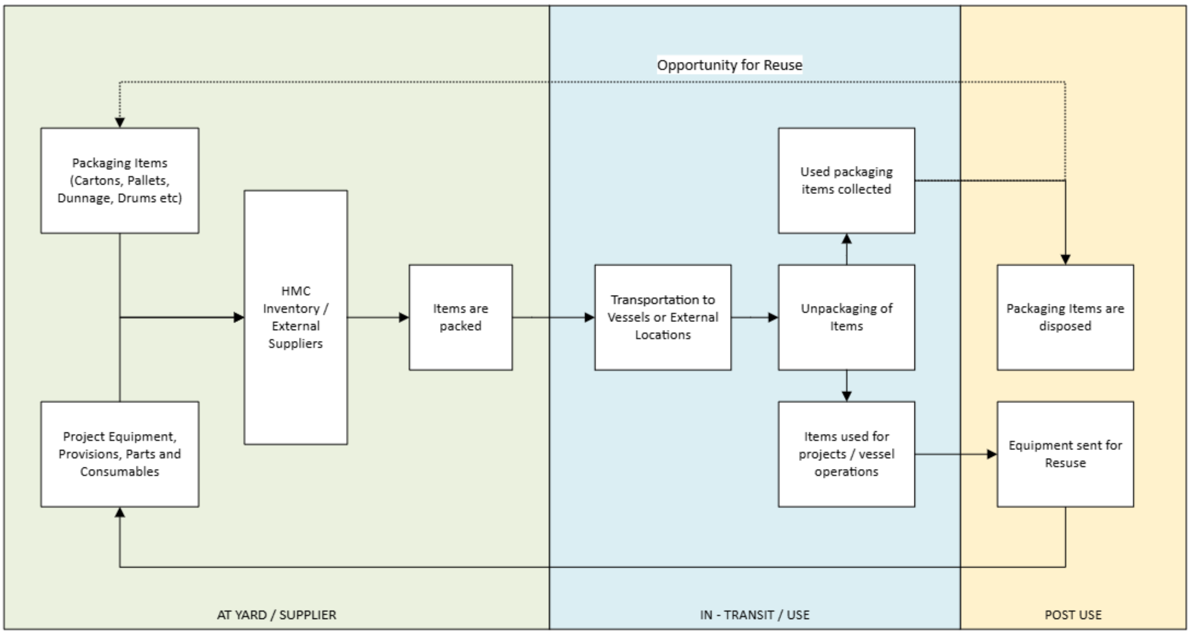

Figure 1.4: Material flow through the HMC logistics system

used to contain, protect, consolidate, identify, and handle goods such as project equipment, spare parts, crew provisions, and operational supplies as they move through a geographically dispersed network of yards, suppliers, ports, vessels, and offshore locations. Because these goods are often transported over long distances, through multiple handling stages, and under demanding operational conditions, packaging cannot simply be eliminated without affecting transport feasibility, handling efficiency, or the condition in which goods arrive for use. The practical intervention space therefore lies not in removing packaging altogether, but in redesigning the packaging system so that the same logistical function can be provided with lower environmental burden.

Figure 1.4 illustrates this logic schematically. Goods required for offshore operations enter the logistics system together with packaging items that enable packing, transport, handling, and unpacking. After delivery and use of the goods, the packaging may either leave the system as waste or be retained within a reuse loop. This post-use pathway is the central focus of the present study.

A central challenge is that the company's enterprise resource planning (ERP) system records packaging only at a relatively coarse level. Package records contain unit-of-measure (UOM) categories such as cartons, boxes, pallets, bundles, and individual items, but do not systematically record detailed packaging characteristics such as exact dimensions, material composition, or the physical use of supporting transport items. This makes it difficult to determine both the current mass of packaging used in the logistics system and the emissions associated with that packaging.

The problem is further complicated by the nature of offshore logistics. HMC operates in a project-based environment in which goods are shipped to ports, yards, vessels, and offshore locations under varying logistical conditions. Packaging therefore differs not only by type of item shipped, but also by route, destination, and handling requirements. As a result, the environmental performance of reusable packaging cannot be assessed through generic assumptions alone, but must be evaluated in the specific operational context in which it is intended to function.

This creates the need for a comparative framework that can quantify the current single-use packaging system, define functionally equivalent reusable alternatives, and assess the relative GHG emissions of both systems under realistic case-specific assumptions. In addition, because reusable packaging performance depends on uncertain parameters such as reverse logistics burden and transport-item lifetime, the framework must also be able to test the sensitivity of the comparative results to these assumptions.

1.3.2. Research Questions

The objective of this thesis is to develop and apply a comparative decision-support framework for evaluating single-use and reusable packaging systems in the logistics operations of an offshore contractor. The study focuses on GHG emissions and uses HMC as an empirical case through which the framework is implemented and tested.

The central research question is:

> How can the greenhouse-gas impact of packaging in the logistics operations of an offshore contractor be assessed, and to what extent can a reusable packaging system reduce that impact?

This question is addressed through the following subquestions:

1. How can the mass of packaging material used in the current single-use packaging system be estimated?
2. What LCA methodology is appropriate for estimating the greenhouse-gas impact of packaging materials in this offshore logistics domain?
3. To what extent does the greenhouse-gas impact of the packaging system change when reusable packaging is introduced in place of the current single-use system?

1.3.3. Scope

The thesis is limited to a comparative GHG assessment of packaging systems within the logistics operations studied at HMC. It does not constitute a full multi-impact life cycle assessment, nor does it assess the environmental impact of the complete logistics system. Instead, the focus is specifically on the emissions associated with packaging production, transport, and end-of-life treatment for single-use and reusable packaging configurations.

The empirical scope of the case study is based on historical logistics data extracted from the HMC ERP system for the period 2012–2025. This data is used to reconstruct observed package flows and to represent the logistical conditions under which packaging is used in practice. The baseline characterization of packaging mass and emissions is performed for the full analytical dataset. The comparative assessment of reusable packaging is restricted to the in-house subset of package flows within the company-controlled logistics boundary, since externally supplied purchase-order flows would require additional repackaging and handling steps that are outside the scope of the present model.

In supply chains, packaging is commonly classified into three levels: primary packaging, which is in direct contact with the product; secondary packaging, which groups primary packages for handling and distribution; and tertiary packaging, which supports large-scale transport, handling, and storage[15, 16]. The present study focuses primarily on tertiary packaging and selected forms of secondary packaging that are relevant to transport, handling, and distribution. Primary packaging is excluded, since it is generally determined by suppliers and lies outside the direct control of HMC. This boundary reflects the practical decision space available to the company when evaluating reusable packaging strategies.

Because the ERP system does not record all relevant physical packaging characteristics directly, several packaging attributes had to be inferred through case-specific estimation methods. These include the assignment of transport items, the estimation of packaging mass, and the representation of certain support materials such as dunnage and stretch wrap. Validation activities were therefore incorporated into the case study in order to assess whether the resulting assumptions provided a credible representation of actual yard practice.

Finally, the study is intended as a comparative decision-support exercise rather than as a detailed implementation plan. It therefore evaluates the relative emissions performance of single-use and reusable packaging systems under a defined set of assumptions, together with the sensitivity of the results to key operational parameters such as reverse logistics burden and reusable transport-item lifetime.

1.4. Structure of the Report

The remainder of this thesis is structured as follows:

- Chapter 2 reviews the relevant literature on circular economy, reusable packaging systems, and comparative environmental assessment methods that inform the framework developed in this study.
- Chapter 3 presents the methodological approach, including the comparative assessment framework, system boundaries, model formulation, and sensitivity-analysis design.
- Chapter 4 describes the HMC case study, including the data sources, packaging-system representation, transport-item assignment, environmental inputs, and validation approach used to implement the framework in practice.
- Chapter 5 presents the main findings of the study, including validation results, the estimated mass and emissions of the existing single-use packaging system, the comparative results for reusable packaging, and the sensitivity and scenario analyses.
- Chapter 6 discusses the interpretation and implications of the results, reflects on the main limitations of the study, and considers their relevance for both HMC and the broader application of reusable packaging systems.
- Chapter 7 concludes the thesis by answering the research questions, summarizing the main findings, and providing recommendations for future work.

2

Literature Review

2.1. Reusable packaging as a circularity strategy

Reusable packaging systems are widely presented in literature as a CE strategy for reducing packaging waste, retaining material value, and distributing production impacts over multiple use cycles. In contrast to single-use packaging, which is disposed of after one logistics cycle, reusable systems are designed to keep packaging assets in circulation through repeated reuse and recovery[17, 15, 18]. This logic is especially relevant for secondary and tertiary packaging, where pallets, crates, containers, and dunnage perform transport and handling functions rather than direct product-contact functions [18].

Within the CE literature, reusable packaging is generally understood as a strategy that slows and narrows resource flows by extending the functional life of packaging assets and reducing demand for virgin materials [17, 18]. However, the literature also makes clear that reuse is not a benefit in itself. A reusable packaging system must be embedded in an effective logistics and return loop for its potential environmental advantage to materialize. Coelho et al. note that reusable packaging can reduce material use and environmental burden, but that impacts depend strongly on system design and implementation [17]. Bradley and Corsini reach a similar conclusion, arguing that reusable packaging should not be assumed to be more sustainable than single-use alternatives without context-specific assessment [15].

For transport packaging, this system perspective is particularly important. Katsanakis et al. emphasize that returnable transport items (RTIs) should be understood as part of a broader lifecycle management system involving ownership, circulation, maintenance, repair, and end-of-life recovery [18]. In this sense, reusable packaging is not only a material substitution but also a logistics-system intervention. This framing is directly relevant to offshore contractor logistics, where packaging performance depends not only on the packaging item itself, but also on routing, custody, return opportunities, and operational control.

2.2. Comparative environmental assessment of reusable and single-use packaging

The environmental comparison of reusable and single-use packaging is most commonly carried out using life cycle assessment (LCA) and related comparative approaches [17, 15]. Across this literature, a common conclusion emerges: reusable packaging often outperforms single-use alternatives only when sufficient reuse cycles are achieved and when the additional burdens associated with return logistics, cleaning, and handling remain limited [17, 15, 19, 20]. Reuse therefore tends to be environmentally advantageous only under certain system conditions.

Several comparative case studies illustrate this conditionality clearly. Koskela et al. compared reusable HDPE plastic crates with recyclable corrugated cardboard boxes in a real bread distribution system and found that the recyclable cardboard system performed better across all studied impact categories under the defined assumptions [19]. The authors identified transport as a dominant contributor and concluded that weights and transport distances strongly affected the outcome. Del Borghi et al. reached a different result in a comparative study of food crates, finding that reusable plastic crates could perform best when an effective recovery system and multiple reuse cycles were achieved, while transport distance and recycling rates still exerted significant influence on results [20]. Together, these studies show that comparative outcomes are highly case-specific and should not be generalized without attention to package-flow conditions and end-of-life (EOL) treatment.

This context dependency is also reflected in broader review literature. Bradley and Corsini synthesize a wide range of reusable-packaging studies and identify major factors affecting sustainability, including return rate, supply-chain length, standardization, customer retention, and system design [15]. Coelho et al. similarly note that reusable systems often show environmental benefits over single-use systems, but that decision-support models and stronger empirical evidence are still needed, particularly when logistics become more complex [17]. The implication for the present thesis is clear: the environmental performance of reusable packaging should be evaluated comparatively and case by case, rather than assumed on the basis of CE principles alone.

2.3. Methodological choices in comparative LCA and EOL accounting

A further theme in the literature is that comparative results are shaped not only by the packaging systems being compared, but also by the methodological choices used to model them. One of the most important distinctions is between attributional and consequential LCA. Ekvall defines attributional LCA (ALCA) as an approach that estimates what share of global environmental burdens belongs to a product, typically using average data and allocation procedures, whereas consequential LCA (CLCA) estimates how total environmental burdens change as a result of a decision, typically relying more heavily on marginal data and system expansion [21]. The distinction matters because different methodological choices can lead to different interpretations of the same system.

For a packaging comparison such as the present study, the most relevant methodological issue is the treatment of EOL burdens and credits. Vogtländer describes cut-off and system-expansion logic as two consistent but different ways of handling by-products, waste, and recycling in LCA [22]. Under a cut-off approach, the studied system is assigned burdens up to disposal or recovery, while downstream benefits are attributed to the next product system. Under system expansion or avoided burden, the studied system may receive credits when recovered material or energy displaces primary production elsewhere [22]. These choices are especially relevant in packaging systems where recycling and waste-to-energy play an important role.

Applied packaging studies show that these accounting choices can materially affect conclusions. In comparative packaging LCAs, recycling credits and energy-recovery assumptions often reduce the attributed burden of single-use systems, sometimes narrowing or even reversing the apparent benefit of reuse. The literature therefore supports the view that EOL accounting should not be treated as a minor technical detail, but as a central methodological determinant of comparative results [21, 22, 20]. This is directly relevant to the present thesis, where the comparison between cut-off and system-expansion treatments is one of the main analytical design choices.

2.4. Key drivers of reusable packaging performance

Across the reusable-packaging and RTI literature, several drivers consistently determine whether reuse performs well or poorly. The first is reverse logistics burden. Because reusable systems introduce return flows, empty repositioning, and additional transport segments, transportation often becomes the dominant burden or the dominant source of uncertainty [15, 19, 20]. Where return loops are consolidated and efficient, reusable systems may realize clear benefits; where return flows are fragmented or distance-intensive, these benefits can be eroded quickly.

A second major driver is service life, or the number of effective reuse cycles achieved in practice. The environmental advantage of a reusable item depends on production impacts being amortized across multiple uses. If loss, damage, or poor return rates reduce the realized number of cycles, the per-use burden rises substantially [17, 15, 18]. This is particularly important in systems where assets are distributed across multiple actors and where packaging is not tightly tracked. In such cases, theoretical durability alone is not enough; what matters is realized reuse intensity.

A third driver is system organization. Literature on industrial RTIs repeatedly emphasizes the importance of standardization, pooling, fill rate, and operational coordination. Standardized packaging can improve asset interchangeability, reduce unnecessary return trips, and support higher cube utilization [15, 23]. Dubisz et al. show that standardizing reusable packaging in an internal automotive supply chain reduced the number of shipments and lowered transport-related $\mathrm{CO_2}$ emissions by changing the reverse-logistics structure [23]. The importance of standardization and control suggests that reusable packaging performance is governed not only by material choice, but by the degree to which the surrounding logistics system enables efficient circulation.

Finally, EOL treatment remains a further driver even in reusable systems. If single-use packaging in a baseline system has high recycling rates or receives substantial recovery credits, the comparative benefit of switching to reuse may be reduced. Conversely, where disposal is dominated by landfill and recovery potential is low, reuse may appear more favorable. Taken together, the literature shows that reusable packaging should be evaluated as a system-level intervention shaped by reverse logistics, realized reuse intensity, operational efficiency, and EOL treatment, rather than as a packaging-material decision in isolation [15, 21, 22].

2.5. Summary of selected literature on reusable packaging systems

Table 2.1 summarizes selected studies most relevant to the present thesis. The table highlights a common pattern: most reusable-packaging studies are concentrated in sectors such as food distribution, pallet systems, consumer goods, and automotive logistics. These contexts typically involve more repetitive and standardized package flows than those found in offshore contractor logistics. The dominant methods are comparative LCAs and review-based analytical frameworks, and the most frequently identified drivers are transport burden, reuse cycles, standardization, and EOL treatment [17, 15, 18, 19, 20, 23, 24, 25].

Table 2.1: Summary of selected literature on reusable packaging systems

Study	**Sector**	**Method**	**Package flow modeling**	**Drivers**	**Main finding**	**Applicability to offshore**
Coelho et al. (2020)	Cross-sector	Literature review	Conceptual system classification	Distance, return rate, pooling, cleaning	Reuse is promising but depends on system design	Medium
Bradley & Corsini (2023)	Cross-sector	Systematic review + framework	Secondary/tertiary reuse systems	Return rate, supply-chain length, standardization	Reusable packaging is not inherently more sustainable	High
Katsanakis et al. (2023)	Industrial logistics	Integrative review	RTI lifecycle management	Repair, reuse, recovery, governance	RTIs require lifecycle and systems thinking	High
Koskela et al. (2014)	Food distribution	Comparative LCA	Real delivery routes with take-back	Transport distance, weight, recycling credit	Cardboard outperformed reusable plastic under case assumptions	Medium
Del Borghi et al. (2020/2021)	Food logistics	Comparative LCA	Single-use vs. multi-use crate systems	Reuse cycles, transport, recycling	Reusable plastic can outperform single-use if recovery is planned	Medium
Dubisz et al. (2023)	Automotive logistics	Case study + carbon comparison	Standardized reverse-flow design	Standardization, fill rate, return routing	Standardization reduced trips and emissions	Medium
Glock (2017)	RTI supply chains	Systematic review	Closed-loop RTI decision models	Cycle time, returns, control	RTI benefits depend on structured loop management	Low–Medium
Kudrenko & Hall (2024)	Machinery / aerospace / automotive	Survey + interviews	Heavy-industry reusable transit packaging	Cost, standards, implementation barriers	Reuse is relevant in heavy industry but underexplored	Medium

2.6. Applicability to offshore logistics and research gap

The literature reviewed above provides a strong conceptual basis for evaluating reusable packaging, but its direct applicability to offshore contractor logistics is limited. Most studies focus on sectors with relatively stable, repetitive, and standardized flows, such as food distribution, pallet pooling, retail, and automotive systems [17, 15, 18, 23, 24]. In these sectors, package loops are often easier to define, return rates are more trackable, and standardization is more feasible. Even where reverse logistics is complex, the overall network structure is usually more repetitive than in project-based offshore operations.

Offshore contractor logistics differs from these dominant literature settings in several important ways. First, package flows are heterogeneous, involving a wide range of equipment, consumables, provisions, and project-specific items. Second, logistics routes are global and often irregular, with variable origins, destinations, and intermediate stops. Third, return opportunities are constrained by project schedules, multimodal routing, and fragmented custody across suppliers, yards, ports, vessels, and subcontractors. Fourth, packaging characteristics are often not systematically recorded in ERP systems, meaning that the physical packaging system must be reconstructed indirectly rather than observed directly. These conditions make offshore contractor logistics a materially different context from the repetitive closed-loop systems that dominate the RTI literature [15, 18, 25].

The research gap therefore lies not simply in the lack of offshore-specific reusable-packaging studies, but in the absence of a comparative framework suited to heterogeneous project logistics and imperfect operational data. Existing literature demonstrates that reusable packaging performance is highly context-dependent and shaped by reverse logistics, reuse intensity, standardization, and EOL treatment. However, it provides limited guidance for evaluating reusable packaging in offshore contractor logistics where packaging systems must be reconstructed from incomplete historical records and validated through case-specific assumptions. The present thesis addresses this gap by developing a case-based comparative framework that uses historical package-flow data to estimate packaging mass and GHG burdens, and then compares single-use and reusable packaging systems under explicit operational and EOL assumptions.

3

Methodology

3.1. Research Design

This thesis adopts a case-based comparative research design to evaluate the greenhouse-gas impact of packaging in offshore contractor logistics. The research is structured around two complementary components. First, a general methodological framework is developed to define how packaging systems can be compared using life-cycle assessment principles, including the choice of LCA perspective, the definition of system boundaries, the specification of the functional unit, and the formulation of the comparative emissions model. Second, this framework is applied to a single case study at Heerema Marine Contractors (HMC), where historical logistics records, packaging assignment rules, case-specific assumptions, and validation steps are used to operationalize the model in a real industrial setting.

This combination of methodological development and case-based application forms the overall research design of the thesis. The methodological component provides the transferable analytical logic required to assess packaging systems in a structured and transparent way. The case-study component provides the empirical basis needed to implement that logic using observed logistics data, realistic packaging representations, and company-specific validation. Together, these two components allow the research questions to be addressed through a comparative assessment of the current single-use packaging system and proposed reusable alternatives. Accordingly, this chapter presents the general methodological framework used in the study, while Chapter 4 describes its implementation in the specific context of HMC.

The core methodological approach used in this study is a comparative analysis of an existing single-use packaging system and a proposed reusable packaging system. The objective of this analysis is to quantify the environmental impacts associated with both systems and to compare their relative environmental performance. The results are intended to support strategic decision-making regarding either the continued use of the current packaging system at the host company or the further development and implementation of a reusable alternative.

Within this framework, a transport cycle is defined as the path a package follows through the logistics network, beginning with loading and closure, continuing through transport to the destination, and ending when the package is received and unpacked. A single-use packaging system therefore consists of transport items used for one transport cycle before disposal and EOL processing. In contrast, a reusable packaging system consists of reusable transport items (RTIs) that are designed to complete multiple transport cycles before final disposal. Consequently, the environmental performance of reusable packaging must be evaluated at the system level rather than at the level of individual items.

A central requirement of the framework is functional equivalence between the two systems. Both alternatives must provide an equivalent level of service in order to satisfy the logistical demands of the network. Differences in packaging design may alter material use, carrying capacity, or handling characteristics, which can distort the interpretation of environmental results if equivalence is not maintained. Ensuring functional equivalence is therefore necessary both for methodological consistency and for confirming that the compared systems satisfy the operational requirements of the host company.

Based on these principles, the framework captures the main life-cycle elements required to assess the environmental performance of both systems. For the single-use system, this includes the impacts associated with packaging production, transport, and EOL processing. For the reusable system, the framework additionally accounts for repeated use and reverse logistics. Although replacement of lost or damaged RTIs may also influence environmental outcomes, this aspect is excluded from the present study because the analysis is limited to comparative environmental performance within the defined scope, rather than dynamic fleet management. Environmental impacts are quantified under consistent modeling assumptions and used to compare the relative performance of the two systems. This conceptual framework forms the basis for the system boundaries and modeling approach described in the following sections.

3.2. LCA Perspective, and System Boundaries

3.2.1. LCA Methods

Attributional and consequential life cycle assessment represent two distinct approaches to environmental modeling. Attributional LCA quantifies the environmental burdens associated with a defined product system, whereas consequential LCA seeks to estimate the wider environmental consequences of a change from one system to another [21]. The distinction is important because it influences both the interpretation of results and the definition of system boundaries.

Consequential LCA aims to capture broader system effects, but requires substantially more assumptions and data than attributional LCA. While a detailed consequential LCA is possible for a singular product or system, it quickly becomes infeasible, particularly when applied to large systems with global supply-chain footprints. Since the present study does not model broader market responses, marginal supply effects, or wider economic consequences, an attributional approach is considered more appropriate.

Similarly, the environmental scope of the assessment is limited to GHG emissions expressed as carbon dioxide equivalent (CO_2eq). Other environmental impact categories, such as eutrophication, acidification, toxicity, and water use, are excluded from the present study. While these factors are also important, they are not as well documented as climate effects and are less intuitive to understand. The environmental analysis should therefore be understood as a GHG focused life-cycle comparison rather than as a full multi-impact environmental LCA.

3.2.2. End-of-Life Treatment and System Boundaries

EOL treatment has a significant influence on the GHG performance of packaging materials and therefore requires explicit treatment in the assessment. In this study, three EOL routes are considered: landfill, incineration with energy recovery, and recycling. These routes differ not only in their direct emissions, but also in whether they generate secondary outputs that may displace virgin material production or conventional energy generation.

Landfill represents the final disposal of waste material with little or no material recovery. For inert materials such as metals and most conventional plastics, GHG emissions from landfilling are generally limited. In contrast, biodegradable materials such as wood and paper may decompose under anaerobic conditions and release methane and carbon dioxide. Incineration with energy recovery causes direct emissions through combustion, but can also generate useful heat or electricity. As a result, part of its environmental burden may be offset if the recovered energy displaces conventional energy production. Recycling similarly requires collection, sorting, and reprocessing, which generate emissions, but may also reduce the demand for virgin material production. The net GHG effect of recycling therefore depends on the balance between reprocessing burdens and the avoided production of primary materials.

Within an attributional framework, the key methodological issue is how the burdens and credits associated with these EOL routes are allocated. Two approaches are applied in this study. In the cut-off approach, the assessed product system carries the burdens up to disposal and waste collection, while any subsequent burdens or benefits associated with recycling or energy recovery are assigned to the next product system. Under this logic, the studied system does not receive credit for the future use of recovered material or energy. In contrast, the system expansion approach with avoided burden assigns credits to the studied system for displacing virgin material production or conventional energy generation through recycling or energy recovery. This means that the studied system carries both the direct burdens of EOL treatment and the potential benefits associated with recovered outputs.

These approaches do not represent separate LCA types, but alternative allocation choices within the same attributional framework. As illustrated in Figure 3.1, the cut-off approach limits the assessed product system to the life-cycle stages up to waste collection, whereas the system expansion approach extends the effective boundary to include downstream EOL processing and the resulting recovered outputs. Applying both approaches in this study allows the sensitivity of the results to EOL accounting assumptions to be evaluated.

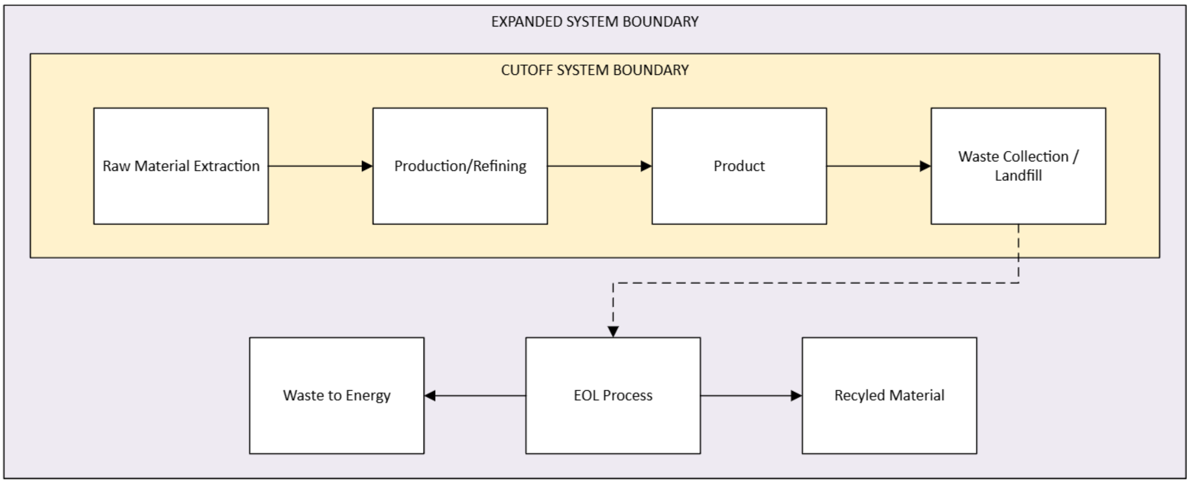

Figure 3.1: System boundaries under cut-off and system expansion approaches

3.3. System Modeling

3.3.1. Functional Unit

A clearly defined functional unit is required to ensure a consistent comparison between the single-use and reusable packaging systems. In this study, the functional unit is defined as an individual observed package flow within the logistics system, represented by the movement of a package from its origin to its final destination under the recorded logistics conditions. Each package may consist of one or more transport items required to transport the relevant goods. This definition was selected because it captures the diversity in packaging configurations, destinations, and transport pathways observed in the historical data of the host company.

For each observed package flow, the historical single-use packaging configuration is compared with an equivalent reusable packaging configuration designed to provide the same transport, protection, and handling function. As a result, both systems are assessed for the same goods movement, along the same route, and under the same logistical conditions. This comparison design ensures that differences in environmental results are attributable primarily to differences in the packaging systems rather than to differences in transport context or delivery function. The material composition and mass of the transport items associated with each packaging configuration are then used to estimate material use for the environmental analysis. In this way, historical logistics records are translated into a consistent material inventory for comparative assessment.

3.3.2. Material Inventory

To quantify the environmental impacts of each packaging system, the observed package-flow records are first translated into a material inventory. For each package flow, the packaging configuration is represented as a set of transport items together with their associated material types and masses. This inventory forms the basis for the subsequent production, transport, and EOL calculations.

For internally prepared shipments, the historical single-use packaging configuration is replaced directly by an equivalent reusable packaging configuration at the point of package preparation. In this case, the company has direct control over the choice of packaging and can therefore substitute the original single-use transport items with reusable alternatives without changing the underlying goods flow. The observed package is thus modeled as a direct one-to-one replacement at the point of dispatch, with both single use and reusable transport items fulfilling the same requirements.

Purchase-order shipments from third-party suppliers follow a different flow logic. In these cases, the original inbound packaging is determined by the supplier and is therefore outside the direct control of the host company. As a result, the historical supplier packaging is assumed to remain unchanged for the inbound leg up to receipt at the yard. After arrival, the goods are repacked into an equivalent reusable transport item for onward transport within the company-controlled logistics system. Under this approach, the original supplier packaging becomes waste at the yard, while the reusable packaging enters the system only from the repacking stage onward.

This distinction is important because it represents two fundamentally different points of intervention in the packaging flow. For internally prepared shipments, reusable packaging substitutes the single-use system at the point of origin. For purchase-order shipments, reusable packaging is introduced only after receipt and repacking, meaning that part of the original single-use packaging burden remains in the system. Distinguishing between these two flow types ensures that the comparative model reflects the actual degree of operational control over packaging selection and avoids overstating the substitution potential of reusable transport items.

Each transport item in both systems is linked to a material category and a corresponding unit mass. The dominant material categories considered in this study are wood, paper-based materials, plastics, and metals. Where a package consists of multiple transport items, the material masses are aggregated to obtain the total inventory associated with that package flow. The result is a package-level material inventory for both the single-use and reusable systems, which is then used for the environmental calculations in the following subsections.

3.3.3. Production Modeling

The production stage represents the upstream GHG burden associated with supplying the transport items used in each packaging system. In this study, production emissions are estimated using cradle-to-gate emission factors, such that the environmental burden of a packaging item is represented up to the point at which it is procured for use in the logistics system.

This approach does not model upstream processes such as raw material extraction, intermediate processing, manufacturing, and upstream transport as separate stages. Instead, these activities are captured implicitly within the cradle-to-gate emission factors used in the assessment. The aim is therefore not to reconstruct the full production chain of each transport item, but to represent the total production-related burden of supplying a finished packaging item in a consistent and comparable manner[22].

For the single-use system, the full cradle-to-gate production burden of each transport item is assigned to the package flow in which it is used. For the reusable system, the production burden of each reusable transport item is distributed across its assumed service life. In this study, service life is expressed as the number of transport cycles completed before disposal. The production burden assigned to an individual package flow is therefore calculated as the total cradle-to-gate burden of the reusable item divided by the assumed number of uses.

Where a package consists of multiple transport items, the allocated production burdens of all items are summed to obtain the total production emissions associated with that package flow. These values form the production component of the analysis.

3.3.4. Transportation

Packages in the analyses logistics system are transported by sea, air, or road between globally distributed addresses. To estimate the GHG emissions associated with these movements, transport distances are modeled for each package and for each segment of its route. Deliveries are also made to offshore destinations for vessel replenishment and the transport of equipment to barges. Since such destinations do not correspond to fixed onshore locations, offshore deliveries are treated separately.

- Sea: Sea transport distances are estimated using the SeaRoute Python library [26]. The library generates navigable maritime routes between two coordinates, accounting for realistic routing around landmasses and the use of major waterways such as the Suez and Panama canals. Distances are calculated between the nearest ports to the specified coordinates.
- Air: Air transport distances are estimated as straight-line great-circle distances using the Haversine formula. This is consistent with standard industry approaches for freight emission estimation [27]. Emissions associated with access transport to and from airports are assumed negligible relative to the air freight leg and are therefore excluded.
- Road: Road transport distances are approximated as straight-line distance multiplied by a detour factor to reflect the additional distance travelled on real road networks. This simplification is adopted for tractability in a global multi-route dataset. A detour factor of 1.3 is adopted, consistent with values reported in the literature for mixed transport networks [28, 29].
- Offshore deliveries: For offshore deliveries to vessels or barges, reconstructing the exact destination position at the time of delivery was considered impractical due to data availability and processing complexity. Instead, a fixed distance of 150 km is adopted as a proxy for a typical offshore delivery run. This value is intended to represent deliveries within the shallow coastal shelf region where most offshore projects are undertaken, while also accounting for additional transit through ports and navigational channels. In this special case, the offshore leg may be completed by either air or sea transport.

Because packages may reach the same destination through different intermediate stops, transport distances are calculated for each segment of the observed route. These distances are combined with mode-specific emission factors to estimate the emissions associated with transporting the packaging items along that route. This approach isolates the transport burden attributable to the packaging itself and thereby supports a fair comparison between the single-use and reusable systems.

For single-use packaging, only forward logistics emissions are included. For reusable packaging, total transport emissions are estimated by applying a reverse logistics factor to the forward transport burden, such that the combined forward and return burden is equal to 1.8 times the forward transport emissions. This simplified treatment is adopted for tractability, as explicit modeling of return routes for each RTI movement would substantially increase data and modeling complexity. The factor of 1.8 reflects the assumption that reverse flows are typically more consolidated and may follow more direct routes than the corresponding outward shipment.

3.3.5. End-of-life Modelling

EOL emissions are modelled using process-specific GHG emission factors rather than by reconstructing waste treatment processes in detail. For each material category, emission factors are assigned for the three waste treatment methods considered in this study: landfill, incineration with energy recovery, and recycling. This provides a consistent and tractable representation of EOL burdens within the comparative assessment.

Because waste materials do not enter a single treatment method exclusively, each material is assigned a set of waste treatment fractions representing the share of waste sent to landfill, incineration, and recycling. These fractions are used to distribute the mass of each material across the relevant EOL methods. The total EOL burden for a material is then calculated as the weighted sum of the method-specific emission factors and the corresponding waste treatment fractions. The waste treatment fractions are assigned on a destination-specific basis using the best available waste management data, with country-level fractions used for onshore destinations. Waste onboard vessels was handled separately and specific waste fractions were derived based on HMC documentation from the Waste Stream Mapping project and operating manuals for the onboard incinerators.

This calculation is performed under both cut-off and avoided-burden accounting approaches. As a result, the EOL emission factors differ depending on whether downstream recycling and energy recovery benefits are excluded or credited to the assessed system. In this way, the model captures both the direct EOL burdens and the sensitivity of results to the chosen EOL accounting method.

For reusable transport items, EOL burdens are allocated over the expected service life using the same amortization logic applied in the production model. Where a package consists of multiple transport items, the allocated EOL burdens of all items are summed to obtain the total EOL emissions associated with that package flow.

As described in the Material Inventory subsection, purchase-order packages are treated separately from in-house packages. This is because the original packaging in purchase-order flows is outside HMC's control and is therefore assumed to be discarded at the yard before the contents are repacked into an RTI. As a result, two slightly different modeling flows are required: one for in-house packages, where the packaging system is tracked from yard packing onward, and one for purchase-order packages, where the original packaging first enters the system as waste before repacking takes place. These two cases are illustrated in Figure 3.2.

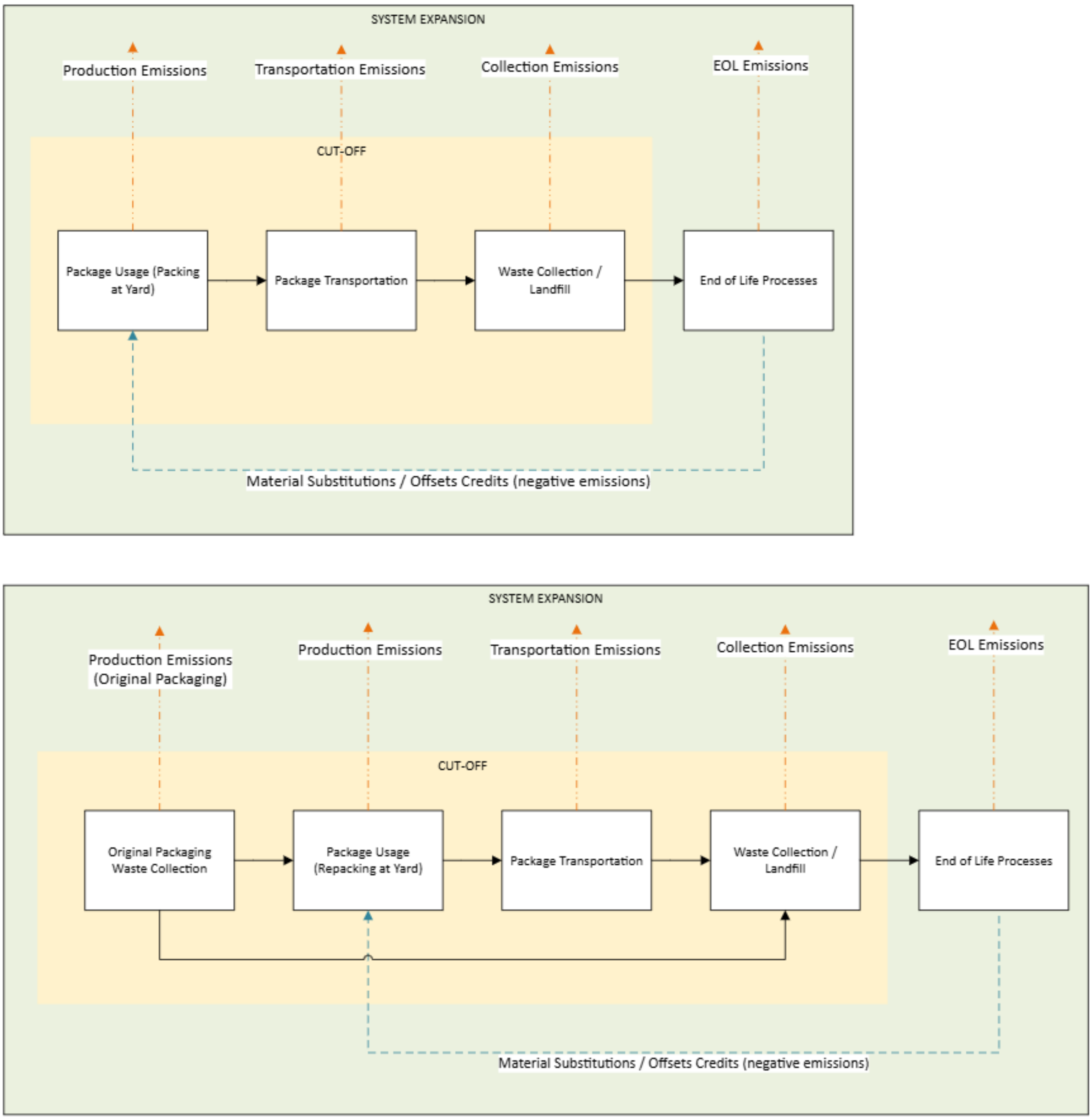

Figure 3.2: Top: Model Flowchart for Inhouse Packages. Bottom: Model Flowchart for Purchase Orders

3.4. Mathematical Formulation of the Model

The GHG accounting model is formulated at the level of an individual package record, which corresponds to the functional unit defined in the earlier sections. For each package record, emissions are calculated as the sum of production, transportation, and EOL burdens associated with the relevant packaging system. These calculations are first performed at package-record level and are then aggregated across the dataset for comparative analysis.

Let:

- $p \in P$ denote a package record,
- $i \in I_p$ denote a packaging item associated with package record p,
- q_p denote the quantity associated with package record p,
- m_i denote the mass of packaging item i,
- α_i denote the cradle-to-gate production emission factor of packaging item i,
- L_i denote the service life of packaging item i, expressed in number of transport cycles,
- M_p denote the total packaging mass associated with package record p,
- τ_p denote the route-specific transport emission factor for package record p,
- λ denote the reverse logistics multiplier applied to reusable packaging transport,
- ϕ_{pr} denote the fraction of waste from package record p assigned to waste treatment method r,
- β_{ir}^{z} denote the EOL emission factor for packaging item i under waste treatment method r and accounting approach z,
- $z \in \{\text{cut-off}, \text{system expansion}\}$ denote the selected EOL accounting approach.

3.4.1. Production Emissions

Production emissions are calculated from the cradle-to-gate burden of the packaging items assigned to a package record. For a given packaging item, the production burden is defined as

$$E_i^{prod} = \frac{m_i \alpha_i}{L_i} \tag{3.1}$$

where $L_i = 1$ for single-use packaging items and $L_i > 1$ for reusable transport items. The total production emissions for package record p are then obtained by summing over all packaging items associated with that record:

$$E_p^{prod} = \sum_{i \in I_p} E_i^{prod} \tag{3.2}$$

3.4.2. Transportation Emissions

Transportation emissions are calculated from the total packaging mass associated with a package record and the route-specific transport emission factor. For the current single-use packaging system, transportation emissions are given by

$$E_p^{trans,SU} = q_p M_p \tau_p \tag{3.3}$$

For the proposed reusable packaging system, reverse logistics are included through a reverse logistics multiplier λ, such that total transportation emissions are given by

$$E_p^{trans,RU} = q_p \lambda M_p \tau_p \tag{3.4}$$

In the baseline case, $\lambda = 1.8$, representing the combined forward and return transport burden of reusable packaging.

3.4.3. End-of-life Emissions

EOL emissions are calculated using waste treatment fractions and method-specific emission factors. For each package record, the effective EOL emission factor of packaging item i is calculated as

$$\gamma_{pi}^{z} = \sum_{r \in R} \phi_{pr} \beta_{ir}^{z} \tag{3.5}$$

where R is the set of waste treatment methods considered in the study. The EOL burden of a package record is then obtained by summing the amortized EOL burdens of all packaging items:

$$E_p^{eol} = \sum_{i \in I_p} \frac{m_i \gamma_{pi}^{z}}{L_i} \tag{3.6}$$

As in the production model, EOL burdens of reusable transport items are distributed across their expected service life.

3.4.4. Current Single-Use Packaging System

For the current single-use packaging system, the total emissions of package record p are defined as

$$E_p^{SU} = q_p \left(E_p^{prod,SU} + E_p^{eol,SU} \right) + E_p^{trans,SU} \tag{3.7}$$

where $E_p^{prod,SU}$, $E_p^{eol,SU}$, and $E_p^{trans,SU}$ denote the production, EOL, and transportation emissions associated with the single-use packaging configuration of that package record.

3.4.5. Proposed Reusable Packaging System

For in-house package records, the proposed reusable packaging system replaces the current single-use packaging at the point of dispatch. The total emissions of package record p are therefore

$$E_p^{RU,in} = q_p \left(E_p^{prod,RU} + E_p^{eol,RU} \right) + E_p^{trans,RU} \tag{3.8}$$

Purchase-order package records follow a different logic. In these cases, the original supplier packaging remains in the system up to receipt at the yard, after which the goods are repacked into reusable transport items. The total emissions of a purchase-order package record are therefore defined as

$$E_p^{RU,po} = q_p \left(E_p^{prod,RU} + E_p^{eol,RU} + E_p^{prod,sup} + E_p^{eol,sup} \right) + E_p^{trans,RU} \tag{3.9}$$

where $E_p^{prod,sup}$ and $E_p^{eol,sup}$ represent the production and EOL burdens of the original supplier packaging that remains in the system until disposal at the yard.

3.4.6. Comparative Benefit and Aggregation

The GHG benefit of the proposed reusable packaging system relative to the current single-use packaging system is defined for each package record as

$$B_p = E_p^{SU} - E_p^{RU} \tag{3.10}$$

where E_p^{RU} is equal to either $E_p^{RU,in}$ or $E_p^{RU,po}$ depending on the package record type. A positive value of B_p indicates that the proposed reusable system has lower emissions than the current single-use system for that package record.

Total emissions across the full dataset are then obtained by aggregation:

$$E_{tot}^{SU} = \sum_{p \in P} E_p^{SU}, \qquad E_{tot}^{RU} = \sum_{p \in P} E_p^{RU}, \qquad B_{tot} = \sum_{p \in P} B_p \tag{3.11}$$

These totals can subsequently be grouped by package type, destination, flow class, or other reporting categories used in the scenario analysis.

3.5. Sensitivity Analysis

The comparative GHG performance of single-use and reusable packaging systems depends on several modeling assumptions that are subject to uncertainty. In particular, the results are sensitive to assumptions that affect the production burden of reusable transport items, the transport burden associated with reverse logistics, and the treatment of EOL accounting. A sensitivity was therefore used to evaluate the robustness of the model results and to identify the assumptions that exert the greatest influence on the comparative outcome.

The purpose of this analysis is not to reproduce every possible real-world operating condition, but to test whether the conclusions of the study remain stable under plausible variation in key assumptions. In this way, the analysis supports interpretation of the results by distinguishing between conclusions that are structurally robust and those that depend strongly on uncertain modeling assumptions.

The sensitivity analysis focuses on the modeling assumptions expected to have the strongest influence on the comparative GHG performance of the single-use and reusable packaging systems. These assumptions were selected because they directly affect the production and transport burdens assigned to reusable packaging relative to the single-use reference system.

- **RTI service life:** The assumed service life of reusable transport items is a key sensitivity parameter because it determines how production and EOL burdens are distributed across repeated use. A longer service life reduces the burden assigned to each individual package flow, whereas a shorter service life increases it. In the present study, baseline service-life values are defined for each RTI type and are varied systematically using a literature-informed multiplier.
- **Reverse logistics factor:** The reverse logistics factor is varied because transport emissions are one of the principal burdens specific to reusable packaging systems. This factor determines the total transport burden assigned to RTIs by representing the additional emissions associated with returning reusable items after delivery. Varying this parameter allows the analysis to test how sensitive the results are to different assumptions regarding consolidation efficiency, route directness, and overall return-transport intensity.

In addition to these sensitivity parameters, the study also compares two alternative EOL accounting treatments: cut-off and system expansion with avoided burden. This comparison is not treated as a conventional parameter variation, but as a methodological comparison of how recycling and energy recovery credits are assigned within the attributional framework. Including both approaches allows the effect of accounting choice on the comparative results to be evaluated.

3.5.1. Scenario Design

The selected modeling assumptions are evaluated using an exhaustive scenario design in which all tested parameter combinations are assessed. This allows the interaction space of the principal uncertain assumptions to be explored and ensures that both individual and combined parameter effects are represented in the analysis.

For interpretation and presentation of results, the scenario outputs are organized into three complementary views. First, a baseline case is reported to provide the central comparative result under the standard modeling assumptions. This baseline is presented under both cut-off and system expansion accounting in order to show the influence of EOL treatment on the main findings.

Second, the comparative study is presented, with the results being restricted to internally prepared packages. The results for both accounting types are presented, grouped together by destination country and packaging type to highlight the differences between them.

Finally, the complete set of scenario results is used to identify best-case and worst-case outcomes for the reusable packaging system. These scenario bounds are used to illustrate the maximum variation in results across the tested parameter space and to assess the extent to which the comparative conclusions remain stable under combined favorable or unfavorable assumptions. Together, these three views provide the basis for assessing the central result, the influence of individual assumptions, and the robustness of the comparative conclusions across the tested parameter space.

The methodological elements described in this chapter define the general analytical framework used in the thesis. The following chapter translates this framework into the specific context of HMC by describing the case-study setting, the available logistics data, the package-flow reconstruction process, the representation of packaging systems, the case-specific environmental inputs, and the validation steps required to apply the model in practice.

4

Case Study

4.1. Case Context

This chapter operationalizes the methodological framework developed in Chapter 3 in the specific context of Heerema Marine Contractors (HMC). While Chapter 3 defined the general comparative logic, system boundaries, functional unit, and modelling approach, the present chapter describes how these elements were implemented using historical ERP data, case-specific packaging assumptions, route reconstruction, environmental inputs, and validation steps. In this way, the chapter provides the empirical basis for applying the comparative framework to a real offshore logistics system.

As mentioned in chapter 2, compared with more stable manufacturing environments, offshore logistics introduces several characteristics that complicate its analysis. HMC operates in a project-based setting in which logistical requirements vary across projects, vessel locations, and operational phases. As a result, package flows vary over time and across destinations, while also including both onshore and offshore delivery conditions.

The company's logistics activities are managed through an ERP system that records package, transport, and inventory information. Within this system, logistics flows are represented through a hierarchy of related entities, including parts, packages, container packages, and transport records. These records form the basis for reconstructing historical package flows and for comparing the existing single-use packaging system with equivalent reusable alternatives.

Figure 4.1 provides an overview of the workflow used to implement the comparative framework in the specific context of HMC. Starting from ERP data extraction, the workflow proceeds through data cleaning and merging, route and logistics calculations, packaging mass estimation, and scenario-based comparative assessment. The subsequent sections of this chapter describe each of these stages in detail, including the data sources and analytical scope, the case-specific representation of packaging systems and material assumptions, the environmental factors and end-of-life data used in the model, the baseline scenario inputs, and the approach used to validate packaging mass estimation.

4.2. Data Sources and Scope of Analysis

As discussed in Section 4.1, offshore contractor logistics is characterized by considerable variation in both package types and transport flows. This variation arises from the project-based nature of offshore operations, in which logistical requirements depend on vessel location, project phase, equipment needs, and maintenance activities. Since detailed logistics is typically not planned more than one year in advance, and future project data is commercially sensitive, constructing a representative forward-looking dataset was not considered practical for this study. Instead, historical company data extracted from the ERP system was used to represent the observed logistics system and to provide a realistic empirical basis for the comparative packaging assessment.

The case study is based primarily on internal logistics data extracted from the HMC ERP system. The ERP system records package movements, transport activities, inventory information, delivery locations,

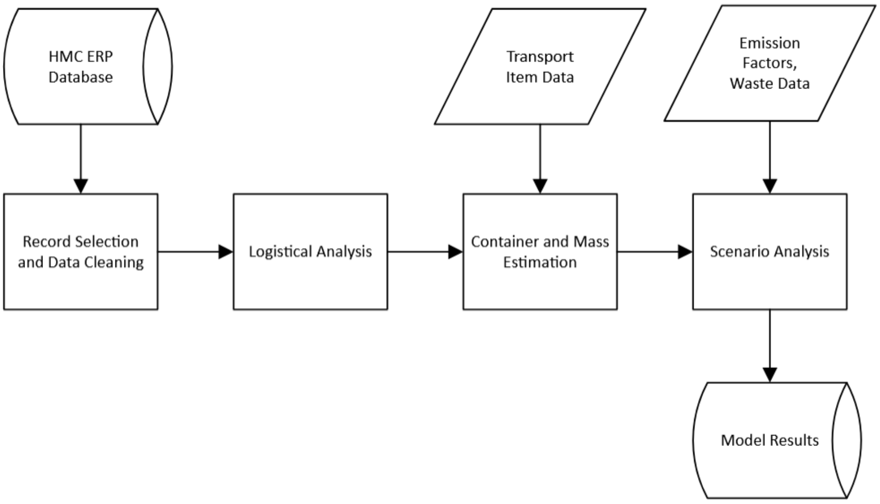

Figure 4.1: Workflow to implement framework at HMC

and part classifications, and therefore provides the core data required to reconstruct historical package flows. In addition to the standard ERP tables, a custom Packagelines query was used to identify the individual transport legs associated with each package and thereby recover complete package routes through the logistics network.

The principal datasets used in the analysis are listed below:

- **Package Data:** Records containing package-level logistics information, including package identifiers, package types, gross weight, and associated transport references.
- **Transport Data:** Records containing shipment-level logistics information, including origin, destination, mode of transport, and relevant dates.
- **Delivery Addresses:** Address records used to identify and geolocate origins, destinations, and intermediate locations within the logistics system.
- **Parts Data:** Records describing the individual parts (i.e. parts, provisions or equipment) shipped in packages, including identifiers and linked classification fields.
- **Material Groups:** Classification data used to group parts according to their functional or material-related characteristics for downstream packaging estimation.
- **Packagelines:** A custom query used to identify the full sequence of transport movements associated with each package and the manifest of parts shipped in the package[30].

The ERP system was implemented in March 2011. To ensure that only complete years were included in the study, the analysis period was defined from 1 January 2012 to 1 January 2025. This time horizon provides a sufficiently long historical record to capture recurring logistical patterns while avoiding distortions associated with partial years.

The selected period is used as a historical representation of the logistics system rather than as a direct forecast of future activity. This is considered appropriate because the purpose of the study is to compare packaging systems under realistic operating conditions observed in practice. The use of historical ERP data therefore allows the model to reflect the diversity of package types, destinations, transport modes, and routing patterns present in the company's logistics operations.

4.3. Record Selection and Data Cleaning

The purpose of this step is to define the analytical dataset used for the case study by identifying package flows originating from the company-controlled logistics system and reconstructing their routes to final destination. More than [redacted] packages in the ERP records were dispatched from three Dutch logistics locations, namely the HMC yard in Vlissingen, [redacted]. Of these, only the HMC yard in Vlissingen (`HMCVL`) forms part of the company-controlled logistics boundary considered in this study. The analysis was therefore restricted to packages dispatched from Vlissingen, after which the associated transport records were cleaned and merged in order to reconstruct complete package routes.

The main data preparation steps are summarized as follows:

- The package table, transport table, and Packagelines query were used as the primary raw inputs for route reconstruction.
- Administrative transport records were identified and cleaned. Where valid storage information was available, missing origin or destination fields were back-filled. Records that could not be linked to a meaningful physical movement were excluded.
- The cleaned transport table was filtered to identify valid transports originating from Vlissingen.
- The Packagelines query was used to identify all packages that were shipped on at least one valid transport originating from Vlissingen.
- Container packages, including shipping containers and skips, were excluded. Only package categories relevant to the packaging comparison were retained.
- For each retained package, Packagelines was used to reconstruct the full route by identifying all associated transport records.
- Packages with more than three route segments between origin and final destination were excluded in order to remove non-standard logistics patterns, particularly for specialized third-party equipment.
- The retained package, transport, and route records were merged into a single analytical dataset for downstream modeling.

The resulting dataset contains package-level records for shipments dispatched from Vlissingen, together with the associated route segments, origins, destinations, and transport modes required for the logistical analysis presented in the following section. A complete log of the cleaning steps is provided in Appendix B.

From the ERP data, packages with category PO-RECEIPTS were treated as third-party supplier flows, whereas packages with categories TPC (long term third party equipment), VARIOUS, and LOOSE were treated as internally prepared flows originating from the yard and were labeled accordingly for use in the scenario analysis.

4.4. Logistical Analysis

The purpose of this step is to translate the selected package-flow records into transport-related GHG burdens that can be used in the comparative packaging model. Using the cleaned dataset produced in the previous section, specific emissions were calculated for each package flow, expressed as emissions per kilogram of transported material, in accordance with the transport modeling approach described in Chapter 3.

This process consisted of three main steps:

- All unique addresses in the dataset were identified and geocoded. Because ERP address fields are not standardized, a preprocessing step was required to extract the most relevant location information. A regular-expression based procedure was used to identify country and postcode information where possible, after which a geocoding API was used to assign coordinates to each address.
- Using the resulting coordinates and the reconstructed package routes, individual transport segments were identified and the distance of each segment was estimated according to the mode-specific methods defined in Chapter 3.
- A transport emission factor corresponding to the mode used on each segment was then applied to estimate the specific emissions associated with that segment. These segment-level values were subsequently combined to obtain the total specific transport burden for the package flow.

For reusable transport items, the resulting forward transport burden was multiplied by the reverse logistics factor to account for the additional emissions associated with return transport. The final output of this step was therefore a package-level estimate of transport emissions for both the single-use and reusable packaging systems, which was then used in the subsequent comparative analysis.

4.5. Packaging System Representation

This section describes how the package records retained in the analytical dataset are translated into comparable packaging configurations for the single-use and reusable systems. Because the ERP package records do not contain complete geometric and material information for the transport items used, the observed package UOMs first have to be interpreted as representative packaging classes before reusable substitutes can be assigned. The representation adopted in this study therefore consists of three steps: defining which package types are included in the comparative analysis, constructing a set of model transport items and material assumptions for those package types, and assigning reusable substitutes to the included categories.

4.5.1. Package Types in Scope

The cleaned dataset contains a range of package unit-of-measure (UOM) categories reflecting the diversity of goods shipped through the HMC logistics system. Figure 4.2 shows the distribution of package types for all packages dispatched from Vlissingen over the selected study period. The UOM abbreviations shown in the figure are imported directly from the ERP system. Where multiple ERP categories served similar logistical functions, they were merged for simplicity; the full mapping of merged categories is provided in Appendix B.

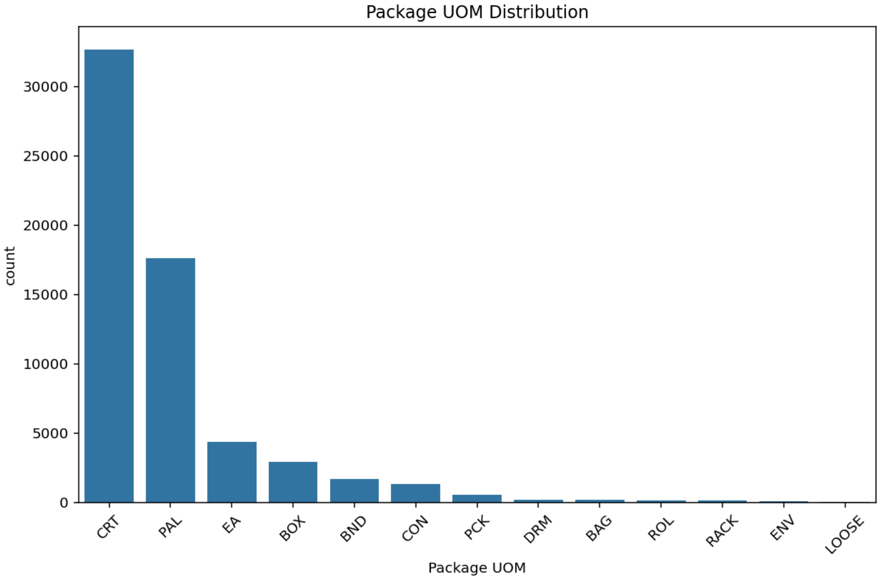

Figure 4.2: Distribution of package UOMs for packages dispatched from `HMCVL` over the selected study period

The distribution of package types is highly unequal. Cartons and pallets account for the largest share of dispatched packages, while a smaller number of boxes, individual items, bundles, and containerized packages are also present. Several other UOM categories occur only infrequently or represent package types that are already reusable in practice. As a result, not all recorded UOMs are included directly in the comparative packaging model.

Table 4.1 summarises the UOM categories identified in the dataset, together with their description, inclusion status, and the main reason for inclusion or exclusion. In general, UOMs were included when they represented a meaningful share of package flows and could be represented through a comparable single-use and reusable packaging configuration. UOMs were excluded where they already represented reusable transport items, occurred only rarely, or required treatment outside the scope of the present comparison.

Table 4.1: Summary of package UOM categories and inclusion status in the comparative model

UOM	Description	Included?	Reason
CRT	Cartons	Yes	Major package category; represented using model containers and compared with reusable substitutes.
BOX	Wooden equipment boxes	Yes	Major package category; represented using model containers and compared with reusable substitutes.
PAL	Wooden pallets	Yes	Major package category; directly represented and compared with longer-life plastic pallet substitutes.
EA	Individual items	Yes	Included through pallet- or dunnage-based handling assumptions depending on package gross weight.
BND	Bundles	Yes	Same as EA.
DRM	Drums / bottles for liquids	Partially	Drum is reusable but may require pallets or dunnage as per EA.
BAG	Bulk bags for loose materials	Partially	Bag has low mass but may require pallets or dunnage as per EA.
CON	Shipping containers / skips	No	Excluded because these package types are already reusable and fall outside the comparative substitution problem.
RACK	Gas racks	Partially	Rack is reusable but may require pallets or dunnage as per EA.
ENV	Envelopes	No	Excluded due to negligible quantity and limited relevance to the overall packaging burden.
LOOSE	Loose / miscellaneous items	Yes	Same as EA
PCK	Pack	Partially	May require pallet or dunnage as per EA
ROL	Material roll	Partially	Rolls/reels are reusable but may require pallets or dunnage as per EA.
FOIL	Stretch foil	Separately	Used to wrap pallets and is accounted for separately

An additional working assumption in this study is that the current logistics system treats all packaging items as single-use, including nominally reusable items such as wooden pallets. Under this assumption, transport items used in the existing system are discarded after delivery and their materials enter end-of-life processing. This assumption was examined during the yard validation study described later in the chapter.

4.5.2. Model Transport Items and Material Assumptions

Because the ERP package records do not contain exact dimensions or detailed packaging specifications, a set of model transport items was defined to represent the main single-use and reusable packaging formats used in the comparative analysis. These model transport items provide a standardised basis for assigning geometry, material composition, and unit mass to package records before record-level selection is carried out in the next section.

The dominant package categories in the dataset were cartons, boxes, and pallets. Model transport items were therefore developed primarily for these package types. Categories such as individual items, bundles, and loose items were not represented through enclosed containers, since they are typically associated with larger or irregular project equipment that cannot be accommodated within standard packaging formats. Instead, these categories were represented through pallet- and dunnage-based packaging, together with stretch foil where relevant. Other UOM categories with low shipping volumes were not modelled in detail, while package types such as shipping containers and gas racks were excluded from the core substitution problem because they already represent reusable transport items in practice.

The single-use transport items for cartons and boxes were modelled using the EUR-pallet footprint as the primary geometric reference. The EUR-pallet is a standardised pallet format widely used in European logistics systems, with broad compatibility across handling and storage operations [31]. Pallets were represented directly using this standard. For cartons and boxes, the EUR-pallet footprint was used as a base unit to generate a family of Euronorm-compatible size classes, allowing different package sizes to be represented while preserving compatibility with palletised transport. In addition to the full-pallet format, smaller and larger classes were generated by subdividing or extending the base footprint. The mass of the single-use wooden pallet itself was represented using literature values for standard EUR-pallets [32, 33].

Reusable transport items were modelled as functionally equivalent load carriers sized to match the same pallet-based and Euronorm-compatible classes. Small reusable containers were represented through KLT-type load carriers, while larger reusable containers were represented through collapsible load carriers and pallet boxes. These were modelled primarily using manufacturer specifications from Rajapack website[34], which provided representative dimensions, material composition, and unit mass values for commercially available reusable transport items. For supporting transport items, plastic pallets and composite wood dunnage[35] were selected as the principal reusable alternatives.

Stretch foil is not directly recorded in the ERP, but it is used in the yard and in purchase orders to palletize items for shipping. A method was developed to estimate this usage and quantify its impact. A potentially more sustainable alternative to plastic foil is paper based foil. This was evaluated as alternative packaging for this application. Compared to RTIs, paper based foil is also single-use. Therefore it is accounted for separately and is not assigned any reverse logistics burden or a reuse lifetime, since it is assumed to be discarded at the destination.

Material assumptions were assigned to each model transport item using literature, technical manuals, and manufacturer specifications. For paper- and board-based packaging, literature and industry references were used to identify representative carton grades and material properties [36, 37]. For wood-based transport items, technical and design references were used to inform thickness assumptions and typical material usage [38, 39]. For reusable plastic transport items, material composition and unit mass were taken primarily from manufacturer specifications and supporting literature [40, 41]. Unless otherwise stated, each modelled packaging type is represented using a baseline material consistent with common industry practice. The full specification tables for the single-use and reusable transport items are provided in Appendix B.

4.5.3. Reusable Substitute Assignment

Once the package types and representative single-use transport items had been defined, reusable substitutes were assigned at UOM level in order to construct a functionally equivalent reusable packaging system. The substitution logic was developed to preserve the primary transport and handling function of the original package while replacing the single-use transport item with a longer-life reusable alternative. In selecting these substitutes, the main design criterion was operational equivalence in terms of footprint, stackability, load support, and compatibility with palletised handling.

For pallets, the single-use baseline is represented by the standard wooden EUR-pallet introduced above. This format was retained as the geometric and handling reference in the reusable system, where it is replaced by a plastic pallet of equivalent EUR-pallet dimensions. The rationale for this substitution is that both pallet types have identical capacity and handling characteristics, while the plastic pallet represents a longer-life alternative to the wooden pallet assumed as single-use in the baseline.

Euronorm is a widely used system of standardized modular dimensions that allows transport items to be efficiently stacked and arranged on EUR-pallets. Since cardboard cartons and wooden boxes in the current system are commonly designed according to these standards, substitute RTIs were chosen to preserve the same dimensional compatibility. Smaller cartons and boxes are replaced by KLT containers commonly used in industrial logistics, while larger cartons and boxes are replaced by collapsible pallet boxes. This distinction was intended to maintain similar packing logic across different size classes while ensuring continued compatibility with standard pallet footprints and handling practices.

For packages recorded as individual items or bundles, pallet or dunnage packaging was assigned according to package gross weight. Packages below 1500 kg were assumed to use pallet-based support, corresponding to the load capacity limit adopted for the EUR-pallet in this study, while heavier packages were assumed to require dunnage. In the reusable system, timber dunnage is represented by composite wood alternatives. These substitutes were selected on the basis that they provide a similar support and handling function to conventional timber dunnage, while offering a longer service life through the use of a more durable material.

These substitution choices were selected to remain as operationally equivalent as possible to the original packaging formats and to provide a realistic and internally consistent basis for comparative modelling of a reusable packaging system. Their purpose in this study is to provide a realistic and internally consistent basis for comparative modelling of a reusable packaging system. Representative images of the principal single-use and reusable packaging types are also provided in Figure 4.3 to illustrate the single use and resuable transport items.

Table 4.2: Summary of UOM-level reusable substitute assignment

UOM	Single-use representation	Reusable substitute
CRT	Cardboard carton in Euronorm-compatible size class	KLT container (small classes) / collapsible pallet box (large classes)
BOX	Wooden or board-based box in Euronorm-compatible size class	KLT container (small classes) / collapsible pallet box (large classes)
PAL	Wooden EUR-pallet	Plastic pallet (EUR pallet dimensions)
EA	Wood pallet (< 1500 kg) / wood dunnage (≥ 1500 kg)	Plastic pallet (< 1500 kg) / composite wood dunnage (≥ 1500 kg)
BND, DRM, BAG, RACK, ROL	Wood pallet (< 1500 kg) / wood dunnage (≥ 1500 kg)	Plastic pallet (< 1500 kg) / composite wood dunnage (≥ 1500 kg)
FOIL	LDPE Stretch foil	Paper Stretch foil (not reusable)

A more detailed substitution table at the individual transport-item level is provided in Appendix B in Table B.8. The assignment of reusable substitutes is necessarily based on idealised packaging classes rather than exact one-to-one observations from the ERP system. In practice, the UOM recorded in the package record may not always fully reflect the exact physical packaging form used in the yard. This issue was considered during the yard validation study and is discussed further in the validation approach section.

4.6. Transport Item Assignment and Mass Estimation

Once the package types, model transport items, and reusable substitutes have been defined, the next step is to assign transport items to individual package records and estimate the associated packaging mass. This step is carried out at the level of the functional unit introduced in Chapter 3, namely the individual observed package flow. In other words, each package record is first assigned a single-use or reusable transport-item configuration based on its UOM, gross weight, and, where relevant, the estimated characteristics of its contents. The corresponding packaging mass is then calculated for that package record. Total packaging use for the dataset is obtained only after these package-level estimates are aggregated across all included records.

In general, the package-level packaging mass for package p may be written as

$$m_p^{\text{pack}} = \sum_{i \in I_p} m_i, \tag{4.1}$$

where I_p is the set of transport items assigned to package p, and m_i is the mass of transport item i.

Figure 4.3: Left - Single-use packaging, Right - Reusable Packaging. From top down: Cartons, Pallets, Boxes, Dunnage

The total packaging mass for the analytical dataset is then obtained by summing across all package records,

$$M^{\text{pack}} = \sum_{p\in P} m_p^{\text{pack}}, \tag{4.2}$$

where P denotes the set of package flows included in the case study. Different assignment rules were required for different UOM categories, depending on the amount of information available in the ERP system and the physical form of the packaging involved.

Cartons, Boxes, and Drums

For cartons, boxes, and similar container-based packaging, transport-item assignment is based on a density-informed sizing method. This was necessary because the ERP package records do not contain explicit dimensions for the packaging used. Instead, the main directly available variables are package UOM and gross package weight. The method adopted here was inspired by the general logic of package-sizing approaches such as that of Heininger and Ortner [42], but was simplified substantially to match the scope of the present study and the data available within HMC.

At package level, the assignment proceeds in four steps:

- **Assignment of density categories to package contents.** Each part recorded in the ERP is associated with a material group describing the type of item being transported. These material groups were used as proxies for the likely density of the packaged contents. A set of representative density bands was therefore defined to span the range of content densities encountered in the dataset. The density categories and their representative values are listed in Appendix B.
- **Estimation of package-content density.** Where Packagelines data was available, the density of the package contents was estimated as a weighted average of the density values assigned to the constituent material groups. For package p, this may be written as

  $$\hat{\rho}_p = \sum_{b \in B} k f_{p,b} \, d_b, \tag{4.3}$$

  where B is the set of density bands, $f_{p,b}$ is the share of package p associated with density band b, k is the fill factor for the package and d_b is the representative density value assigned to that band. For packages that did not appear in Packagelines, a fallback average density value based on the valid observations in the dataset was used.
- **Estimation of package volume.** The estimated content density was combined with the recorded gross package weight to infer an approximate package volume. A packing or fill factor was then applied to account for the fact that packages are not fully occupied by the contents alone, but also contain void space and, where relevant, cushioning or internal packing material.
- **Assignment of model container and packaging mass.** Based on the estimated package volume and density, the package was assigned to the most appropriate model container class from the predefined Euronorm-compatible sizing set introduced in the previous section. Once the model container had been selected, the corresponding packaging mass was taken directly from the relevant transport-item specification.

This method allows each carton- or box-type package record to be mapped to a specific transport-item class and, by extension, to a package-level packaging mass.

Pallets

For pallets, transport-item assignment is more direct because the baseline pallet format is known. Wooden pallets in the existing system are represented using the standard EUR-pallet format introduced in the previous section, and the corresponding packaging mass is therefore assigned directly from the model specification. For the reusable system, the pallet is replaced by the corresponding plastic pallet substitute of the same nominal footprint.

In addition to packages explicitly recorded with pallet UOMs, pallet-based handling was also assumed for certain non-container package categories such as individual items, bundles, and related categories when package gross weight was below the threshold used to distinguish palletised and dunnage-supported loads. In these cases, the assignment rule determines whether the package record receives a pallet and therefore the corresponding package-level packaging mass.

Dunnage Wood

For package categories that are not represented by enclosed containers, pallets or dunnage are assigned according to package gross weight. As introduced in the pallet-assignment logic above, packages with a gross weight below 1500 kg are assumed to be transported on pallets, whereas heavier packages are assumed to require dunnage support. This threshold is consistent with the use of the EUR-pallet as the baseline pallet format in the model.

Dunnage is therefore assigned to package categories such as individual items, bundles, bags, drums, gas racks, and rolls when package gross weight exceeds 1500 kg. Because dunnage use is not explicitly recorded in the ERP, its mass cannot be obtained directly from the package record and must instead be estimated through an indirect rule. In the present study, the mass of single-use wooden dunnage is estimated as 0.5% of the package gross weight. This provides a simple package-level approximation of the timber required to support, stabilize, or distribute the load of heavier and more irregular items during transport. This fraction was tested as part of the validation study.

For the reusable system, wooden dunnage is assumed to be replaced by composite wood dunnage. The assigned dunnage mass is kept equal to that of the single-use case, such that the substitution affects material type rather than the quantity of dunnage required. Under this assumption, the package-level dunnage mass remains unchanged while the production and end-of-life burdens differ according to the material properties of composite wood.

Stretch Foil

Stretch foil is used to stabilise and protect palletised goods during transport. In the present model, stretch foil is assigned only to package records explicitly labelled with pallet UOMs (`PAL`). It is therefore not assigned to other package categories, even in cases where those items may be pallet-supported in practice. This modelling choice reflects the level of packaging information available in the ERP and provides a consistent rule for package-level assignment.

Because stretch-foil use is not systematically recorded in the ERP, its mass must be estimated indirectly. In the present study, the mass of single-use stretch foil is estimated as 0.1% of the package gross weight for all `PAL` records. This provides a simple package-level approximation of the film required to secure palletised loads during transport. The plausibility of this assumption was examined during the yard validation visit through inspection of the pallet-wrapping process and discussion of annual foil consumption.

For the alternate system, the same foil mass is assumed, but the material is changed from LDPE stretch film to paper-based foil. Under this assumption, the quantity of foil required remains unchanged while the production and end-of-life burdens differ according to the material properties of the alternative foil.

4.7. Environmental Inputs and Scenario Parameterization

4.7.1. Environmental Inputs

The comparative assessment requires GHG emission factors for three main life stages of the packaging system: production, transport, and end-of-life treatment. In this study, these inputs were selected to provide a consistent and transparent basis for estimating the package-level emissions associated with the single-use and reusable systems.

For production and transport, GHG emission factors were taken from the Department of Security and Net Zero (DESNZ) emission factor dataset published by the UK government[43]. These factors were used to represent the cradle-to-gate burden of supplying packaging materials and transport items, as well as the emissions associated with road, sea, and air freight. For end-of-life treatment, emission factors were taken from the WRAP CarbonWARM2 dataset[44], which was used to represent landfill, incineration with energy recovery, and recycling scenarios. This separation of sources reflects the fact that DESNZ factors are suitable for production and transport reporting, while CarbonWARM2 provides a more appropriate basis for comparing alternative end-of-life treatment methods. However, both studies were commissioned by the UK government and use similar assumptions allowing for their combination in this study.

These sources were selected for three reasons. First, both datasets are GHG focused and therefore align with the scope of the present study, which is limited to carbon dioxide equivalent (CO_2eq) rather than a full multi-impact life cycle assessment. Second, both datasets are open-access and could therefore be used transparently within the context of a company-linked thesis project. Open-access factor sources were preferred because the study was conducted in a company-linked setting where the use of commercial databases on an academic license wasn't permitted. Third, the use of DESNZ factors is broadly consistent with the company's internal sustainability reporting context, since parts of the

DESNZ framework are already used within ongoing CSRD-related reporting activities at HMC. Taken together, these factors provide a coherent basis for a streamlined comparative GHG assessment.

Where a factor for the exact packaging material or transport item was not available, a representative proxy factor was selected based on the closest material match. This was necessary because the study models a range of practical packaging forms rather than a single standardized product. The full list of selected factors for material production, EOL and transportation is provided in Appendix B on tables B.10,B.9,B.11,B.12.

The use of DESNZ and CarbonWARM2 factors also introduces limitations. Both datasets are UK-based, whereas the logistics system studied here is global, albeit with a substantial share of activity in the Netherlands. The selected factors should therefore be interpreted as an approximation of the underlying production, transport, and waste-treatment conditions rather than as exact representations of all regional contexts in the dataset. As a result, the factor framework is considered more robust for relative comparison between the single-use and reusable systems than for precise quantification of absolute real-world carbon footprints.

4.7.2. Waste Treatment Fractions

In addition to process-specific end-of-life emission factors, the model requires waste treatment fractions that determine what share of waste mass is assigned to landfill, incineration with energy recovery, and recycling. Defining these fractions was challenging because the logistics network has a global footprint, meaning that waste treatment practices differ substantially across destinations. As a result, it would not have been realistic to apply a single national waste profile, such as that of the Netherlands, to all package flows in the dataset.

To address this, country-specific waste treatment fractions were derived primarily from the What a Waste 2.0 dataset published by the World Bank[45]. These data were used to assign destination-country fractions for onshore waste treatment. In the absence of more detailed material-specific disposal data for most countries in the dataset, a fixed set of waste treatment fractions was assumed for all packaging materials disposed within a given country. Although this simplification does not capture material-specific treatment pathways in detail, it provides a geographically differentiated and transparent basis for modeling end-of-life treatment across a global logistics network.

Waste generated onboard vessels required a separate treatment logic. In these cases, part of the waste is incinerated onboard in accordance with the vessel incinerator operating guidance[46], while the remaining waste is retained onboard for later disposal ashore. During supply runs or when the vessel returns to port, a licensed waste contractor is engaged to collect and process the accumulated waste. Based on the vessel incinerator manual and waste invoices describing the applied downstream waste treatment methods, a separate set of waste treatment fractions was defined for offshore vessel-generated waste. This approach was adopted to better reflect the operational reality of offshore waste handling, which differs from standard onshore municipal waste treatment systems.

The full set of waste treatment fractions used in the model is reported in Appendix B.

4.7.3. Baseline Values and Scenario Inputs

This subsection defines the case-specific baseline values and scenario inputs used to instantiate the sensitivity and scenario design introduced in Chapter 3. While Chapter 3 explains the logic of the scenario analysis at a methodological level, the present subsection specifies the actual values and ranges adopted in this case study.

Baseline service-life values were assigned to each reusable transport item (RTI) included in the model. As these values differ by RTI type, they are not presented in full in the main text. Instead, the complete set of baseline RTI specifications, including the assumed service life and corresponding literature source, is provided in Appendix B, Table B.6. Since these service-life values are derived from literature, they are inherently uncertain and should be regarded as estimates rather than fixed parameters. In practice, the effective lifetime of an RTI may vary substantially depending on the characteristics of the handling system, including circulation frequency, damage rates, loss rates, and the degree of control within the return loop. To reflect this uncertainty, a sensitivity analysis was conducted in which baseline RTI lifetimes were varied using a life-factor multiplier. The tested range extends from 0.5 to 1.5 times the baseline value, representing a plausible range of values.

The baseline reverse logistics factor was set to 1.8, such that the total transport burden of reusable packaging is equal to 1.8 times the forward transport burden. A detailed reverse logistics network was not modelled in this study, since the available data primarily represents a forward logistics system and the development of an explicit return-flow network would have required a substantially greater modeling effort beyond the project scope. Instead, reverse transport was represented using a fixed multiplier applied to the forward transport burden. Under the baseline assumption, the return leg contributes 80% of the emissions of the forward leg, reflecting the expectation that return flows can be organized more efficiently through higher vehicle utilization, consolidated loads, and more direct routing to return yards. Since this is a simplifying assumption, it is associated with uncertainty. To account for this, the sensitivity analysis varies the reverse logistics factor between 1.6 and 2.0.

Waste treatment fractions are not varied as part of the sensitivity analysis. Instead, a single destination-specific set of waste treatment fractions is used throughout the case study, based on the environmental input framework described in the preceding subsection. This choice was made because varying waste treatment fractions would add uncertainty to the model without materially improving the robustness of the results.

Unlike the numerical scenario inputs, end-of-life accounting treatment is not represented by a single baseline value. Instead, both cut-off and system expansion with avoided burden are evaluated in parallel and presented side by side in the results. This allows the influence of end-of-life accounting choice to be assessed directly without privileging one treatment as the sole reference case.

Detailed baseline values, scenario ranges, and implementation settings for the single-use and reusable packaging systems are reported in Appendix B.

4.8. Validation Approach

Because several elements of the comparative model rely on inferred packaging characteristics rather than directly recorded ERP fields, a validation study was conducted to assess whether the main estimation methods and modeling assumptions were reasonable in the operational context of HMC. The purpose of this validation was not to verify every individual record in the historical dataset, but to test whether the assumptions used for package representation, density estimation, pallet and dunnage assignment, and disposal practice were consistent with observed yard operations.

The validation was carried out through a site visit to the HMC yard at Vlissingen, combined with discussions with Robert Desitter (Senior Shipping and Receiving Coordinator) and Marjo van Gijs (Equipment Resource Coordinator). This provided two complementary forms of evidence: direct physical observation and measurement of packaging practice at the yard, and personnel input regarding routine handling, material usage, and post-use disposal. The validation therefore combined quantitative checks for those elements that could be measured directly with qualitative checks for assumptions that could only be assessed through observation and operational knowledge.

Cartons and Boxes

A first validation component focused on cartons and boxes, for which the model estimates packaging mass through a density-based sizing method. Selected packages at the yard were measured physically to obtain their external dimensions, and these measurements were combined with the gross weight recorded in the ERP to calculate an observed package density, denoted by ρ_p. The same package records were then processed through the estimation model to obtain the corresponding predicted density values, denoted by $\hat{\rho}_p$.

To improve agreement between observed and predicted densities, the representative density-band values were recalibrated using a least-squares optimization of the form

$$\min_{d_b} \sum_{p \in P} \left(\rho_p - \hat{\rho}_p\right)^2 , \tag{4.4}$$

where P is the set of validated packages, ρ_p is the observed density of package p, and $\hat{\rho}_p$ is the corresponding model-estimated density. The optimization was subject to simple physical constraints on the ordering and admissible range of the density categories, while keeping the packing factor fixed. This validation step was therefore used both to assess and to calibrate the density-based estimation method for cartons and boxes.

Dunnage Wood

A second validation component concerned dunnage wood. Because dunnage use is not explicitly recorded in the ERP, validation was based on yard inspection combined with staff statements. Dunnage stockpiles present at the yard were inspected to understand the approximate amount of material held in stock, and discussions with the warehouse personnel were used to determine how frequently these stocks are replenished and whether the provisional dunnage parameters used in the model were consistent with operational expectations. This information was used to assess whether the dunnage estimation method provided a reasonable representation of actual yard practice.

Stretch foil

A third validation component concerned stretch foil. The use of stretch film was examined by inspecting the pallet-wrapping equipment at the yard and observing how foil is applied in practice. This was supplemented by discussion with the warehouse personnel regarding annual roll consumption. These observations were used to assess the plausibility of the stretch-foil estimation method and the assumptions regarding the extent of wrapping applied to outbound packages.

Broader Modeling Assumptions

The packaging mass-estimation methods developed for the different package UOMs were based on two broader assumptions about the logistics system. The first assumption was that UOM labels recorded in the ERP do not always correspond exactly to the physical packaging format used at the yard. In practice, operational constraints may require additional pallets, dunnage, or other handling materials that are not explicitly recorded in the ERP. As a result, the package label in the database may not fully describe the physical packaging configuration observed in the yard.

The second assumption was that packages are generally discarded after arrival at the vessel or other destination rather than being routinely returned into a reuse loop within the current system. This assumption was also applied to transport items such as wooden boxes and pallets, which are nominally capable of reuse over multiple transport cycles. Although the ERP includes a field indicating whether a package is discarded, this is an administrative field and does not directly track the physical fate of the packaging material. A conservative modeling choice was therefore made to assume that the recorded package was discarded after use.

Therefore, in addition to the material-specific validation steps described above, the validation study also examined these broader modeling assumptions. They were assessed qualitatively through discussions with yard personnel and by comparing recorded package categories with observed handling practices.

Where direct measurements were available, validation was based on comparison between observed and model-estimated values. Where direct measurement was not feasible, validation was based on consistency between the implemented modeling assumptions, observed yard practice, and staff feedback. The resulting validation findings are presented in Chapter 5, together with their implications for the reliability and limitations of the case-specific modeling approach.

5

Results

5.1. Validation Results

This section reports the main findings of the yard-based validation described in Chapter 4. Since the validation approach has already been introduced in the case-study chapter, the focus here is on the resulting observations and their implications for the comparative model.

Overall, the validation produced two main outcomes. First, it confirmed that ERP package labels do not always correspond closely to the physical packaging observed at the yard. Second, it showed that the assumption of universal one-way disposal in the existing system does not fully reflect practice, since yard and vessel store keepers maximize the reuse of packaging materials where possible. These findings are discussed below together with their implications for the modeling approach.

Broader modeling assumptions

Assumption 1: ERP package labels may not match physical packaging reality

This assumption was supported by the yard visit. Observations at the Vlissingen yard showed that packages recorded under generic ERP UOM categories such as EA, BND, and PCK are often still handled using pallets or dunnage, depending on the size, weight, and geometry of the shipped item. Smaller items were commonly placed on pallets, while larger or irregular items were supported using dunnage. In practice, the use of these transport items is therefore not always reflected explicitly in the ERP package description.

This finding supports the modeling choice adopted in the case study for these package classes. In particular, it justifies the use of pallet- and dunnage-based representation rules for package categories whose ERP label alone would otherwise under represent the physical packaging required for transport. However, this is still a workaround and true numbers of these additional transport items cannot be accurately accounted for.

Figure 5.1: Left to Right: Big bags stored on pallets, Heavy equipment on pallet, Slings on pallet

Assumption 2: all packaging in the existing system is discarded after use

This assumption was not supported by the yard visit. Both vessel and yard personnel make a practical effort to reuse packaging materials wherever possible. During backloading operations, that is, the return flow from vessel to yard, empty shipping containers are used where feasible to return used pallets, wooden boxes, and dunnage wood, provided that these items remain in acceptable condition. The existing system therefore includes a degree of informal reuse that is not captured in the ERP data. Large amounts of wooden pallets, boxes and cartons were returned from the vessels and stored at the yard for reuse for shipping. Some examples are seen in figure 5.2

Figure 5.2: Packaging Materials backloaded from Vessels - Left to Right: Used Pallets, Used Dunnage, Miscellaneous items

At the same time, packaging material is not treated as an asset class within the ERP system and is therefore not tracked systematically. As a result, the volume of returned and reused packaging cannot be estimated reliably from the available records, and even yard personnel were unable to estimate this inflow with confidence. For this reason, the modeling assumption that all packaging in the existing system is treated as single-use was retained as a conservative simplification for the present analysis.

This choice should be interpreted carefully. By excluding existing informal reuse from the baseline system, the model likely overestimates the emissions of the current packaging system and therefore introduces a bias in favor of the proposed reusable alternatives. This does not invalidate the comparison, but it does represent an important limitation that is discussed further in Chapter 6.

Carton and box density calibration

The yard validation showed that the original density parameterization used for cartons and boxes systematically overestimated package density. Comparison between 55 measured package dimensions and model estimates indicated a mean overprediction of approximately 0.3 kg/l, corresponding to about 65% relative to the observed values. This result showed that the original density-band values were too high for the package sample observed at the yard and would therefore tend to overestimate package volume and associated packaging mass for these UOM categories.

To improve the fit, the density-band values were recalibrated using the least-squares optimization described in Chapter 4. The resulting adjusted density values were lower across all categories, with the largest reductions occurring in the lower-density bands. Table 5.1 compares the original and recalibrated density-band values adopted in the model.

Table 5.1: Original and recalibrated density-band values used for carton and box estimation

Category	Original value	Adjusted value
Ultra Low Density	0.2	0.1
Low Density	0.6	0.2
Medium Density	0.8	0.5
High Density	1.0	0.8
Ultra High Density	1.2	0.9
Metallic	1.6	1.2

Although the recalibration substantially reduced the structural overprediction present in the original model, a non-negligible residual error remained. The recalibrated model produced a root-mean-square error of approximately 0.2 kg/l. Given an average density of around 0.8 kg/l in the validation sample, this corresponds to roughly 25% of the average value. This level of error was considered too large to ignore entirely, even though the recalibrated model was judged to provide a more realistic representation of package density than the original parameterization.

To examine the effect of residual uncertainty in these density assumptions, a sensitivity analysis was also performed in which the density values were varied between 50% and 150% of their calibrated baseline values. Figure 5.3 shows that total single-use packaging emissions changed less than 5% across this range. Emissions were somewhat more unstable at the lower end of the density range, but the overall effect remained limited, with variation of approximately 3%. This indicates that although density calibration improves record-level realism, the aggregate comparative results are not highly sensitive to this parameter.

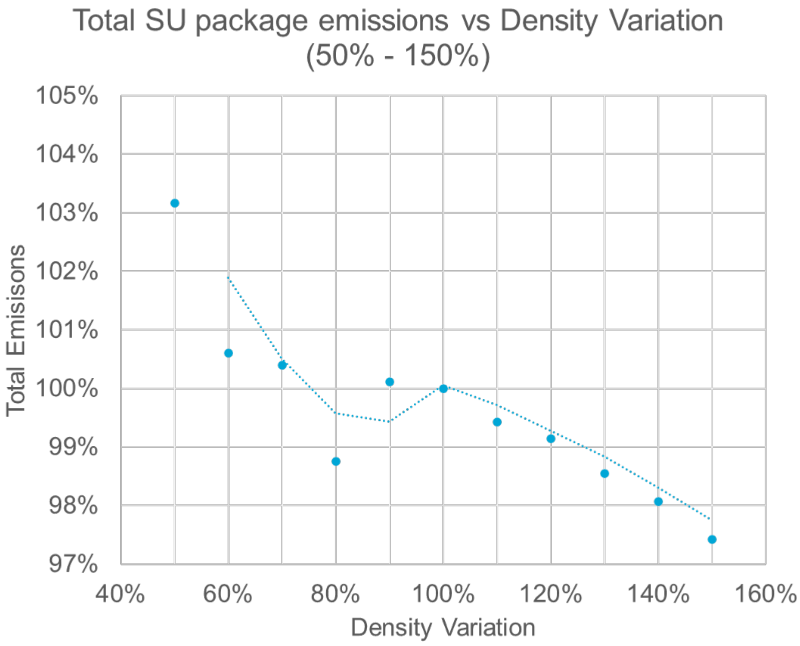

Figure 5.3: Relative Emissions vs Density variation

Dunnage usage validation

Figure 5.4: Dunnage Piles observed at yard

Unlike cartons, boxes, and foil, dunnage usage is not tracked explicitly within the ERP system and yard staff were therefore not able to provide direct quantitative records of annual consumption. However, discussions with yard personnel suggested that the original dunnage fraction of 1% of gross weight was likely too high. Based on operational experience, it was recommended that this fraction should be reduced slightly, and the model value was therefore adjusted to 0.5% of gross weight.

To obtain an independent check on aggregate dunnage usage, wood piles present at the Vlissingen yard were measured during the yard visit. The combined stock of dunnage wood visible at the yard was estimated at [redacted]. The staff further indicated that this [redacted], implying an [redacted]. Figure 5.4 shows examples of dunnage wood observed during the validation visit.

Using these yard-based estimates, aggregate dunnage usage was extrapolated for the 13 year period of the dataset and compared with the model output. Only internally packaged records were selected and purchase orders were excluded. The adjusted model predicted a total dunnage usage of 283 mt, while the estimate derived from the yard study was [redacted] This corresponds to a percentage error of approximately [redacted] indicating very good agreement between the modelled and observed aggregate dunnage usage.

The dunnage validation therefore provides strong support for the adjusted dunnage assumption used in the case model. Although dunnage cannot be validated at individual package level, the close agreement at aggregate level suggests that the modeling approach provides a credible representation of overall dunnage usage in the logistics system.

Table 5.2: Comparison of model-predicted and yard-estimated aggregate dunnage usage

Type	Mass (mt)
Predicted by model	283
Actual usage	[redacted]
Percentage error	[redacted]

Foil usage validation

Figure 5.5: Left to Right: Cartons palletized using foil, Cables wrapped in foil

Foil is used in the logistics system primarily for parralletization of cartons and mixed loads. In practice, stretch foil is wrapped around cartons placed on pallets in order to stabilize the load during handling and transport. In addition, some parts were observed to arrive already wrapped in foil as part of their inbound packaging configuration. Figure 5.5 illustrate typical examples of foil use observed during the yard visit.

Discussion with yard personnel indicated that approximately [redacted] at the Vlissingen yard. Based on the corresponding roll specifications[34], this was estimated to represent approximately [redacted] or about [redacted] for the entire period of the dataset. By comparison, the original model predicted a total foil consumption of only 400 kg for internally packaged flows in the same time period. This implies that the initial parameterization underestimated foil use significantly.

Upon further discussion with yard staff, it was discovered that parallelization of cartons and loose items is not recorded in the ERP, which may explain the discrepancy between the model estimates and the yard estimates. Since, there is no good method to account for this behavior in the model, instead the yard estimate was considered the more accurate reference point. Accordingly, values predicted by the model were scaled by a factor of 5 to have greater agreement with observations.

Table 5.3: Comparison of model-predicted and observed annual foil use

Type	Mass (kg)
Predicted by model	400 kg
Actual yard estimate	[redacted]
Percentage error	[redacted]

Summary of validation findings

The validation results provide support for the main package-representation method used in the model, while also highlighting an important limitations. The yard visit confirmed that ERP package labels do not always correspond directly to the physical packaging used in practice, which supports the modeling choice to assign pallets or dunnage to generic package classes where appropriate. At the same time, the validation showed that some packaging materials are in fact reused within the current system through backloading and yard-level reuse, meaning that the assumption of fully single-use operation is conservative and likely favours the reusable scenarios.

For cartons and boxes, the validation further showed that the original density assumptions were too high and required recalibration. The adjusted values improved agreement with observed packages, while the accompanying sensitivity analysis indicated that the aggregate emissions results are only moderately affected by plausible variation in density. Taken together, these findings suggest that the case model provides a reasonable simplified representation of packaging practice at HMC, while also making clear where conservative assumptions and residual uncertainty remain.

5.2. Model Results - Single Use Packaging

5.2.1. Mass of single-use packaging

This subsection reports the estimated mass of single-use packaging in the current logistics system, based on the package representation and mass-estimation procedures described in Chapter 4. Results are reported for the full analytical dataset (containing data between 2012 and 2025) and include both internally prepared packages and purchase-order receipt packages. Unless stated otherwise, all values in this subsection are cumulative over the full study period. Where relevant, package categories are linked to the ERP UOM abbreviations introduced in Table 4.1. For presentation clarity, the main-text figures use grouped packaging categories, while full results are reported in Appendix C. The category *Dunnage* combines BAG, BND, DRM, EA, RACK, and ROL, since these package classes are all assumed to use primarily dunnage in the model. PAL is shown separately, while BOX, CRT, and FOIL are also retained as distinct categories.

As seen in table 5.4, across the full study period, the estimated total mass of single-use packaging was approximately 1546 mt. Of this, around 444 mt originated from internally prepared packages, while 1102 mt originated from purchase-order receipts. Purchase-order receipts therefore account for the majority of the estimated single-use packaging mass, representing approximately 71% of the total, while in-house flows account for the remaining 29%.

Table 5.4: Estimated mass of single-use packaging by flow type over the full study period

Flow type	Mass (mt)	Share of total (%)
In-house prepared flows	444	29
PO-receipt flows	1102	71
Total	1546	100

In material terms, the packaging mass remains overwhelmingly dominated by wood-based transport items. Wood accounts for approximately 1513 mt, or about 98% of the total estimated packaging mass, while LDPE stretch foil contributes around 20 mt and carton around 14 mt. The overall mass burden of the current system is therefore determined almost entirely by timber-based packaging materials.

Figure 5.6 provides a more detailed breakdown of the estimated packaging mass by grouped packaging category, while also distinguishing between in-house and PO-receipt flows. The figure shows that the largest contribution arises from PAL, at approximately 830 mt, followed by Dunnage at around 610 mt. By comparison, BOX contributes roughly 76 mt, while FOIL and CRT contribute only around 20 mt and 14 mt respectively. The dominance of PAL is driven primarily by purchase orders, which account for the large majority of pallet-associated packaging mass. By contrast, Dunnage forms the largest in-house category, while also contributing substantially within PO-receipt flows. These results indicate that the total mass of the current single-use packaging system is concentrated in a limited number of wooden packaging types, particularly palletised purchase order and outsize items shipped internally from HMC.

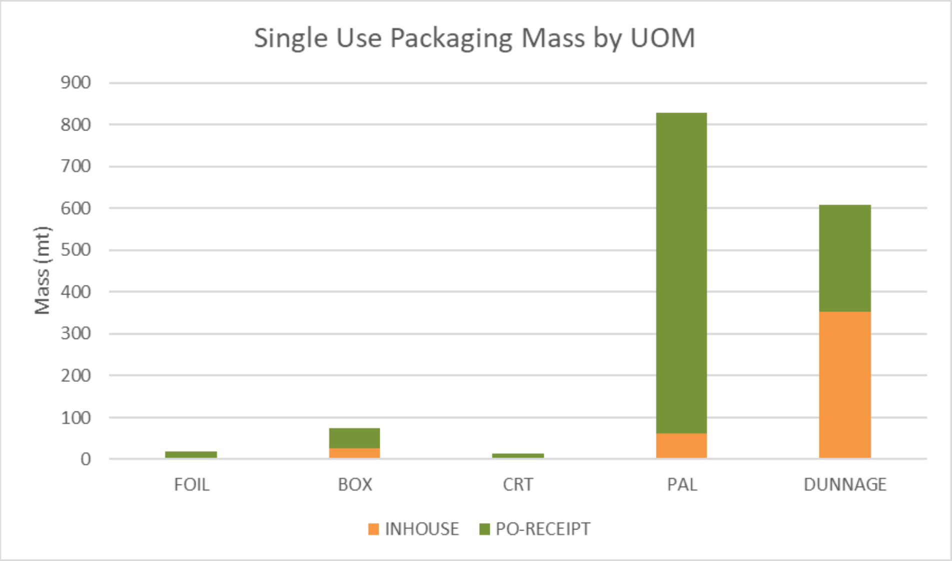

Figure 5.6: Estimated mass of single-use packaging by grouped packaging category and flow type over the full study period

5.2.2. Emissions impact of the existing single-use packaging system

This subsection reports the greenhouse-gas emissions associated with the existing single-use packaging system, based on the package representations, transport calculations, and end-of-life assumptions described in Chapter 4. Results are reported for the full analytical dataset and include both internal and purchase orders. Unless stated otherwise, all values in this subsection are cumulative over the full study period.

Table 5.5 summarises the total emissions of the single-use packaging system by accounting method, flow type, and life-cycle stage over the full study period. Across the full study period, total emissions amount to 1141 mt CO_2eq under cut-off accounting and 783 mt CO_2eq under system-expansion accounting. In both cases, production and transportation emissions are identical, with the difference between the two totals arising entirely from the treatment of end-of-life emissions. Transportation is the largest positive contributor, accounting for 562 mt CO_2eq over the study period, followed by production emissions at 455 mt CO_2eq. Under cut-off accounting, end-of-life contributes an additional 124 mt CO_2eq, whereas under system expansion it contributes -235 mt CO_2eq due to recovery credits.

Table 5.5: Emissions of the existing single-use packaging system by accounting method, flow type, and life-cycle stage over the full study period

Accounting	Flow type	Total (mt CO_2eq)	Production (mt CO_2eq)	Transport (mt CO_2eq)	EOL (mt CO_2eq)
Cut-off	In-house	328	123	163	41
	PO-receipt	813	332	399	82
	Total	**1141**	**455**	**562**	**124**
System expansion	In-house	222	123	163	-65
	PO-receipt	561	332	399	-170
	Total	**783**	**455**	**562**	**-235**

A breakdown by flow type shows that the majority of baseline emissions arise from purchase-order receipt flows rather than internally prepared flows. Under cut-off accounting, purchase-order receipts account for 813 mt CO_2eq, or approximately 71.3% of total emissions, while in-house flows account for 328 mt CO_2eq, or 28.7%. Under system-expansion accounting, the split remains similar, with purchase-order receipts contributing 561 mt CO_2eq (71.6%) and in-house flows 222 mt CO_2eq (28.4%). This mirrors the mass results presented in Section 5.2.1, where PO-receipt flows also account for the majority of total single-use packaging mass.

Under cut-off accounting, all three life-cycle stages contribute positively to the overall result. Figure 5.7 shows the distribution of these emissions by grouped packaging category. The figure indicates that emissions are dominated by PAL, which contributes approximately 581 mt CO_2eq in total, followed by Dunnage at around 392 mt CO_2eq. BOX contributes roughly 99 mt CO_2eq, while FOIL and CRT contribute approximately 38 mt CO_2eq and 31 mt CO_2eq respectively. This pattern is consistent with the mass results presented in Section 5.2.1, where palletised and dunnage-supported flows account for the large majority of total packaging mass. Under cut-off accounting, end-of-life emissions remain positive for the dominant wood-based packaging categories and therefore add to the total burden of the single-use system.

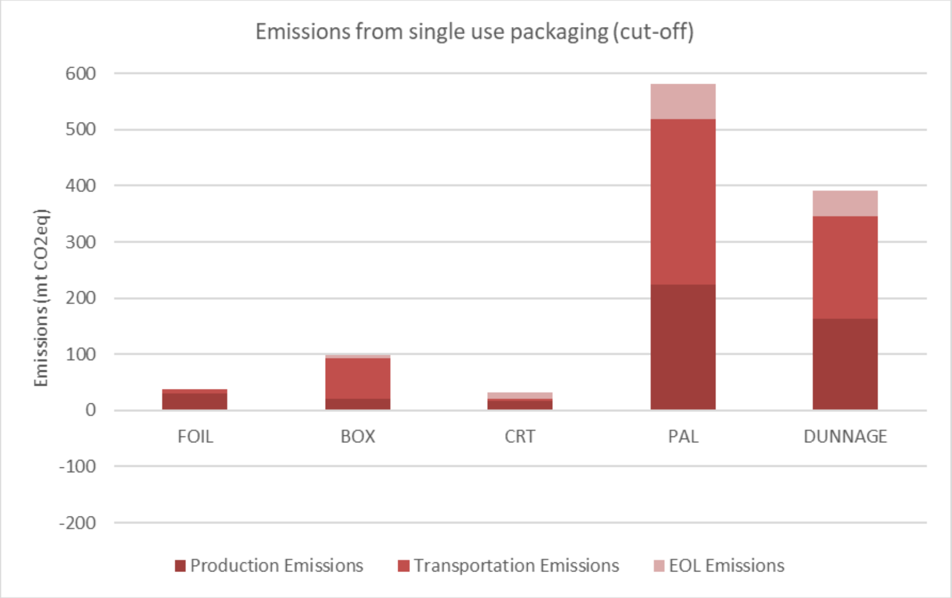

Figure 5.7: Emissions from the existing single-use packaging system by grouped packaging category under cut-off accounting over the full study period

Table 5.6 reports the same cut-off results aggregated by material. The emissions profile is strongly dominated by wood, which accounts for 1072 mt CO_2eq, or 94% of the total. Carton contributes 31 mt CO_2eq (3%), while LDPE contributes 38 mt CO_2eq (3%). The cut-off results therefore confirm that the emissions of the existing system are driven primarily by wood-based packaging materials.

Table 5.6: Emissions of the existing single-use packaging system by material under cut-off accounting over the full study period

Material	Emissions (mt CO_2eq)	Share of total (%)
Carton	31	3
Wood	1072	94
LDPE	38	3

Under system-expansion accounting, production and transportation emissions remain unchanged, but end-of-life emissions become negative overall due to the credits associated with material recovery. As shown in Figure 5.8, this reduces the total emissions attributed to the dominant grouped categories, particularly PAL and Dunnage. However, the overall distribution by packaging category remains broadly unchanged. PAL remains the largest contributor at approximately 390 mt CO_2eq, followed by Dunnage at around 247 mt CO_2eq, while BOX, FOIL, and CRT contribute approximately 81 mt CO_2eq, 35 mt CO_2eq, and 30 mt CO_2eq respectively. The accounting treatment therefore lowers the total burden most strongly for the packaging categories, but does not change the overall ranking between them.

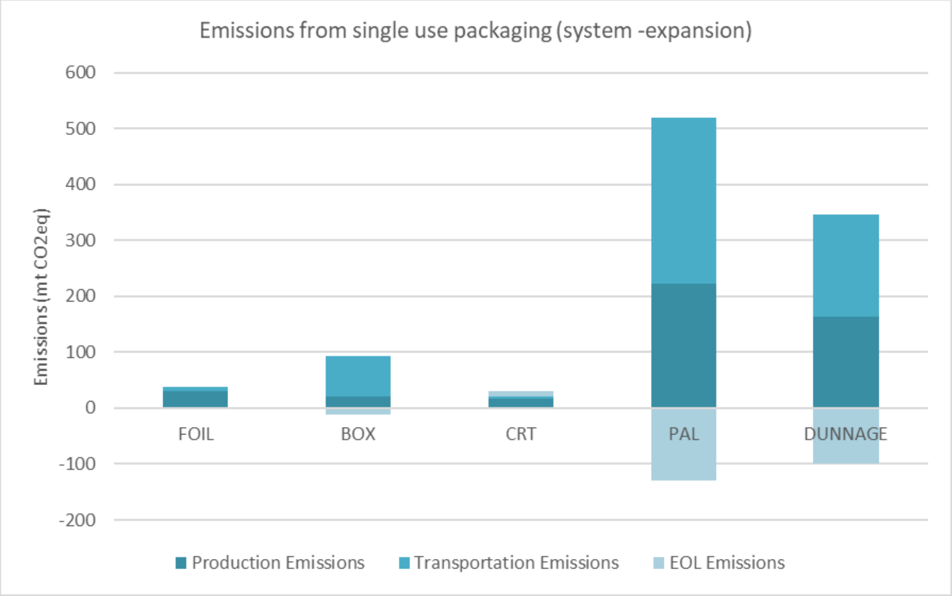

Figure 5.8: Emissions from the existing single-use packaging system by grouped packaging category under system-expansion accounting over the full study period

Table 5.7 presents the system-expansion results aggregated by material. Wood again dominates the total emissions profile, accounting for 718 mt CO_2eq, or 92% of the total. Carton contributes 30 mt CO_2eq (4%), while LDPE contributes 35 mt CO_2eq (4%). Although the accounting treatment lowers the burden attributed to wood through end-of-life credits, the overall material ranking remains unchanged.

Table 5.7: Emissions of the existing single-use packaging system by material under system-expansion accounting over the full study period

Material	Emissions (mt CO_2eq)	Share of total (%)
Carton	30	4
Wood	718	92
LDPE	35	4

Taken together, these results show that the emissions of the existing single-use packaging system are concentrated in a limited number of wood-dominated packaging types and are strongly affected by the treatment of end-of-life. Nevertheless, emissions magnitude roughly tracks with the mass of packaging and the same broad structure remains visible under both accounting approaches: transportation and production are the main positive contributors to total emissions, Pallets is the dominant packaging category, Dunnage is the second largest contributor, and wood is by far the dominant material. The full set of results is provided in Appendix C.

5.3. Model Results - Comparison of Packaging Systems

This section presents the comparative results for the existing single-use packaging system and the proposed reusable packaging system under the baseline scenario assumptions. In contrast to Sections 5.2.1 and 5.2.2, which considered the full analytical dataset, the comparative analysis reported here is restricted to only internally shipped packages, while purchase-orders from external suppliers were excluded from the substitution analysis.

This scope restriction was adopted because reusable packaging is evaluated here as a substitution strategy within the company-controlled logistics boundary. For externally supplied purchase-order flows, implementation of reusable packaging would in many cases require additional repackaging, handling, and coordination steps that are not represented in the present model. These records were therefore retained in the baseline analysis of current packaging mass and emissions for completeness, but were excluded from the comparative assessment. Under the baseline reusable scenario, the reverse logistics multiplier was set to 1.8 and the RTI life multiplier was set to 1.0.

Net emissions benefit is defined here as the emissions of the single-use packaging system minus the emissions of the reusable packaging system. Positive values therefore indicate that reusable packaging results in lower emissions than the corresponding single-use packaging system, while negative values indicate that reusable packaging results in higher emissions.

5.3.1. Overall comparative result

Table 5.8 summarises the overall comparative result for the in-house subset under the baseline scenario. Under cut-off accounting, the reusable packaging system yields a small net emissions benefit of 4.3 mt CO_2eq over the full study period. Under system-expansion accounting, the comparative result reverses, and the reusable packaging system yields a net emissions disadvantage of 101.5 mt CO_2eq. The overall comparative outcome is therefore close to break-even under cut-off accounting, but clearly unfavorable under system expansion.

Table 5.8: Overall comparative result for the in-house subset under the baseline scenario

Accounting	Single-use (mt CO_2eq)	Reusable (mt CO_2eq)	Benefit (mt CO_2eq)
Cut-off	327.7	323.4	4.3
System expansion	221.7	323.2	-101.5

Although the aggregate totals provide a useful summary, they conceal substantial variation across destination countries and packaging categories. The following subsections therefore show a granular presentation of the comparative results to identify and highlight this variation.

5.3.2. Comparative result by destination country

Since destination-specific end-of-life fractions were assigned at country level, the comparative results were also aggregated by destination country, with a separate category for offshore delivery locations. For clarity, Figures 5.9 and 5.10 include only the countries with results of greater than 1 mt CO_2eq. Countries with results of magnitude below this threshold have been grouped into a category labeled 'Others'. The full results are reported in Appendix C.

Under cut-off accounting, shown in Figure 5.9, the positive net benefit is concentrated in a limited number of destinations, most notably the Netherlands at 35 mt CO_2eq and the United States at 11 mt

CO_2eq. Smaller positive contributions are also observed for the United Kingdom and Norway, at 3 mt CO_2eq each. These gains are offset by negative contributions from Mexico (-15 mt CO_2eq), Singapore (-12 mt CO_2eq), offshore destinations (-10 mt CO_2eq), Taiwan (-8 mt CO_2eq), and Trinidad and Tobago (-4 mt CO_2eq). The cut-off result is therefore not uniformly favourable across all contexts, but depends on a relatively small number of stronger positive cases.

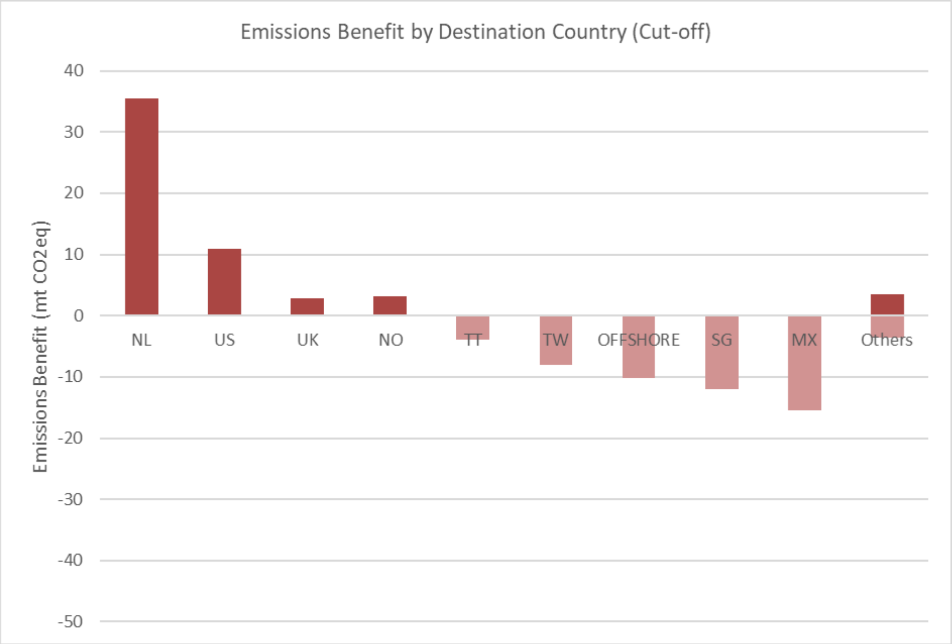

Figure 5.9: Net emissions benefit of reusable packaging relative to single-use packaging by destination country under cut-off accounting for the in-house subset

Under system-expansion accounting, shown in Figure 5.10, the country-level pattern changes substantially. The United States remains the strongest positive contributor, with a benefit of 10 mt CO_2eq, while the United Kingdom contributes a much smaller positive value. However, these gains are outweighed by large negative contributions from offshore destinations (-46 mt CO_2eq), the Netherlands (-20 mt CO_2eq), Mexico (-15 mt CO_2eq), Singapore (-14 mt CO_2eq), and Taiwan (-10 mt CO_2eq). Compared with the cut-off result, the system-expansion result is therefore both more negative overall and more strongly dominated by a few high-impact unfavourable destination contexts.

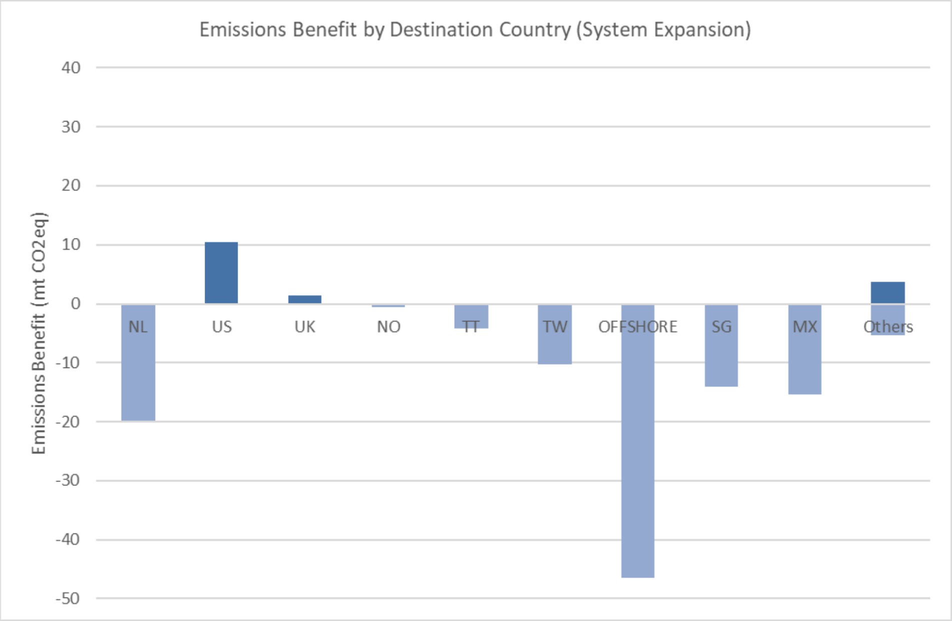

Figure 5.10: Net emissions benefit of reusable packaging relative to single-use packaging by destination country under system-expansion accounting for the in-house subset

Taken together, the country-level results show that the comparative performance of reusable packaging is highly context-dependent. Under cut-off accounting, the near-neutral overall result arises from a balance between a few strongly positive and several negative destination contexts. Under system expansion, the overall disadvantage is driven primarily by offshore deliveries and a limited number of other high-impact destinations.

5.3.3. Comparative result by packaging category

To further interpret the comparative result, Figures 5.11 and 5.12 dis-aggregate the country-level results by grouped packaging category. For presentation clarity, FOIL is omitted from the main-text figures because its contribution remains below 1 mt CO_2eq across all destination. Full results including FOIL are reported in Appendix C.

Under cut-off accounting, shown in Figure 5.11, the dominant positive contributions are associated with Dunnage, particularly in the Netherlands (37 mt CO_2eq) and the United States (10 mt CO_2eq). PAL also contributes positively in several destination contexts, though at much smaller magnitudes, including the Netherlands and the United States at 3 mt CO_2eq each. By contrast, BOX is consistently unfavorable and shows its largest negative contribution for offshore destinations at -20 mt CO_2eq, followed by Taiwan at -9 mt CO_2eq and Singapore at -7 mt CO_2eq. CRT remains negligible throughout, with only a small negative contribution for offshore destinations. The cut-off result is therefore driven primarily by a trade-off between positive Dunnage outcomes and negative BOX outcomes.

Under system-expansion accounting, shown in Figure 5.12, the category-level picture becomes more unfavourable. Dunnage, which was the main positive driver under cut-off accounting, becomes strongly negative in several key contexts, most notably offshore destinations (-19 mt CO_2eq), Mexico (-15 mt CO_2eq), and the Netherlands (-12 mt CO_2eq). BOX remains consistently negative and again contributes strongly to the unfavourable result, especially for offshore destinations (-23 mt CO_2eq), Taiwan (-9 mt CO_2eq), Singapore (-7 mt CO_2eq), and the Netherlands (-7 mt CO_2eq). PAL remains comparatively small in magnitude, with modest positive contributions for the United States and Others, but negative contributions for offshore destinations. CRT again remains negligible.

These results show that the comparative outcome is not only destination-specific, but also strongly dependent on packaging category. Dunnage is the main driver of both favourable and unfavourable results depending on the accounting method and destination context, while BOX is consistently associated with negative outcomes. PAL contributes positively in some cases, but at a much smaller scale,

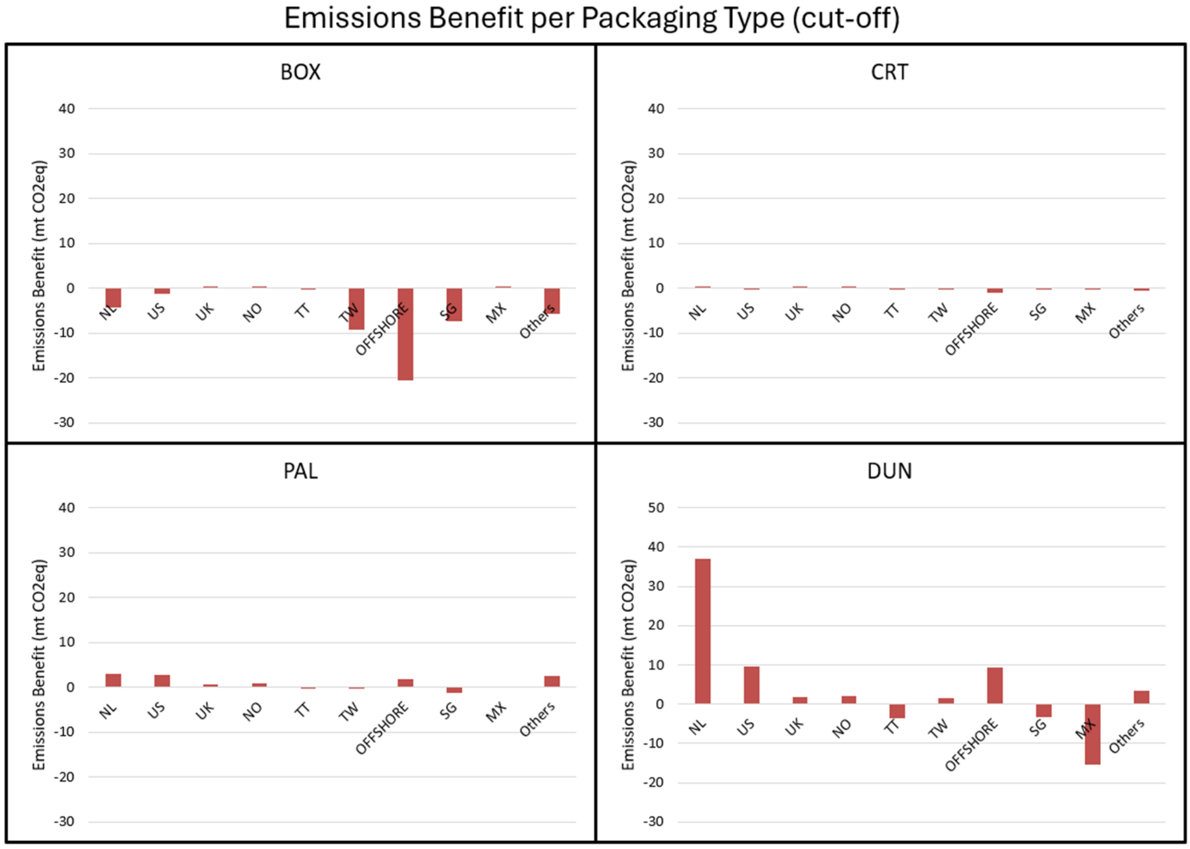

Figure 5.11: Net emissions benefit by destination country and packaging category under cut-off accounting for the in-house subset

and CRT remains negligible throughout due to the low overall mass being used.

5.3.4. Sensitivity analysis

Because the baseline comparative result is small under cut-off accounting, it is important to test the sensitivity of the result to variation in the main reusable-system assumptions. The sensitivity analysis was carried out using the cut-off model, since the tested parameters relate to operational characteristics of the reusable packaging system rather than to the accounting treatment of end-of-life. To facilitate comparison across scenarios, the resulting net emissions benefit was normalised to the emissions of the single-use baseline system, such that the plotted values represent the relative advantage or disadvantage of the reusable system as a percentage of single-use emissions.

Figure 5.13 shows the effect of varying the RTI life multiplier while holding the reverse logistics multiplier fixed at its baseline value of 1.8. As expected, higher RTI life improves the comparative result with diminishing returns with container life. This non-linearity arises from distributing production and EOL impacts over the expected number of uses (i.e. lifetime). However, the magnitude of this improvement remains relatively modest. Over the tested range, the normalised net benefit increases from approximately -3% at a life multiplier of 0.5 to around 2% at a multiplier of 1.5. The life multiplier therefore affects the strength of the comparative result, but does not dominate it.

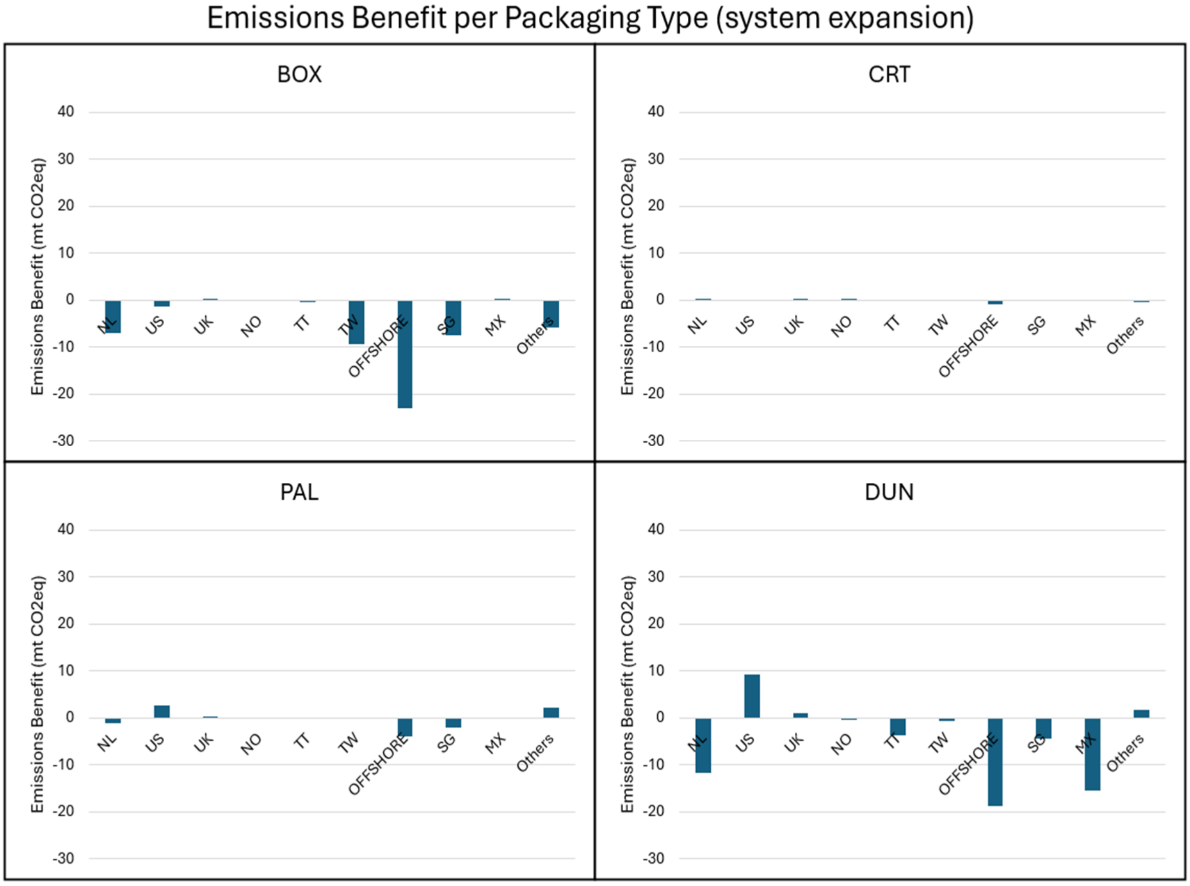

Figure 5.12: Net emissions benefit by destination country and packaging category under system-expansion accounting for the in-house subset

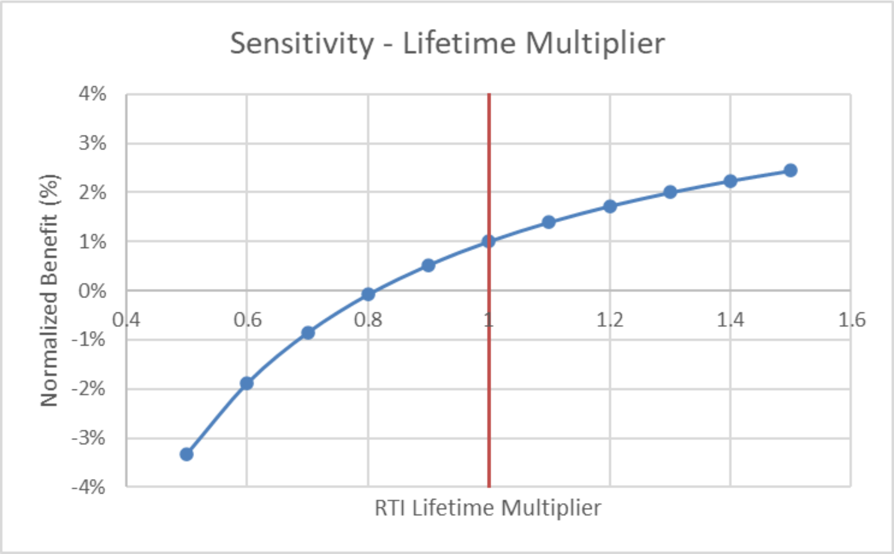

Figure 5.13: Normalized net benefit as a function of RTI life multiplier, with reverse logistics fixed at 1.8

Figure 5.14 shows the effect of varying the reverse logistics multiplier while holding the RTI life multiplier fixed at 1.0. In contrast to RTI life, reverse logistics has a much stronger influence on the comparative outcome. The normalized net benefit decreases from approximately 11% at a reverse logistics multiplier of 1.6 to around -9% at a multiplier of 2.0, crossing the break-even point close to the baseline scenario.

This indicates that the assumed return-flow burden is substantially more influential than the assumed RTI life within the tested range.

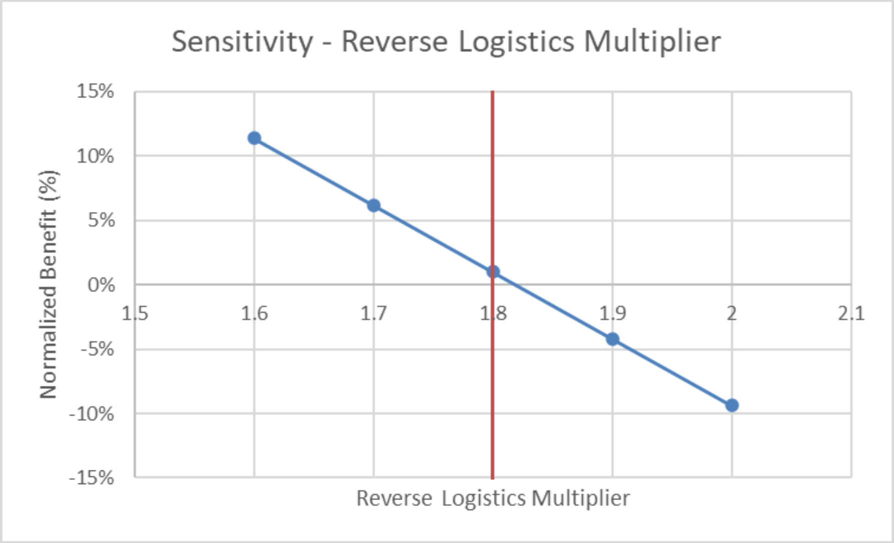

Figure 5.14: Normalized net benefit as a function of reverse logistics multiplier, with RTI life fixed at 1.0

The combined effect of both assumptions is shown in Figure 5.15. The contour plot confirms that the comparative result is more sensitive to reverse logistics than to RTI life, as indicated by the predominantly vertical orientation of the break-even boundary. The baseline scenario at a reverse logistics multiplier of 1.8 and an RTI life multiplier of 1.0 lies close to this boundary and yields a normalized net benefit of approximately 1%. This confirms that the baseline cut-off result is not robustly positive, but instead lies near the transition between favourable and unfavourable performance. The region of positive benefit expands toward lower reverse logistics multipliers and higher RTI life values, while increasingly negative results arise when reverse logistics is less efficient.

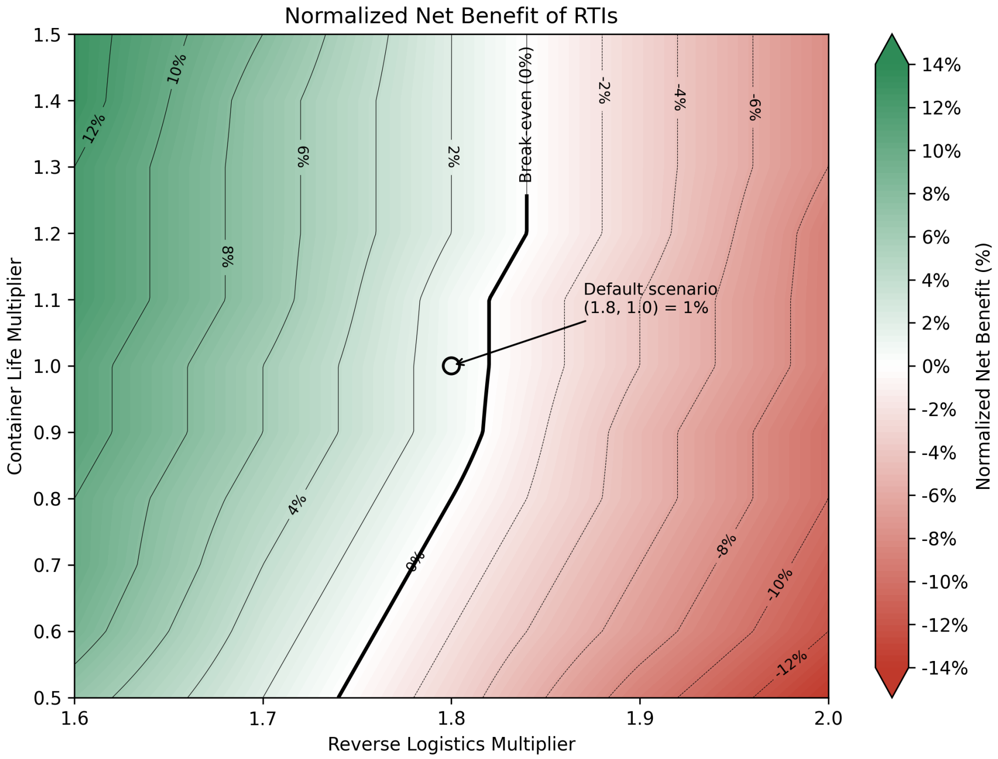

Figure 5.15: Normalized net benefit of reusable packaging as a function of reverse logistics multiplier and RTI life multiplier

Overall, the comparative analysis shows that the emissions performance of reusable packaging depends strongly on both accounting treatment and logistical context. Under cut-off accounting, the baseline result is close to break-even and is driven by a balance between favourable Dunnage outcomes and unfavourable BOX outcomes across different destinations. Under system-expansion accounting, the result becomes clearly negative and is dominated by large disadvantages in offshore and other high-impact destination contexts. The sensitivity analysis further shows that reverse logistics assumptions are more influential than RTI life within the tested parameter range, and that the baseline scenario lies close to the break-even boundary.

6

Discussion

6.1. Interpretation of baseline and comparative results

Baseline packaging system and single-use emissions

The results show that the current packaging system is dominated by wooden transport items, particularly pallets and dunnage. This is consistent with the operational context of HMC, where large project equipment, vessel supplies, and fabricated project equipment are commonly transported. The baseline mass results further show that most packaging mass lies outside direct HMC control. Approximately 70% of estimated packaging mass originates from purchase-order packages, while around 30% originates from internally prepared packages. This is primarily driven by the need to procure both new project equipment, consumables and provisions required for ship operations. The distribution observed here aligns well with the findings of another project conducted by the Sustainability team concerning the circularity of project equipment.

The distinction between pallets and dunnage is also operationally meaningful. Purchase orders are primarily delivered from third party suppliers on pallets, contributing to the majority of the pallets flowing through the logistics system. A similar trend is also seen for cartons and boxes. In contrast, dunnage has more even split between purchase orders and internal packages. This is driven by the need to transport project equipment and parts from company stocks to either vessel or suppliers for returns or refurbishment. These items are often outsize or irregularly shaped requiring dunnage to facilitate shipping. Consequently the majority of packaging mass consists of wood, with a much smaller fraction of cartons and LDPE used for stretch foil.

Naturally, under both accounting approaches, the single-use system is dominated by production and transportation emissions associated with wood-based packaging. At the same time, the treatment of end-of-life has a large effect on the total result. Under cut-off accounting, end-of-life contributes positively to the total burden, whereas under system expansion the same stage contributes substantial avoided-burden credits through recycling and energy recovery. This produces a large difference between the two total results even though the physical packaging system being modelled remains the same. The baseline emissions should therefore be understood not only as a reflection of packaging mass and transport activity, but also as a consequence of the accounting perspective used to represent waste treatment.

Comparative performance of reusable packaging

The comparative results show that reusable transport items are not unambiguously preferable to the current system. Under cut-off accounting, the reusable system yields only a marginal net emissions benefit of 4.3 mt CO_2eq over the full study period. Under system-expansion accounting, the result reverses and the reusable system performs worse than the single-use baseline by 101.5 mt CO_2eq. The main implication is therefore not that reusable packaging is either clearly beneficial or clearly disadvantageous in general, but that its performance depends strongly on the accounting framework and on the operational context in which it is deployed.

The country-level results show that the comparative outcome varies substantially across destinations. This is driven first by differences in package volume, which explains the large magnitudes associated with the Netherlands and offshore destinations compared with countries with smaller package volumes such as the UK or Norway, and second by differences in assumed end-of-life treatment. Destinations with higher assumed recycling or energy-recovery shares show a larger shift between cut-off and system-expansion results, since more of the single-use burden is offset through avoided-burden credits. By contrast, destinations with more landfill-dominated waste treatment show much smaller changes between the two accounting approaches. This is best seen in the results for the US, which are almost identical for both accounting methods. The comparative result is therefore shaped not only by logistics activity, but also by the assumed downstream treatment of packaging waste.

A similarly strong contrast appears across packaging categories. Boxes perform poorly under both accounting approaches, since reusable plastic boxes are substantially heavier than their single-use counterparts and the resulting increase in transportation burden offsets reductions in production and end-of-life impacts. Cartons show a similar pattern, but their absolute effect is much smaller because both the single-use and reusable masses are low. Pallets show a small benefit under cut-off accounting in several destinations, but this largely disappears under system expansion because wooden pallets receive substantial end-of-life credits through recycling and energy recovery. Dunnage shows the strongest comparative benefit under cut-off accounting, especially in the Netherlands and the United States, but much of this advantage also disappears under system expansion for the same reason. Taken together, these results show that the comparative performance of reusable packaging is highly uneven and that the aggregate result is driven primarily by a small number of high-impact destination and package type combinations.

6.2. Sensitivity and operational realism

The sensitivity analysis shows that the comparative outcome is much more strongly influenced by the reverse logistics multiplier than by the RTI life multiplier. This is consistent with the structure of the model. For reusable packaging, the dominant recurring burden is transportation, and changes to the reverse logistics multiplier therefore have a direct and approximately proportional effect on total emissions. By contrast, the RTI life multiplier affects only the amortized production and end-of-life burdens of the reusable transport items. As a result, improvements in RTI lifetime do improve performance, but their effect is more limited than changes in the burden associated with returning empty containers.

This behavior is visible in the one-at-a-time sensitivity results. When the reverse logistics multiplier is reduced from the baseline value of 1.8 to 1.6, the normalized net benefit increases to approximately 11% of single-use baseline emissions. When the reverse logistics multiplier is increased to 2.0, the comparative result becomes clearly negative at approximately -9%. The break-even boundary is therefore crossed within the tested range, showing that relatively small changes in return-loop efficiency can determine whether the reusable system performs better or worse than the single-use baseline. In contrast, variation in RTI life over the tested range produces a more moderate change. At a life multiplier of 0.5, the normalized net benefit is approximately -3%, while at a multiplier of 1.5 it rises to around 2%. RTI life therefore changes the strength of the result, but does not influence it as strongly as reverse logistics.

The contour plot reinforces this interpretation by showing the combined effect of both parameters. The predominantly vertical orientation of the break-even boundary indicates that the result is more sensitive to reverse logistics than to RTI life. The most favourable tested combination yields a normalized emissions reduction of approximately 13%, while increasingly burdensome return logistics quickly eliminate the benefit of reusable packaging even when RTI life is improved. This means that the environmental case for reusable packaging at HMC depends primarily on whether an efficient return loop can be achieved in practice. In the absolute worst case scenario, with inefficient returns and lower RTI lives, the resuable system has 14% more emissions than the existing single use system.

At the same time, the most favourable combinations in the sensitivity space are unlikely to be fully achievable under the operating conditions considered in this thesis. RTI lifetime is strongly influenced by handling conditions. In highly standardized and automated logistics systems, containers may achieve long service lives with relatively low damage rates. In offshore project logistics, by contrast, handling is often more manual, less standardized, and subject to rough operating conditions. Under such circumstances, a 50% improvement over the baseline RTI life assumption appears optimistic and should be interpreted as an upper-bound sensitivity case rather than as a likely operational outcome.

A similar argument applies to reverse logistics. The baseline reverse logistics multiplier of 1.8 already assumes that return logistics are somewhat more efficient than forward logistics, for example through consolidation of empty containers, the use of slower but more efficient transport modes, or direct batch returns where possible. Although such measures are theoretically feasible, they are themselves operationally demanding in a project-based offshore logistics system. Achieving substantially lower reverse logistics burdens, such as those associated with the most favourable tested cases, would require a highly coordinated return system and may not be realistic in routine operations. The sensitivity analysis should therefore not be read as evidence that the maximum modeled benefit is readily attainable, but rather as an indication of the operational conditions under which reusable packaging could perform well.

Taken together, the sensitivity results show that the baseline cut-off result is not robustly positive. Instead, it lies close to the transition between favourable and unfavourable performance. This is an important finding for interpretation of the overall study. It means that even where reusable packaging appears beneficial under the baseline cut-off assumptions, that benefit remains contingent on maintaining an efficient reverse loop and on achieving sufficient RTI lifetime in practice.

6.3. Limitations

Several limitations constrain the scope of this study and should be considered when interpreting the results. First, the assessment is limited to greenhouse-gas emissions. This choice is consistent with current corporate reporting practice, including the GHG Protocol[47] and the CSRD-reporting context at HMC, where climate-related emissions are a primary focus of accounting. Accordingly, the study was designed as a comparative GHG assessment rather than a full multi-impact environmental assessment. Other environmental impacts, such as water use, resource depletion, eutrophication, and terrestrial or marine toxicity, were not considered. These impact categories are also more difficult to represent consistently in the present case because open-access factor data are more limited, especially for a logistics system with a large geographical footprint. This creates an important blind spot, particularly in relation to non-GHG impacts associated with different packaging materials, including plastics. The conclusions of this thesis should therefore be interpreted specifically in terms of carbon dioxide equivalent (CO_2eq) performance rather than broader environmental sustainability.

Second, the study evaluates packaging systems only in terms of greenhouse-gas emissions and does not include a full operational or economic assessment. The modeled logistics system is therefore a simplified representation of real operations. Operational factors such as delivery time, damage, inspection, cleaning, and return-logistics management were either simplified or excluded. For the same reason, a detailed fleet-sizing model for the different RTI types was not developed. As a result, costs were also not quantified. Implementing a reusable-packaging system would require upfront investment to procure the RTIs, as well as additional effort to establish a system for storing, tracking, and managing containers in circulation and to train personnel in its use. Beyond these initial investments, recurring costs associated with cleaning, replacement of damaged units, and reverse logistics would also need to be considered. The results should therefore not be interpreted as a complete business case for implementation, but rather as an environmental comparison under a defined set of assumptions. For the present study, this level of detail was sufficient to address the research objective, since the work was intended as a preliminary assessment of the concept rather than as a final implementation study. A detailed business case would only be justified if the environmental results were compelling enough to support further investigation.

A further scope limitation is that the study focuses primarily on tertiary packaging and selected forms of secondary packaging associated with transport, handling, and distribution. Primary packaging was excluded, since it is generally determined by suppliers and product-specific requirements and lies largely outside HMC's direct decision space. The results therefore do not represent the full packaging footprint associated with all goods moving through the logistics system, but rather the part of the packaging system most relevant to HMC's transport and handling operations. This also means that the total packaging-related emissions reported in the study should be interpreted as partial rather than exhaustive. Finally, the reusable substitution logic developed in this study is necessarily simplified. Reusable substitutes were assigned on the basis of functional similarity, packaging class, and dimensional compatibility, but the model does not represent the full operational complexity of deployment in practice. Issues such as packaging standardization across suppliers, space constraints during storage and return, loss and breakage in circulation, and the interaction between different package types in mixed loads were not represented explicitly. The results should therefore be interpreted as an assessment of the comparative emissions potential of reusable packaging, rather than as a fully resolved implementation design.

Taken together, these limitations do not invalidate the study, but they do define its scope. The thesis provides a structured greenhouse-gas comparison of single-use and reusable packaging under data-constrained conditions, but it does not by itself establish the full environmental, operational, or economic case for system-wide implementation.

6.4. Uncertainty in Results

Beyond the broader scope limitations discussed above, the study is also affected by several sources of uncertainty that influence the numerical results. These uncertainties do not all act in the same direction, and not all can be quantified rigorously. However, several of the most important unquantified effects are likely to reduce the apparent advantage of reusable packaging rather than increase it. This is particularly important because the baseline comparative result under cut-off accounting is already close to break-even, while the result under system expansion is negative.

A first source of uncertainty concerns the representation of packaging from ERP data. The validation showed that ERP package labels do not always correspond closely to the physical packaging configuration observed in practice. Generic package classes may still involve pallets, dunnage, or foil even when these are not explicitly recorded. While the assignment rules developed in this thesis provide a structured way to reconstruct packaging, they remain an approximation. In some cases, this may overstate packaging burdens, especially where large or irregular items are assigned dunnage by rule even though some real shipments may require little or no support material. This is particularly relevant for equipment such as forklifts, enclosed units, or other robust items that may be transported without dedicated dunnage. Since such cases could not be identified systematically from the administrative records, the model likely overstates some portion of baseline dunnage use.

A second and more important source of uncertainty concerns reuse already occurring within the nominally single-use baseline. Yard observations showed that pallets, wooden boxes, and dunnage are already reused informally where operationally feasible. Because this reuse is not tracked systematically in the ERP system, it could not be quantified and was therefore excluded from the model. The baseline was therefore represented as fully single-use even though the real system is already partially circular. This likely favours the reusable scenarios, since any reuse of existing wooden transport items reduces their emissions per transport cycle and raises the number of cycles a reusable alternative must survive in order to break even.

A third source of uncertainty concerns end-of-life modelling. Waste-treatment fractions were assigned primarily using country-level datasets, with a separate logic for offshore waste. This provides a transparent and geographically differentiated basis for modelling, but it remains a proxy for the actual treatment of industrial packaging waste. In most countries, fixed fractions were applied across all packaging materials, even though real treatment pathways may differ by contractor, port, or waste stream. A related uncertainty concerns the emission factors used to represent production, transportation end-of-life processes. The DESNZ and CarbonWARM2 datasets provide a coherent and transparent factor emission factors, but both are based on studies conducted within the context of the UK and may not be fully representative of conditions around the globe. They are therefore more robust for relative comparison than for precise quantification of absolute emissions.

Finally, uncertainty remains in the assumed performance of the reusable system itself. The sensitivity analysis shows that the comparative outcome is much more sensitive to reverse logistics than to RTI lifetime. Any practical underperformance of the return loop, such as low backhaul utilization, inefficient routing, or fragmented return flows, would quickly erode the already small cut-off benefit. Likewise, if reusable packaging experiences shorter service life under manual handling and harsh offshore conditions than assumed in the baseline case, the result would shift further against reusable deployment.

Taken together, these uncertainties do not justify a stronger claim in favour of reusable packaging. On the contrary, several of the most important unquantified effects, especially informal reuse in the current system, possible overstatement of some dunnage use, and optimistic assumptions regarding reverse logistics efficiency, are likely to reduce the apparent benefit of reusable packaging further. The study therefore does not provide robust evidence that a broad shift to reusable packaging would reduce packaging-related greenhouse-gas emissions under realistic HMC operating conditions. At most, the results support a more selective and context-dependent interpretation, where any potential benefit must be assessed carefully by packaging type, destination, and operational setting.

6.5. Implications for HMC

From a practical perspective, the results do not support a strong case for a broad transition from the current packaging system to a formal reusable-packaging system. Within the company's current sustainability reporting context, the cut-off perspective is the more relevant basis for interpretation, since HMC does not participate in recycling-credit schemes and does not directly control the downstream recovery of packaging once it leaves the company boundary. Even under this more favorable accounting perspective, however, the modeled emissions benefit of reusable packaging remains marginal.

This weakens the strategic relevance of reusable packaging as a climate measure. Compared with the direct emissions associated with vessel operations and other major operational sources, the packaging-related emissions identified in this study are small. In addition, only around 30% of the packaging mass in the model is associated with packages prepared internally, while the remaining 70% originates from supplier-delivered purchase orders. This means that much of the packaging burden lies outside HMC's immediate operational control, further limiting the practical scope for company-led intervention. In addition, the study focuses mainly on tertiary packaging and selected forms of secondary packaging, meaning that the practical improvement potential identified here relates only to the part of the packaging system that is most relevant to HMC's transport and handling decisions.

The case for a broad rollout becomes weaker still when the study uncertainties are taken into account. Several of the most important uncertainties, including possible overstatement of some dunnage use, informal reuse already taking place in the current system, and optimistic assumptions regarding reverse-logistics efficiency and RTI lifetime, are more likely to reduce the apparent benefit of reusable packaging than to increase it. Since the modeled cut-off benefit is already close to break-even, these effects further reduce confidence that a large-scale reusable-packaging system would deliver a meaningful emissions reduction under realistic operating conditions.

This does not mean that packaging should be ignored within HMC's sustainability agenda. On the contrary, the study makes packaging visible as a distinct emissions source within offshore logistics and shows how it can be assessed in a structured way despite incomplete data. It also identifies where the dominant packaging burdens lie, particularly in supplier-delivered pallets and in dunnage-supported shipments associated with internal equipment flows. The main practical implication is therefore not that HMC should fully replace the existing system, but that any intervention should be selective, targeted, and operationally justified.

In this respect, reusable dunnage appears more promising than a broad replacement of boxes, cartons, or pallets. A limited deployment of reusable composite dunnage for use in the yard and onboard vessels may therefore be a more realistic direction for future investigation than a company-wide reusable-packaging system. More generally, the study suggests that the environmental case for reuse in offshore logistics is conditional rather than automatic, and that this should be reflected in HMC's future circularity efforts.

6.6. Academic contributions of the study

The main academic contribution of this thesis lies in the development of a structured methodology for assessing packaging-related greenhouse-gas emissions in a logistics system where packaging characteristics are not directly recorded and operational data are incomplete. Rather than relying on aggregated annual estimates, assumed packaging mixes, or simplified transport assumptions, the study demonstrates how ERP-derived package-flow records can be translated into a package-level environmental model through a combination of package interpretation rules, transport reconstruction, packaging substitution logic, end-of-life modelling, and targeted yard validation.

More specifically, the thesis addresses a recurring challenge in applied environmental assessment: in many industrial settings, the limiting factor is not the complete absence of data, but the absence of the physical detail needed to construct a meaningful inventory. This study shows how incomplete administrative logistics data can nevertheless be transformed into a structured packaging inventory suitable for comparative greenhouse-gas assessment. In doing so, it contributes a transparent approach for linking operational records to packaging mass estimates, transport burdens, and end-of-life scenarios under explicit and testable assumptions.

A second academic contribution lies in the study's treatment of data-constrained comparative assessment. The framework does not assume that packaging information is directly available, but instead reconstructs it through an interpretation of package records and their logistics context. This is methodologically relevant because it reflects a common problem in real industrial systems: environmental assessment often depends on translating partial administrative data into physically meaningful model inputs. The thesis therefore contributes not a universally deployable model, but a replicable modelling logic for situations in which packaging systems must be inferred rather than directly observed.

A further contribution lies in the generalizability of the framework. Although the parameterization developed in this thesis is specific to HMC, the broader methodological logic is transferable to other logistics environments characterized by heterogeneous shipments, incomplete packaging records, and complex transport chains. The framework is therefore potentially relevant not only to offshore logistics, but also to other sectors involving project cargo, industrial equipment flows, and mixed packaging configurations. In methodological terms, the study demonstrates how packaging-related emissions can be assessed in operational environments where data quality is constrained, but where sufficient administrative structure exists to support a transparent reconstruction approach.

The academic contribution of this thesis is therefore primarily methodological. It does not propose a universally valid result about reusable packaging, but it does provide a structured and transferable framework for conducting packaging-related emissions assessments in real-world logistics systems with imperfect data availability.

7

Conclusion and Recommendations

7.1. Conclusion

This thesis set out to answer the following central research question:

> *How can the greenhouse-gas impact of packaging in the logistics operations of an offshore contractor be assessed, and to what extent can a reusable packaging system reduce that impact?*

Overall, the study shows that the greenhouse-gas impact of packaging in offshore logistics can be assessed through a structured comparative framework that combines ERP-derived package-flow records, packaging-assignment rules, transport reconstruction, end-of-life modelling, and targeted yard validation. Applied to the case of Heerema Marine Contractors, this framework shows that reusable packaging is not robustly superior to the current system. Under cut-off accounting, the reusable system yields only a marginal net emissions benefit, while under system-expansion accounting it performs worse than the single-use baseline. The study therefore concludes that reusable packaging cannot be assumed to reduce packaging-related GHG emissions in this context, and that any potential benefit is highly dependent on packaging type, destination, end-of-life accounting, and reverse-logistics performance.

Answer to Subquestion 1

How can the mass of packaging material used in the current single-use packaging system be estimated?

The mass of packaging material can be estimated by reconstructing packaging configurations from administrative logistics data. In this study, ERP package records were translated into packaging mass estimates using package type, gross weight, density assumptions, and assignment rules for pallets, dunnage, cartons, boxes, and foil. This approach made it possible to estimate the packaging mass of the current system despite the absence of direct packaging records. The resulting baseline showed that the packaging system is dominated by wooden pallets and dunnage, with the majority of packaging mass associated with purchase-order packages rather than internal packages.

Answer to Subquestion 2

What LCA methodology is appropriate for estimating the greenhouse-gas impact of packaging materials in this offshore logistics domain?

A comparative attributional LCA framework focused on greenhouse-gas emissions was found to be appropriate for this case. The framework combines package-level production, transport, and end-of-life emissions using open-access emissions factors and geographically differentiated waste-treatment assumptions. Because end-of-life treatment proved highly influential, both cut-off and system-expansion accounting approaches were applied. This showed that the selected accounting perspective has a major effect on the result and should therefore be treated as a central methodological choice rather than a secondary modelling detail.

Answer to Subquestion 3

To what extent does the greenhouse-gas impact of the packaging system change when reusable packaging is introduced in place of the current single-use system?

The results show that the change in greenhouse-gas impact is limited and highly context-dependent. Under cut-off accounting, the modeled reusable system provides only a small net emissions benefit over the study period. Under system expansion, the same substitution leads to a net emissions disadvantage. The comparative outcome also differs strongly by destination and packaging category. Boxes perform poorly under both accounting approaches, pallets show only limited benefit, and dunnage appears to be the most promising category under cut-off accounting. However, sensitivity analysis and broader uncertainty considerations show that even this benefit is not robust under realistic operating conditions.

Taken together, the answers to these subquestions show that the framework developed in this thesis is suitable as a comparative decision-support tool for packaging assessment in offshore logistics, but that the case for a broad transition to reusable packaging at HMC is weak on greenhouse-gas grounds alone. The results instead support a more selective and cautious interpretation, in which any future reusable-packaging intervention should be assessed carefully by packaging type, destination, and operational setting.

7.2. Recommendations

Recommendations for HMC

Based on the results of this study, a broad rollout of reusable packaging across the HMC logistics system is not recommended at this stage. The modeled cut-off benefit is too small to provide a robust justification for system-wide implementation, while the system-expansion result is clearly unfavourable. When combined with the practical uncertainties and the limited share of packaging directly under HMC control, the environmental case for a full transition remains weak with respect to reducing GHG emissions.

Instead, HMC should adopt a more selective and evidence-based approach to packaging improvement. In particular, reusable dunnage appears more promising than reusable boxes, cartons, or pallets and may warrant targeted exploration in the yard and onboard-vessel context. Any such intervention should be treated as a focused pilot rather than as a broad strategic shift.

A first practical recommendation is therefore to improve packaging-data visibility before pursuing further implementation decisions. Better tracking of packaging type, reuse events, support materials, and return flows would significantly strengthen future assessments and reduce the uncertainty associated with inferred packaging inventories. In particular, tracking the informal reuse of pallets, dunnage, and boxes in the current system would help establish a more realistic baseline against which any reusable alternative could be judged.

A second recommendation is to prioritize packaging interventions only where HMC has meaningful operational influence. Since most packaging mass enters the system through supplier-delivered purchase-order packages, internal packaging changes alone can only affect a limited share of the total burden. If packaging is to become a more active part of HMC's circularity strategy, supplier engagement and standardization of inbound packaging would likely be necessary.

A third recommendation is that any future packaging initiative should be evaluated not only on greenhouse-gas performance, but also on operational feasibility and broader environmental trade-offs. Before any scaled implementation is considered, a more detailed assessment would be required to examine tracking requirements, damage and loss rates, storage implications, reverse-logistics costs, and non-GHG environmental impacts associated with different packaging materials.

Recommendations for future research

Future research should first address the main uncertainties identified in this study. The most important priority is quantifying reuse already taking place in the current packaging system. Since informal reuse of wooden transport items is likely to reduce the apparent advantage of reusable alternatives, a clearer understanding of this baseline behaviour is essential for more robust comparison.

A second priority is to improve the representation of packaging from operational data. Further work could focus on reducing uncertainty in package-assignment rules, especially for dunnage-supported shipments, and on capturing consolidation practices such as palletization and foil use more explicitly. This would strengthen the physical realism of the package inventory and reduce dependence on simplified assumptions.

A third priority is to extend the assessment beyond greenhouse-gas emissions. While the present study was intentionally aligned with a GHG-focused corporate reporting perspective, future work could examine non-climate impacts such as resource use, toxicity, and waste-management externalities in order to provide a more complete environmental comparison between wood-based and plastic-based packaging systems.

A fourth priority is to integrate the environmental framework with a more detailed operational and economic model. This could include RTI fleet sizing, damage and loss behaviour, inspection and cleaning requirements, reverse-logistics design, and implementation cost. Such an extension would make it possible to evaluate not only whether reusable packaging can reduce emissions, but also whether it is operationally and economically viable in a project-based offshore logistics setting.

Finally, future work could explore the transferability of the framework beyond the HMC case. The methodological logic developed here is potentially relevant to other offshore contractors and to other industrial logistics systems characterized by heterogeneous shipments, incomplete packaging records, and complex transport chains. Applying the framework to additional cases would help test its robustness and clarify under what conditions reusable packaging can provide meaningful environmental benefit.

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A

Academic Paper based on Report

Assessing Packaging Systems in Offshore Logistics

A comparative framework for evaluating GHG emissions from single-use and reusable packaging

A. Laghate, A. Napoleone, D. Biegel and F. Schulte

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Abstract

This paper develops and applies a comparative decision-support framework to assess the greenhouse-gas (GHG) impact of packaging in the logistics operations of an offshore contractor and to evaluate the extent to which reusable packaging can reduce that impact. The study is based on Heerema Marine Contractors (HMC), where packaging is recorded only at a coarse administrative level in the enterprise resource planning system. To address this limitation, historical package-flow records from 2012–2025 were translated into a package-level environmental model through route reconstruction, packaging-system interpretation, transport-item assignment rules, and targeted yard validation.

The framework compares the existing single-use packaging system with functionally equivalent reusable alternatives under consistent assumptions for production, transport, and end-of-life treatment. Two end-of-life accounting approaches, cut-off and system expansion, are applied in parallel, and sensitivity analysis is used to test the influence of reverse logistics and reusable transport-item lifetime.

The results show that the current packaging system is dominated by wood-based transport packaging, particularly pallets and dunnage. Across the analytical dataset, the estimated total mass of single-use packaging was 1546 mt, with associated emissions of 1141 mt CO_2eq under cut-off accounting and 783 mt CO_2eq under system expansion. For the in-house subset, the reusable system yields only a marginal net emissions benefit of 4.3 mt CO_2eq under cut-off accounting, while under system expansion the result reverses to a net emissions disadvantage of 101.5 mt CO_2eq. Sensitivity analysis shows that the comparative result is more strongly influenced by reverse logistics than by reusable transport-item lifetime, with the baseline case lying close to the break-even boundary. Reusable packaging should therefore be understood as a conditional and context-dependent emissions-reduction option rather than an inherently superior alternative.

Introduction

Context and literature background

Packaging is an essential but often overlooked component of industrial logistics systems. In offshore contractor logistics, packaging is used to contain, protect, consolidate, identify, and handle goods such as project equipment, spare parts, crew provisions, and operational supplies as they move through geographically dispersed networks of yards, suppliers, ports, vessels, and offshore locations. In a predominantly single-use system, this packaging contributes both to material waste and to the greenhouse-gas (GHG) burden associated with logistics operations.

This issue is relevant within the broader transition from linear to circular material systems. Circular-economy (CE) models aim to reduce raw-material demand and waste generation by retaining value within the system for as long as possible[1, 2, 3]. Within this logic, reuse is particularly important because it preserves the function of a product or asset more directly than downstream strategies such as recycling or energy recovery. For transport packaging, this principle is especially relevant at the secondary and tertiary levels, where pallets, crates, transport boxes, containers, and dunnage perform transport and handling functions rather than direct product-contact functions[4, 5, 6].

The literature generally presents reusable packaging as a promising CE strategy, but not as an unconditional environmental improvement. Coelho et al. describe reusable packaging as a means of slowing and narrowing resource flows, while emphasizing that its environmental performance depends strongly on system design, transport distance, return rate, pooling, and implementation conditions[4]. Bradley and Corsini reach a similar conclusion in their review of reusable secondary and tertiary packaging systems, arguing that reusable packaging should not be assumed to be more sustainable than single-use alternatives without context-specific assessment[5]. Katsanakis et al. further stress that returnable transport items (RTIs) should be understood not merely as packaging assets, but as elements of a broader lifecycle management system involving circulation, repair, reuse, recovery, and governance[6]. Reuse, in other words, is not only a material substitution, but also a logistics-system intervention.

Comparative case studies reinforce this point. Koskela et al. compared reusable HDPE plastic crates with recyclable corrugated cardboard boxes in a bread distribution system and found that the recyclable cardboard system performed better across the impact categories considered under the case assumptions, with transport identified as a dominant contributor and both weight and transport distance strongly affecting the outcome[7]. Del Borghi et al. reached a different result in a comparative study of food crates, showing that reusable plastic crates could perform better when sufficient reuse cycles and an effective recovery system were achieved, while transport distance and recycling assumptions still exerted a strong influence on results[8]. At a broader level, Bradley and Corsini identify return rate, supply-chain length, standardization, customer retention, and system design as major determinants of reusable-packaging sustainability[5]. These studies show that comparative outcomes are highly case-specific and cannot be generalized without attention to package-flow conditions and system organization.

A further theme in the literature is that comparative results are shaped not only by the packaging systems being compared, but also by the methodological choices used to model them. Ekvall distinguishes attributional life cycle assessment (ALCA), which estimates the share of environmental burdens attributable to a product system, from consequential life cycle assessment (CLCA), which estimates how total burdens change as a result of a decision[9]. For packaging comparisons, one of the most important methodological issues is the treatment of end-of-life (EOL) burdens and credits. Vogtländer describes cut-off and system-expansion logic as two internally consistent but analytically different ways of allocating burdens and benefits related to recycling and energy recovery[10]. In packaging systems with substantial recycling or waste-to-energy potential, this choice can narrow, eliminate, or reverse the apparent benefit of reuse[9, 10, 8]. EOL accounting should therefore not be treated as a minor technical detail, but as a central determinant of comparative outcomes.

The literature also identifies several recurring drivers of reusable-packaging performance. Reverse logistics burden is one of the most important, because reusable systems introduce additional transport, repositioning, and empty backhaul requirements[5, 7, 8]. Realized service life is another, since production impacts can only be distributed effectively if reusable assets remain in circulation for enough cycles[4, 5, 6]. A third driver is system organization. Standardization, pooling, fill rate, and operational coordination can reduce unnecessary return trips and improve the efficiency of circulation[5, 11]. Dubisz et al. show, for example, that standardizing reusable packaging in an internal automotive supply chain reduced the number of shipments and lowered transport-related CO_2 emissions by changing the reverse-logistics structure[11]. Taken together, these studies suggest that reusable packaging performance is governed not only by material choice, but by the extent to which the surrounding logistics system supports efficient circulation.

Most of the reusable-packaging literature, however, is concentrated in sectors with relatively repetitive and standardized flows, such as food distribution, pallet systems, consumer goods, and automotive logistics[4, 5, 6, 11, 12]. Offshore contractor logistics differs materially from these settings. Package flows are heterogeneous and project-based, routes are global and often irregular, return opportunities are fragmented across multiple actors, and packaging characteristics are not systematically recorded in enterprise resource planning (ERP) systems[5, 6, 13]. The resulting research gap is therefore not only the lack of offshore-specific reusable-packaging studies, but also the lack of a comparative framework suited to heterogeneous logistics flows and incomplete operational data.

Problem description

This gap is directly relevant to Heerema Marine Contractors (HMC), an offshore contractor based in the Netherlands. HMC specializes in offshore construction projects, particularly the transport, installation, and removal of offshore infrastructure, and supports these activities through a global logistics chain serving vessels, ports, yards, and offshore locations[14]. These operations are supported by highly specialized and capital-intensive marine assets, which in turn place strong demands on logistics reliability, timing, and material availability[14]. Packages containing project equipment, spare parts, crew provisions, and operational supplies are often transported globally and well in advance of use, meaning that packaging is a necessary supporting element rather than a dispensable auxiliary feature.

Within HMC's broader sustainability strategy, packaging is a relevant intervention point because it is necessary for logistics, contributes to waste generation, and represents a distinct but previously unquantified source of greenhouse-gas emissions.[15]. Offshore operations generated 10,690 m^3 of waste in 2024, with operational waste, domestic waste, and plastic waste forming the largest reported categories[15]. Although the packaging share is not separately reported, packaging disposal forms part of this broader waste stream. In a predominantly single-use system, this leads not only to material loss, but also to missed opportunities to retain packaging within the logistics chain through reuse.

The practical problem is that the current packaging system and its associated emissions have not previously been quantified in a structured way within the company. A central challenge is that the ERP system records packaging only at a relatively coarse level. Package records contain unit-of-measure (UOM) categories such as cartons, boxes, pallets, bundles, and individual items, but do not systematically record exact dimensions, material composition, or the physical use of supporting transport items. This makes it difficult to determine both the current mass of packaging used in the logistics system and the emissions associated with that packaging.

The problem is further complicated by the nature of offshore logistics. HMC operates in a project-based environment in which goods are shipped to ports, yards, vessels, and offshore locations under varying logistical conditions. Packaging therefore differs not only by shipped item, but also by route, destination, and handling requirement. As a result, the environmental performance of reusable packaging cannot be assessed through generic assumptions alone, but must be evaluated in the specific operational context in which it is intended to function.

This creates the need for a comparative framework that can quantify the current single-use packaging system, define functionally equivalent reusable alternatives, and assess the relative GHG emissions of both systems under realistic case-specific assumptions. In addition, because reusable packaging performance depends on uncertain parameters such as reverse logistics burden and transport-item lifetime, the framework must also be able to test the sensitivity of the comparative results to these assumptions.

Objective and contributions

The objective of this paper is to develop and apply a comparative decision-support framework for evaluating single-use and reusable packaging systems in the logistics operations of an offshore contractor. The study focuses on GHG emissions and uses HMC as an empirical case through which the framework is implemented and tested.

The paper aims to make the following contributions:

1. It provides an offshore-specific comparative assessment of single-use and reusable packaging in a logistics context that is largely absent from the reusable-packaging literature.
2. It develops a case-based framework for translating incomplete administrative logistics records into a physically interpretable packaging model through route reconstruction, package assignment, validation, and comparative emissions modeling.
3. It shows how methodological choices, particularly end-of-life accounting, can materially affect the comparative result between single-use and reusable packaging systems.
4. It identifies the operational conditions that most strongly govern reusable-packaging performance in the case study, with particular attention to reverse logistics burden and reusable transport-item lifetime.

Methodology

Research design and assessment perspective

This study adopts a case-based comparative research design to evaluate the greenhouse-gas (GHG) impact of packaging in offshore contractor logistics. The research combines two complementary components. First, a general methodological framework is developed to define how packaging systems can be compared using life-cycle assessment principles, including the choice of assessment perspective, the definition of system boundaries, the specification of the functional unit, and the formulation of the comparative emissions model. Second, this framework is applied to a single case study at Heerema Marine Contractors (HMC), where historical logistics records, packaging assignment rules, case-specific assumptions, and validation steps are used to operationalize the model in an industrial setting.

The core methodological approach is a comparative analysis of an existing single-use (SU) packaging system and a proposed reusable packaging system. The objective is to quantify the GHG emissions associated with both systems and compare their relative performance under consistent assumptions. Within this framework, a transport cycle is defined as the path a package follows through the logistics network, beginning with loading and closure, continuing through transport to the destination, and ending when the package is received and unpacked. A single-use packaging system therefore consists of transport items used for one transport cycle before disposal and end-of-life (EOL) processing, whereas a reusable packaging system consists of reusable transport items (RTIs) designed to complete multiple transport cycles before final disposal. Reusable packaging must therefore be assessed at the system level rather than at the level of an individual packaging item.

A central requirement of the framework is functional equivalence between the two systems. For each observed package flow, the historical SU packaging configuration is compared with a reusable configuration designed to provide the same transport, protection, and handling function. This ensures that differences in environmental results are attributable primarily to differences in the packaging systems rather than to differences in route, destination, or delivery function.

Attributional and consequential life cycle assessment represent two distinct approaches to environmental modeling. Attributional LCA quantifies the environmental burdens associated with a defined product system, whereas consequential LCA seeks to estimate the wider environmental consequences of a change from one system to another[9]. Since the present study does not model broader market responses, marginal supply effects, or wider economic consequences, an attributional approach is considered more appropriate. The environmental scope is limited to GHG emissions expressed as carbon dioxide equivalent (CO_2eq). Other impact categories are excluded. The analysis should therefore be understood as a GHG-focused comparative life-cycle assessment rather than as a full multi-impact LCA.

Functional unit and system boundaries

A clearly defined functional unit is required to ensure a consistent comparison between the SU and reusable packaging systems. In this study, the functional unit is defined as an individual observed package flow within the logistics system, represented by the movement of a package from its origin to its final destination under the recorded logistics conditions. Each package may consist of one or more transport items required to transport the relevant goods. This definition was selected because it preserves the diversity in packaging configurations, destinations, and transport pathways observed in the historical logistics data.

The system boundary includes packaging production, transport, and end-of-life treatment. For the SU system, the full burden of each transport item is assigned to the package flow in which it is used. For the reusable system, production and end-of-life burdens are amortized across the assumed service life of each RTI, while transport burdens additionally include reverse logistics. Dynamic fleet-management effects such as replacement of lost or damaged RTIs are excluded, as the analysis is limited to comparative environmental performance within the defined scope rather than dynamic asset management.

EOL treatment has a significant influence on packaging GHG performance and is treated explicitly. Three EOL routes are considered: landfill, incineration with energy recovery, and recycling. These routes differ not only in their direct emissions, but also in whether they generate secondary outputs that may displace virgin material production or conventional energy generation. Within an attributional framework, the key methodological issue is how the burdens and credits associated with these routes are allocated. Two approaches are applied in this study. In the cut-off approach, the assessed system carries the direct burdens associated with disposal and treatment, while any downstream benefits from recovered material or recovered energy are assigned to the next product system. In contrast, the system-expansion approach with avoided burden assigns credits to the assessed system where recovered material or energy is assumed to displace virgin production or conventional energy generation[10]. Figure 1 illustrates the difference between these two accounting perspectives and the corresponding system boundaries used in the study.

Comparative modelling framework

For each package flow, the observed package record is translated into a material inventory consisting of one or more transport items, each with an associated material type and unit mass. This inventory forms the basis for the production, transport, and EOL calculations.

For the baseline characterization of the current packaging system, both internally prepared packages and purchase-order packages are included, since both contribute to the overall packaging burden observed in the logistics system. For the comparative assessment of reusable packaging, however, the analysis is restricted to internally prepared package flows. This scope restriction was adopted because packaging choice is directly controlled by HMC only for packages prepared within the company-controlled logistics system. Purchase-order packages delivered by third-party suppliers were therefore excluded from the substitution analysis in order to avoid overstating the practical intervention potential of reusable transport items.

Under this representation, the comparative model evaluates the extent to which reusable transport items can substitute single-use packaging within the part of the logistics system that lies under direct operational control. This distinction is important because it reflects the actual intervention boundary of the case study and ensures that the comparative result is not inflated by packaging flows that HMC cannot realistically redesign unilaterally.

The package-level emissions model is formulated as the sum of production, transportation, and end-of-life burdens:

$$E_p = E_p^{\text{prod}} + E_p^{\text{trans}} + E_p^{\text{eol}} \tag{1}$$

Production emissions are calculated from cradle-to-gate emission factors. For a packaging item i with

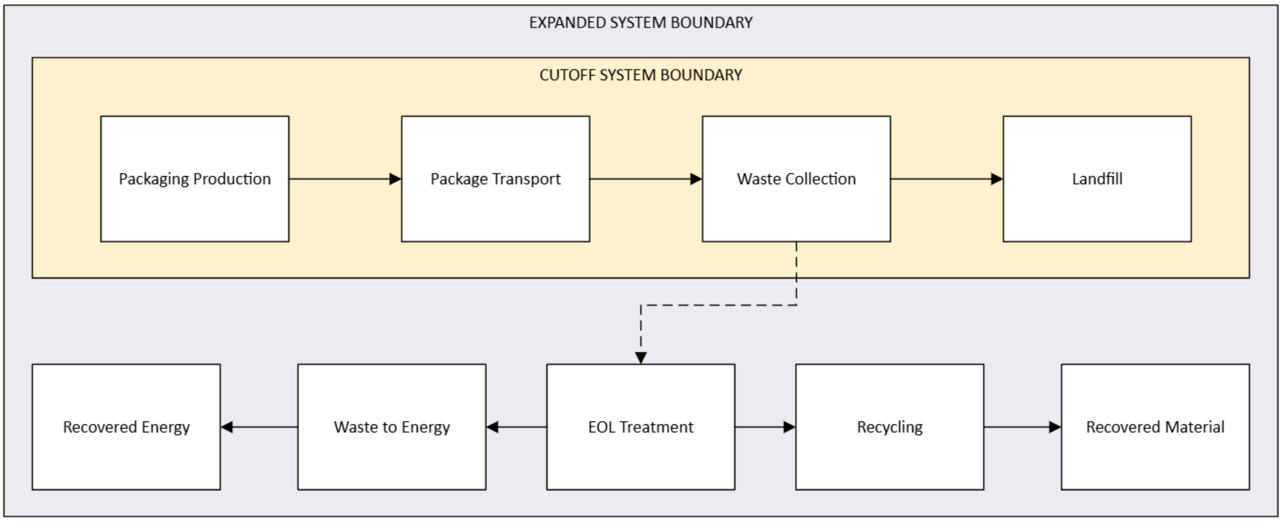

Figure 1: *Conceptual system boundaries used for packaging assessment under cut-off accounting and system expansion with avoided burden. Under cut-off accounting, the assessed system includes direct disposal and treatment burdens but excludes credits from recovered material and recovered energy. Under system expansion, recovered outputs are included through avoided-burden credits.*

mass m_i, production factor α_i, and service life L_i, the burden assigned to an individual package flow is

$$E_i^{\text{prod}} = \frac{m_i \alpha_i}{L_i} \tag{2}$$

where $L_i = 1$ for SU items and $L_i > 1$ for reusable transport items. Summing over all packaging items linked to a package record yields the total production burden for that package.

Transportation emissions are calculated from the total packaging mass associated with a package record and a route-specific transport emission factor. For SU packaging, only forward logistics are included. For reusable packaging, reverse logistics are represented by a multiplier λ applied to the forward transport burden:

$$E_p^{\text{trans,SU}} = q_p M_p \tau_p \tag{3}$$

$$E_p^{\text{trans,RU}} = q_p \lambda M_p \tau_p \tag{4}$$

where q_p is the package quantity, M_p is the total packaging mass, and τ_p is the route-specific transport emission factor. In the baseline case, $\lambda = 1.8$.

EOL emissions are modeled using waste-treatment fractions and method-specific emission factors. For each package record, the effective EOL factor depends on the destination-specific waste-treatment fractions and the selected accounting approach. As in the production model, EOL burdens of reusable transport items are distributed across expected service life.

The comparative GHG benefit of reusable packaging relative to single-use packaging is defined as

$$B_p = E_p^{\text{SU}} - E_p^{\text{RU}} \tag{5}$$

where a positive value indicates that the reusable system has lower emissions than the SU system for the package flow considered. Total system-level results are obtained by aggregation across all relevant package records.

Transport and end-of-life modelling choices

Packages in the analyzed logistics system are transported by sea, air, or road between globally distributed addresses. Transport distances are calculated for each segment of the observed route and combined with mode-specific emission factors to estimate the burden attributable to the packaging itself.

Sea transport distances are estimated using the SeaRoute Python library, which generates navigable maritime routes between two coordinates while accounting for realistic routing around landmasses and the use of major waterways such as the Suez and Panama canals[16]. Air transport distances are estimated as great-circle distances using the Haversine formula, consistent with standard freight-emissions practice[17]. Road transport distances are approximated as straight-line distance multiplied by a detour factor of 1.3, consistent with reported values for mixed transport networks[18, 19]. Offshore deliveries are treated separately using a fixed proxy distance of 150 km, representing a typical offshore delivery run within the shallow coastal shelf region.

EOL emissions are modeled using material-specific emission factors for landfill, incineration with energy recovery, and recycling. Because waste materials do not enter a single route exclusively, each material is assigned a set of waste-treatment fractions that distribute waste across the three EOL routes. The total EOL burden is then calculated as the weighted sum of the method-specific factors and the corresponding fractions. Waste-treatment fractions are assigned on a destination-specific basis using the best available waste-management data, with country-level fractions used as the primary basis for onshore destinations and contractor-specific fractions applied where more specific information is available.

Sensitivity analysis

The comparative GHG performance of SU and reusable packaging depends on several assumptions that are subject to uncertainty. Sensitivity analysis is therefore used to test the robustness of the comparative outcome and identify the assumptions that exert the greatest influence on results.

Two operational parameters are treated as the principal sensitivity variables. The first is RTI service life, expressed as the number of transport cycles completed before disposal. This parameter is important because it determines how production and EOL burdens are distributed across repeated use. A longer service life reduces the burden assigned to each package flow, whereas a shorter service life increases it. The second is the reverse logistics factor, which determines the total transport burden assigned to reusable packaging by representing the additional emissions associated with return transport. This parameter captures uncertainty related to consolidation efficiency, route directness, and overall return-transport intensity.

In addition to these operational parameters, the study applies both cut-off and system-expansion EOL accounting in order to test the influence of end-of-life allocation on the comparative result.

The sensitivity outputs are interpreted through two complementary views. First, one-at-a-time sensitivity analysis is used to isolate the effect of individual parameters while holding all others at baseline values. Second, the combined effect of RTI service life and reverse logistics is evaluated across the tested parameter space in order to identify the conditions under which reusable packaging provides a positive or negative comparative result. This combined sensitivity is presented as a contour plot of normalized net benefit.

The methodological elements described in this section define the general analytical framework used in the study. The following section describes how this framework was implemented in the specific case of HMC using historical logistics data, package-flow reconstruction, packaging-system representation, and case-specific validation.

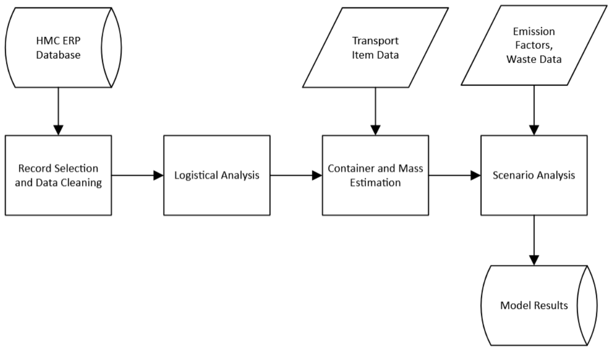

Figure 2: *Workflow used to implement the comparative packaging assessment framework in the HMC case study.*

Case Study

Case context

This section operationalizes the methodological framework presented in Methodology section in the specific context of Heerema Marine Contractors (HMC). HMC is an offshore contractor operating in a project-based logistics environment in which package flows vary across projects, vessel locations, destinations, and operational phases. Compared with more stable manufacturing settings, offshore logistics is characterized by heterogeneous goods movements, irregular routing, and a mix of onshore and offshore delivery conditions. These features make packaging-system assessment more complex, but also make the case analytically relevant for testing reusable packaging in a non-standard logistics setting.

HMC manages its logistics activities through an enterprise resource planning (ERP) system that records package, transport, and inventory information. Within this system, logistics flows are represented through related records for parts, packages, container packages, and transport movements. These data form the basis for reconstructing historical package flows and comparing the existing single-use packaging system with equivalent reusable alternatives.

Data basis and analytical scope

The case study is based primarily on internal logistics data extracted from the HMC ERP system. The principal datasets used in the analysis are package records, transport records, delivery-address data, parts data, material-group classifications, and a custom *Packagelines* query used to identify the transport legs associated with each package and to reconstruct complete package routes[20]. Because detailed logistics is typically not planned more than one year in advance and future project data are commercially sensitive, historical data were used as the empirical basis for the study. Figure 2 shows the high level workflow used to transform ERP data into useful model results.

The ERP system was implemented in March 2011. To ensure that only complete years were included, the analysis period was defined from 1 January 2012 to 1 January 2025. This period was treated as a historical representation of the logistics system rather than as a forecast of future activity. The use of historical ERP data is appropriate here because the objective is to compare packaging systems under realistic operating conditions observed in practice.

The analysis was restricted to package flows dispatched from the HMC yard in Vlissingen (`HMCVL`), which defines the company-controlled logistics boundary considered in this study. More than 60% of packages in the ERP records were dispatched from three Dutch logistics locations, but only Vlissingen lies fully within the case-study boundary. The baseline characterization of packaging mass and emissions is performed for the full analytical dataset resulting from this selection. The comparative assessment of reusable packaging is restricted to the in-house subset of package flows, since packaging choice is directly controlled by HMC only for packages prepared within the company-controlled logistics system. Externally supplied purchase-order flows were therefore excluded from the substitution analysis.

Package-flow reconstruction

The purpose of the data-preparation step was to define the analytical dataset and reconstruct package routes from origin to final destination. The package table, transport table, and *Packagelines* query were used as the primary raw inputs. Administrative transport records were first cleaned, and where valid storage information was available, missing origin or destination fields were back-filled. Records that could not be linked to a meaningful physical movement were excluded. The cleaned transport table was then filtered to identify valid transports originating from Vlissingen, after which the associated packages were identified and their complete routes reconstructed.

Container packages, including shipping containers and skips, were excluded because they already represent reusable transport solutions and therefore fall outside the comparative substitution problem. In addition, packages with more than three route segments between origin and final destination were excluded to remove non-standard logistics patterns, particularly for specialized third-party equipment. The resulting analytical dataset contains package-level records together with associated route segments, origins, destinations, and transport modes.

For scenario purposes, package categories labelled `PO-RECEIPTS` were treated as supplier-controlled flows, whereas categories such as `TPC`, `VARIOUS`, and `LOOSE` were treated as internally prepared flows originating from the yard. This classification was used later to distinguish package flows included only in the baseline characterization from those included in the comparative reusable-packaging assessment.

Packaging-system representation

Because the ERP package records do not contain complete geometric and material information for the transport items used, the observed package UOMs first had to be interpreted as representative packaging classes before reusable substitutes could be assigned. The dominant package categories in the dataset were cartons, boxes, pallets, and item-like categories such as `EA` and `BND`. Not all UOMs were included directly in the comparative model. Categories were retained when they represented a meaningful share of package flows and could be represented through a comparable single-use and reusable packaging configuration. Categories were excluded where they already represented reusable transport items, occurred only rarely, or were outside the intended substitution problem.

A set of model transport items was then defined to represent the principal packaging formats. For cartons and boxes, Euronorm-compatible size classes were used so that single-use and reusable alternatives could be compared on a functionally equivalent geometric basis. Single-use pallets were represented using the standard EUR-pallet format, while reusable alternatives were represented using longer-life plastic pallets. Small reusable containers were represented using KLT-type load carriers and larger reusable containers using collapsible pallet boxes, primarily based on manufacturer specifications from Rajapack[21]. Material assumptions for wood, paper-based materials, plastics, and metals were assigned using literature, technical manuals, and manufacturer specifications[22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Reusable substitutes were assigned at UOM level in order to create a functionally equivalent reusable system. Cartons and boxes were replaced by reusable container classes of corresponding size, pallets by plastic pallets, and heavy or irregular item categories by pallet- or dunnage-based reusable substitutes depending on package gross weight. Stretch foil was treated separately because it is not directly recorded in the ERP but is known to be used in practice. In the baseline single-use system it was represented using LDPE stretch film, while a paper-based foil was used as the alternative material in the comparative model. Its comparative contribution remained small relative to the main transport-item categories.

Transport, environmental inputs, and validation

Transport-related emissions were estimated by geocoding the addresses contained in the ERP records, reconstructing route segments, and applying mode-specific distance and emissions calculations as defined in Methodology section. Sea distances were estimated using the SeaRoute library[16], air distances as great-circle distances consistent with freight-emissions practice[17], and road distances using a straight-line distance multiplied by a detour factor[18, 19]. Offshore deliveries were represented using a fixed offshore proxy distance.

Production and transport emission factors were taken from the DESNZ GHG conversion factors dataset[32], while end-of-life factors were taken from the WRAP CarbonWARM2 dataset[33]. Waste-treatment fractions were assigned on a destination-specific basis, primarily using country-level data from the World Bank What a Waste 2.0 dataset[34]. Offshore vessel-generated waste was treated separately using vessel incinerator guidance[35] and contractor-specific disposal information.

Because several elements of the comparative model rely on inferred packaging characteristics rather than directly recorded ERP fields, a validation study was conducted through a site visit to the HMC yard at Vlissingen and discussions with operational staff. Validation focused on the main estimation methods and assumptions used in the model, including carton and box density estimation, dunnage representation, stretch-wrap usage, and broader assumptions concerning package labels and disposal practice. Direct measurements were used where possible, while qualitative checks were used where validation depended on observed yard operations and practitioner knowledge. The resulting findings are used in the results section to assess the credibility and limitations of the case-specific modeling approach.

Results and Discussion

Validation and baseline interpretation

Because the ERP system does not record exact packaging dimensions, material compositions, palletization choices, or support-item usage directly, the credibility of the case model depends on whether the inferred package representations provide a reasonable approximation of actual yard practice. The validation results support the main package-representation logic used in the model, while also revealing one important limitation in the treatment of the current packaging system.

First, the yard visit confirmed that ERP package labels do not always correspond directly to the physical packaging configuration observed in practice. Generic UOM categories such as `EA`, `BND`, and `PCK` were often still handled using pallets or dunnage depending on the size, weight, and geometry of the shipped item. Smaller items were commonly placed on pallets, while larger or irregular items were supported using dunnage. This supports the modelling choice adopted in the case study to assign pallet- and dunnage-based packaging to these generic package classes, even where such support items are not explicitly visible in the ERP description.

Second, the validation led to targeted adjustment of key estimation rules. For cartons and boxes, the original density assumptions systematically overestimated package density. Comparison between measured and model-estimated package characteristics showed an average overprediction of approximately 0.3 kg/l, corresponding to about 65% of the observed values. After recalibration, the root-mean-square error was reduced to approximately 0.2 kg/l. Although this residual error remains non-negligible, a separate sensitivity analysis showed that varying the calibrated density values between 50% and 150% of baseline changed total single-use packaging emissions by less than 5%. Density calibration therefore improves record-level realism, but aggregate emissions results are only moderately sensitive to this parameter.

Validation of support materials further strengthened confidence in the reconstructed package inventory. For dunnage, the original 1% of gross weight rule was considered too high during the yard visit and was reduced to 0.5% of gross weight. Using this adjusted rule, the model predicted a total dunnage usage of 283 mt over the study period for internally prepared package flows, compared with an independent yard-based estimate of 273 mt. This corresponds to a percentage error of approximately +3%, indicating strong agreement at aggregate level and providing support for the adjusted dunnage assumption.

Foil use required a larger correction. Discussions with yard personnel indicated that approximately 10 rolls of stretch foil are used annually at the Vlissingen yard, corresponding to about 2080 kg over the full study period based on the relevant roll specifications[21]. By comparison, the original model predicted only 400 kg for internally prepared package flows over the same period. This discrepancy appears to arise because palletization and wrapping of cartons and loose items are not explicitly recorded in the ERP system. Since there was no reliable way to reconstruct this behavior directly from the available records, the yard estimate was treated as the more credible reference point and the modelled foil values were scaled by a factor of 5.

The most important validation finding, however, concerns the representation of the current system itself. The yard visit showed that the current HMC packaging system is not fully single-use in practice. Yard and vessel personnel already attempt to reuse pallets, wooden boxes, dunnage, and other packaging materials through backloading and local reuse wherever possible. Because this reuse is not tracked systematically and could not be quantified with sufficient confidence, it was excluded from the model and the baseline was retained as fully single-use. This was a pragmatic simplification, but it likely overstates the emissions of the current packaging system and therefore introduces a bias in favor of the proposed reusable alternatives. The comparative results should therefore be interpreted as potential gains relative to a conservative representation of current practice rather than as gains relative to a fully measured real-world baseline.

Current single-use packaging system: greenhouse-gas impact

Across the full analytical dataset, the estimated total mass of single-use packaging in the current logistics system was approximately 1546 mt. Of this total, around 444 mt originated from internally prepared package flows, while 1102 mt originated from supplier-delivered purchase-order packages. The baseline packaging system is therefore dominated by packaging entering through supplier-controlled inbound flows rather than by packaging prepared directly within the company-controlled logistics system. In material terms, the packaging burden remains overwhelmingly dominated by wood-based transport items, with much smaller contributions from carton and LDPE stretch foil.

This structure is also visible when the results are grouped into the main packaging categories used in the present paper. Pallets represent the largest mass contribution, followed by dunnage, while boxes, foil, and cartons contribute much smaller shares. The baseline packaging system should therefore be understood primarily as a wood-based transport-packaging system dominated by pallets and dunnage rather than by lighter packaging formats.

Figure 3 shows the greenhouse-gas emissions of the current single-use packaging system by grouped packaging category under cut-off and system-expansion accounting. Across the full study period, total emissions amount to 1141 mt CO_2eq under cut-off accounting and 783 mt CO_2eq under system expansion. In both cases, production and transportation emissions are identical, while the difference between the two totals arises entirely from the treatment of end-of-life emissions. Transportation is the largest positive contributor, followed by production. Under cut-off accounting, end-of-life adds a positive burden, whereas under system expansion the credited recovery of material and energy reduces the attributed end-of-life burden substantially.

The figure also shows that the baseline burden is concentrated in the pallet and dunnage categories. Under cut-off accounting, pallets are the largest contributor, followed by dunnage, while boxes, foil, and cartons remain much smaller. Under system expansion, the same overall ranking remains visible, but the attributed burdens of the dominant wood-based categories are reduced by avoided-burden credits. The current-system results should therefore be interpreted as a modeled packaging burden dominated by wood-based pallets and dunnage, while also showing that end-of-life accounting is a major determinant of the absolute GHG burden assigned to the existing single-use system.

Comparative performance of single-use and reusable packaging

The comparative assessment was restricted to the in-house subset of package flows. This differs from the baseline single-use characterization above, which considered the full analytical dataset. The restriction was adopted because reusable packaging is evaluated here as a substitution strategy within the company-controlled logistics boundary. Under the baseline reusable scenario, the reverse logistics multiplier was set to 1.8 and the RTI life multiplier to 1.0.

Net emissions benefit is defined here as the emissions of the single-use packaging system minus the emissions of the reusable packaging system. Positive values therefore indicate that reusable packaging performs better than the corresponding single-use configuration, while negative values indicate that the reusable system performs worse.

At aggregate level, the comparative result is close to break-even under cut-off accounting and unfavourable under system expansion. For the in-house subset, the reusable system yields a net emissions benefit of only 4.3 mt CO_2eq under cut-off accounting. Under system-expansion accounting, the result reverses and the reusable system performs worse than the single-use baseline by 101.5 mt CO_2eq. The main implication is therefore not that reusable packaging is generally better or worse, but that its performance depends strongly on the accounting treatment of end-of-life and on the logistics context in which it is deployed.

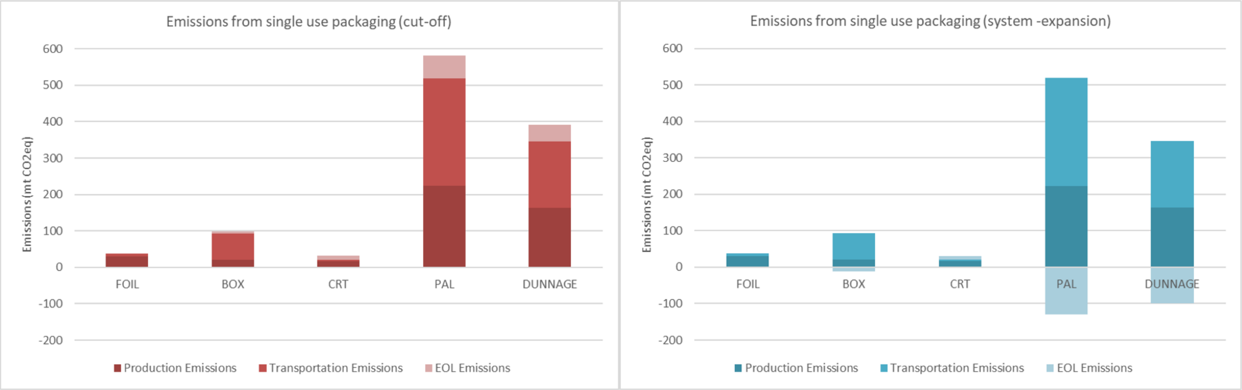

Figure 3: *Emissions from the current single-use packaging system by grouped packaging category under cut-off accounting (left) and system-expansion accounting (right). Each bar is decomposed into production, transportation, and end-of-life contributions.*

Figures 4 and 5 present the comparative results by destination country and grouped packaging category under the two accounting approaches. Under cut-off accounting, positive net benefit is concentrated in a limited number of destinations, most notably the Netherlands and the United States, while offshore destinations, Singapore, Taiwan, Mexico, and Trinidad and Tobago contribute negatively. Under system expansion, the country-level pattern changes substantially. The United States remains positive, but large negative contributions arise from offshore destinations, the Netherlands, Mexico, Singapore, and Taiwan. These results show that the comparative outcome is shaped jointly by the structure of the logistics network and by the destination-specific treatment of packaging waste.

The category-level pattern is equally important. Under cut-off accounting, dunnage provides the strongest positive contribution, especially in the Netherlands and the United States, while pallets provide only modest benefits and boxes are consistently unfavourable. Under system expansion, the positive contribution of dunnage largely disappears and becomes negative in several important destinations, while boxes remain consistently negative. This indicates that the aggregate comparative result is driven primarily by a trade-off between positive cut-off results for dunnage and consistently unfavourable results for boxes, with pallets contributing only modestly in comparison.

Taken together, the comparative results suggest that reusable packaging should be understood as a conditional emissions-reduction option rather than as a generally superior alternative. In the present case, the results do not support a strong greenhouse-gas case for a broad transition to reusable packaging, although they do suggest that selected packaging categories and destination contexts may still warrant further consideration.

Sensitivity analysis

The sensitivity analysis examined the effect of varying two reusable-system parameters: the reverse logistics multiplier and the RTI life multiplier. Because the baseline comparative result under cut-off accounting is already small, it is important to test how robust this result is to plausible variation in the main reusable-system assumptions. To isolate the influence of these operational variables, the sensitivity analysis was interpreted primarily through the cut-off model.

Figure 6 shows the combined effect of RTI life and reverse logistics on the normalized net benefit of reusable packaging. The contour plot indicates that the comparative result is much more sensitive to reverse logistics than to RTI life, as shown by the predominantly vertical orientation of the break-even boundary. The baseline scenario at a reverse logistics multiplier of 1.8 and an RTI life multiplier of 1.0 lies close to this boundary and yields a normalized net benefit of approximately 1%. This means that the cut-off result is not robustly positive, but instead lies close to the transition between favourable and unfavourable performance.

The most favourable tested combination yields a normalized benefit of approximately 13%, while increasingly burdensome return logistics quickly eliminate the benefit of reusable packaging even when RTI life is improved. At the opposite end of the tested range, the comparative result becomes clearly negative. RTI life still matters, since higher service life reduces the production and end-of-life burden assigned to each transport cycle, but its influence is secondary compared with the burden associated with returning empty containers.

This finding is consistent with the structure of the model. Reusable packaging only provides a greenhouse-gas advantage if the additional burden of reverse transport can be offset by distributing production and end-of-life burdens across enough cycles.

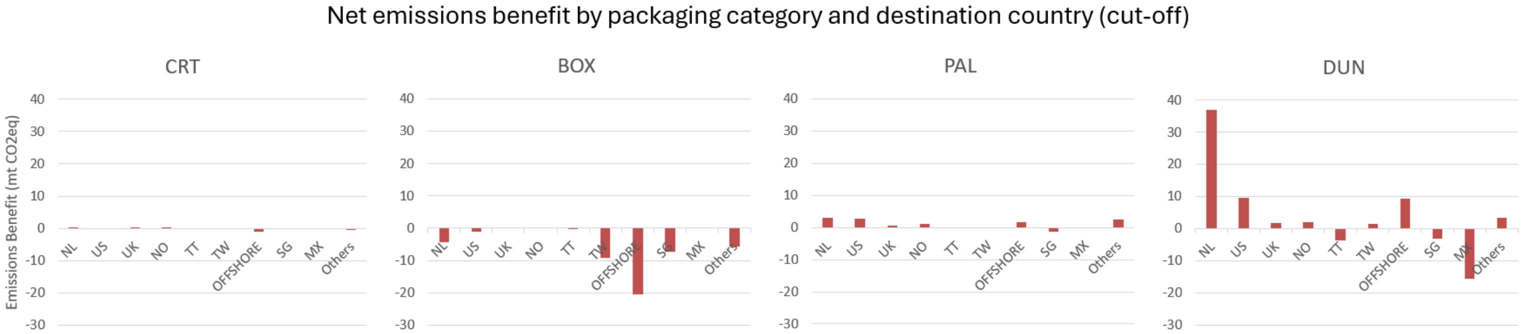

Figure 4: *Net emissions benefit of reusable packaging relative to single-use packaging by destination country and packaging category under cut-off accounting for the in-house subset. Positive values indicate an emissions benefit from reuse.*

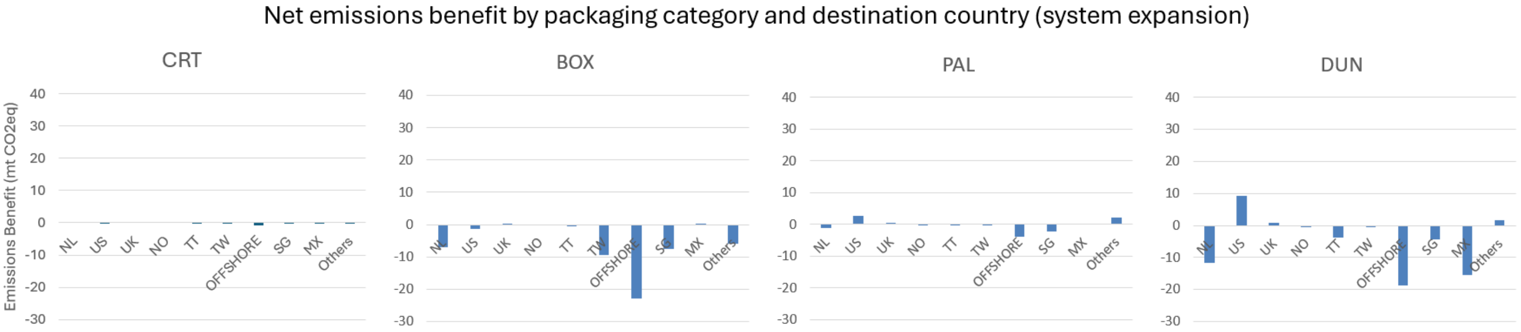

Figure 5: *Net emissions benefit of reusable packaging relative to single-use packaging by destination country and packaging category under system-expansion accounting for the in-house subset. Positive values indicate an emissions benefit from reuse.*

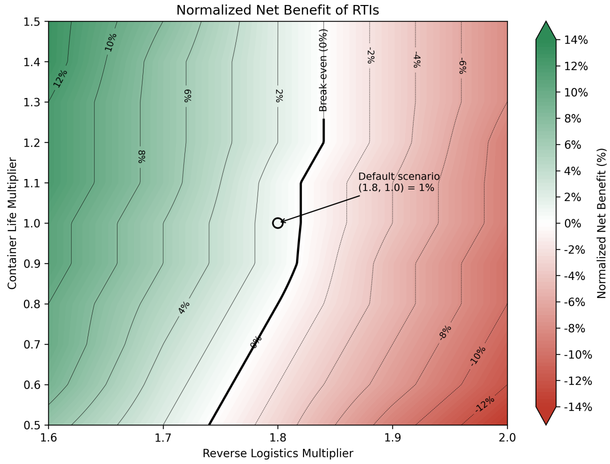

Figure 6: *Normalized net benefit of reusable transport items as a function of RTI life multiplier and reverse logistics multiplier under cut-off accounting. The baseline scenario is indicated on the contour.*

In offshore logistics, where return flows may be fragmented and routing can be irregular, the environmental success of reusable packaging therefore depends primarily on the efficiency of the return loop rather than on marginal improvements in theoretical RTI service life.

Implications and limitations

Taken together, the results show that the current HMC packaging system has a measurable greenhouse-gas burden that is dominated by wood-based pallets and dunnage. Reusable packaging can reduce this burden under some assumptions, but the result is strongly conditional on both end-of-life accounting and reverse-logistics performance. The framework therefore supports a more restrained interpretation than a simple circularity narrative: reuse is a potentially useful intervention, but not an inherently superior one.

From a practical perspective, the results do not support a strong case for a broad transition from the current packaging system to a formal reusable-packaging system. Even under cut-off accounting, which is the more relevant accounting perspective for the company's reporting context, the modeled benefit is only marginal. This weakens the strategic relevance of reusable packaging as a climate measure, especially when packaging-related emissions are viewed alongside the much larger direct emissions associated with vessel operations and other major operational sources. In addition, only a limited share of the total packaging burden is directly controlled by HMC, since most packaging mass enters the system through supplier-delivered purchase-order packages.

At the same time, the study does not suggest that packaging should be ignored. Rather, it shows that packaging is a distinct emissions source within offshore logistics and that it can be assessed in a structured way despite incomplete data. It also indicates that limited and selective interventions may still be justified. In particular, dunnage appears more promising than boxes, cartons, or pallets, especially under cut-off accounting and in specific destination contexts. The practical implication is therefore not that HMC should broadly replace the existing system, but that any packaging intervention should be selective, targeted, and operationally justified.

From a methodological perspective, the study shows that comparative packaging assessment is still possible even when packaging attributes are not directly recorded in operational databases. By combining route reconstruction, package-assignment rules, case-specific material assumptions, yard validation, and comparative emissions modelling, the framework translates incomplete administrative logistics data into a structured decision-support model. Its main value therefore lies not in the exact parameterization used for HMC, but in the methodological logic through which package flows can be reconstructed and compared under data-constrained conditions.

Several limitations constrain the strength of the claims that can be made. First, the framework depends on inferred packaging representations because the ERP system does not record exact dimensions, material composition, palletization practices, foil use, or support items systematically. Second, the analysis is limited to greenhouse-gas emissions and does not include a broader multi-impact environmental assessment or a full operational and economic evaluation. Third, the waste-treatment fractions and emission factors used in the model are based on geographically differentiated but still simplified proxy datasets and may not fully reflect the actual treatment of industrial packaging waste in all destinations. Finally, the study does not model implementation dynamics such as RTI procurement cost, loss and damage, cleaning requirements, storage, or administrative tracking. The results should therefore be interpreted as a comparative environmental assessment under defined assumptions rather than as a complete implementation or business case.

Conclusion

This paper developed and applied a comparative decision-support framework to assess the greenhouse-gas (GHG) impact of packaging in the logistics operations of an offshore contractor and to evaluate the extent to which a reusable packaging system could reduce that impact. Using historical ERP-derived package-flow data from Heerema Marine Contractors (HMC), the framework reconstructed package routes, estimated package-level material inventories, and compared the emissions of the existing single-use packaging system with those of functionally equivalent reusable alternatives under different accounting assumptions and operational conditions.

The results show that the current packaging system has a measurable GHG burden and is dominated by wood-based transport packaging, particularly pallets and dunnage. Across the analytical dataset, the estimated total mass of single-use packaging was approximately 1546 mt. The associated emissions amounted to 1141 mt CO_2eq under cut-off accounting and 783 mt CO_2eq under system-expansion accounting. The baseline burden is therefore driven primarily by wood-intensive support packaging rather than by lighter materials such as cartons or foil, while the difference between the two accounting results is determined mainly by end-of-life treatment.

The comparative assessment further shows that reusable packaging is not unambiguously preferable in this case. For the in-house subset, the reusable system yields only a marginal net emissions benefit of 4.3 mt CO_2eq under cut-off accounting, while under system expansion the result reverses and becomes a net emissions disadvantage of 101.5 mt CO_2eq. The comparative outcome therefore depends strongly on end-of-life accounting and cannot be interpreted as robustly favourable to reusable packaging. The results also vary substantially by destination and packaging category, with dunnage appearing more promising than boxes, cartons, or pallets under cut-off accounting, but with much of this advantage weakening or disappearing under system expansion.

Sensitivity analysis reinforces this interpretation. The contour results show that reusable-packaging performance is much more sensitive to reverse logistics than to RTI life. The baseline case lies close to the break-even boundary, indicating that the cut-off result is not robustly positive. This means that the environmental success of reusable packaging in offshore logistics depends primarily on the efficiency of the return loop rather than on modest improvements in theoretical service life.

Taken together, these findings suggest that reusable packaging should be interpreted as a conditional emissions-reduction option rather than as a generally superior alternative. In the HMC context, the results do not support a strong case for a broad transition to a formal reusable-packaging system on GHG grounds alone. Reusable packaging appears more relevant as a selective intervention for specific packaging categories and operational contexts than as a broad decarbonization strategy.

Methodologically, the study shows that packaging-related emissions can be assessed even when packaging characteristics are not directly recorded in operational databases. By combining route reconstruction, package-assignment rules, validation, and comparative emissions modelling, the framework provides a structured approach for translating incomplete administrative logistics data into a comparative packaging assessment. Its main contribution therefore lies not in the specific parameterization used in this case, but in the broader methodological logic it offers for data-constrained logistics systems.

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Supplementary Modelling Factors

This appendix reports the modelling assumptions most directly needed to interpret the case implementation and reproduce the main comparative results. Only the load-bearing assumptions used in the paper are retained here. Detailed ERP cleaning logs, full transport-item catalogues, and the full country-level waste-fraction tables are omitted from the article version.

Key package-assignment assumptions

Main reusable transport items

The reduced RTI set retained in the article appendix is shown in Table 2. These are the principal reusable substitutes used in the comparative model; the full transport-item catalogue remains available in the thesis appendix.

Reduced substitution logic

Table 3 summarizes the substitution logic used in the comparative model at a reduced level. The full one-to-one mapping between all modeled single-use classes and reusable transport items is omitted from the paper version.

Scenario parameters

Table 4 reports the scenario parameters used in the sensitivity and scenario analysis.

Transport and production emission factors

Transport and production emission factors were taken from the DESNZ emission factor dataset[32]. Table 5 reports the transport factors used in the package-level transport model, while Table 6 reports the material production factors used in the cradle-to-gate production model.

Supplementary Results

This appendix reports the numerical values underlying the main results presented in the article. Only the result tables most directly related to the main paper figures are included here.

Baseline single-use packaging results

Table 7 reports the numerical values underlying Figure 3 in the main text.

Comparative results under cut-off accounting

Table 8 reports the numerical values underlying Figure 4 in the main text. Only the destinations displayed in the figure are shown explicitly, with the remaining destinations aggregated under *Others*. Positive values indicate an emissions benefit from reusable packaging relative to the single-use baseline.

Table 1: *Key package-assignment and mass-estimation assumptions used in the case model.*

Assumption	Code	Value	Role in the model
Ultra-low density band	UL	0.1 kg/l	Used in carton and box density estimation for very light package contents.
Low density band	LW	0.2 kg/l	Used in carton and box density estimation for low-density contents.
Medium density band	MD	0.5 kg/l	Used in carton and box density estimation for medium-density contents.
High density band	HG	0.8 kg/l	Used in carton and box density estimation for high-density contents.
Ultra-high density band	UH	0.9 kg/l	Used in carton and box density estimation for very high-density contents.
Metallic density band	MT	1.2 kg/l	Used in carton and box density estimation for metallic contents.
Packing factor	PF	0.8	Applied when converting estimated content density to package volume in order to reflect realistic fill ratios.
Pallet/dunnage threshold	–	1500 kg	Package categories such as EA, BND, BAG, DRM, RACK, and ROL are assigned pallets below this threshold and dunnage at or above it.
Dunnage mass rule	–	0.5% of gross weight	Used to estimate the mass of single-use wooden dunnage where dunnage use is not explicitly recorded in the ERP.
Stretch-wrap assignment	–	0.1% of gross weight	Applied only to package records explicitly labelled `PAL`.
Foil correction factor	–	×5	Applied to modelled foil use after yard validation showed that the original estimate captured only about 20% of observed use.

Comparative results under system-expansion accounting

Table 9 reports the numerical values underlying Figure 5 in the main text. Only the destinations displayed in the figure are shown explicitly, with the remaining destinations aggregated under *Others*. Positive values indicate an emissions benefit from reusable packaging relative to the single-use baseline.

Sensitivity analysis

Table 10 reports the normalized net emissions benefit matrix underlying Figure 6 in the main text. Columns correspond to the reverse logistics multiplier and rows correspond to the RTI life multiplier.

Table 2: *Reduced set of reusable transport items retained in the article appendix.*

Code(s)	Main use	Material	Size class	Baseline lifetime (uses)	Source
C40, C50	Reusable rigid container	HDPE	Full pallet	100	[36]
C43–C46	KLT container family	PP	Large to tiny Euronorm classes	60	[37]
C51, C53, C54, C56	Collapsible / heavy-duty KLT family	PP	Double pallet and selected Euronorm classes	60	[37]
B10–B12	Steel mesh box family	Steel	Full pallet, double pallet, double pallet low	250	[38]
P1	Reusable pallet	Recycled PP	Full pallet	50	[39]
D1	Reusable dunnage	Composite wood	Dunnage unit	25	[24]
F1	Paper foil	Paper	N/A	1	[21]

Table 3: *Substitution logic between the modeled single-use packaging system and the reusable alternative.*

UOM / class	Single-use representation	Reusable substitute	Notes
CRT	Cardboard carton in Euronorm-compatible size class	KLT container (small classes) or collapsible / heavy-duty KLT (larger classes)	Oversized carton classes without a suitable reusable equivalent were excluded.
BOX	Wooden or board-based box in Euronorm-compatible size class	Steel mesh box or reusable container class of corresponding size	Large heavy-duty box classes map to steel mesh alternatives.
PAL	Wooden EUR-pallet	Plastic pallet	Geometric footprint retained.
EA, BND, BAG, DRM, RACK, ROL (< 1500 kg)	Pallet-supported handling	Plastic pallet	Applied where gross package weight is below the pallet/dunnage threshold.
EA, BND, BAG, DRM, RACK, ROL (≥ 1500 kg)	Wooden dunnage	Composite wood dunnage	Material substitution only; dunnage mass is held constant.
FOIL	LDPE stretch foil	Paper foil	Treated as a single-use material substitute; no reverse logistics or reuse lifetime applied.

Table 4: *Scenario parameters used in the sensitivity and scenario analysis.*

Parameter	Baseline	Tested values	Levels	Role in the model
RTI life multiplier	1.0	0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5	13	Scales the baseline lifetime assumptions assigned to reusable transport items.
Reverse logistics multiplier	1.8	1.6, 1.7, 1.8, 1.9, 2.0	7	Scales the total reusable transport burden relative to the forward transport burden.
End-of-life accounting treatment	Both methods	Cut-off; system expansion	2	Alternative accounting treatment evaluated alongside the numerical scenario inputs.

Table 5: *Transport emission factors used in the case model.*

Mode	Value	Unit	Note
ROAD	10.163×10^{-2}	kg CO_2e / ton km	HGV, average diesel truck, average loading
SEA	1.830×10^{-2}	kg CO_2e / ton km	Container/general vessel, average loading
AIR	89.939×10^{-2}	kg CO_2e / ton km	Long-haul freight with indirect effects

Table 6: *Material production emission factors used in the case model. Composite wood is modeled as a recycled material proxy based on a 50–50 mix of recycled HDPE and wood.*

Code	Material	Primary production	Recycled	Unit	Note
C	Cartonboard	1200	1098	kg CO_2e / ton	–
P	Paper	1345	1050	kg CO_2e / ton	–
PP	Polypropylene	2578	1313	kg CO_2e / ton	–
HDPE	High Density Polyethylene	3095	1771	kg CO_2e / ton	–
LDPE	Low Density Polyethylene	2965	1098	kg CO_2e / ton	–
ST	Steel	3824	1639	kg CO_2e / ton	–
W	Wood	270	39	kg CO_2e / ton	–
CW	Composite wood	905	905	kg CO_2e / ton	Recycled feedstock proxy

Table 7: *Estimated emissions of the current single-use packaging system by grouped packaging category under cut-off and system-expansion accounting.*

	Cut-off (mt CO_2eq)				**System expansion (mt CO_2eq)**			
Category	**Prod.**	**Trans.**	**EOL**	**Total**	**Prod.**	**Trans.**	**EOL**	**Total**
Foil	31	7	0	38	31	7	-3	35
Boxes	20	73	6	99	20	73	-12	81
Cartons	16	5	10	31	16	5	9	30
Pallets	223	296	62	581	223	296	-129	390
Dunnage	164	182	46	392	164	182	-99	247
Grand Total	**454**	**563**	**124**	**1141**	**454**	**563**	**-234**	**783**

Table 8: *Net emissions benefit of reusable packaging relative to single-use packaging by destination country and packaging category under cut-off accounting for the in-house subset.*

Destination	Boxes	Cartons	Foil	Pallets	Dunnage	Grand Total
NL	-4.35	0.02	0.32	2.90	36.88	35.77
US	-1.23	-0.16	0.03	2.67	9.65	10.96
UK	0.21	0.00	0.04	0.71	1.86	2.83
NO	0.13	0.01	0.05	0.99	2.06	3.25
TT	-0.17	-0.02	0.00	-0.10	-3.64	-3.93
TW	-9.30	-0.03	0.00	-0.14	1.43	-8.04
OFFSHORE	-20.47	-0.93	0.36	1.78	9.45	-9.82
SG	-7.24	-0.20	0.07	-1.29	-3.24	-11.91
MX	0.02	-0.02	0.00	0.00	-15.44	-15.44
Others	-5.66	-0.40	0.09	2.56	3.51	0.10

Table 9: *Net emissions benefit of reusable packaging relative to single-use packaging by destination country and packaging category under system-expansion accounting for the in-house subset.*

Destination	Boxes	Cartons	Foil	Pallets	Dunnage	Grand Total
NL	-6.96	0.01	0.41	-1.10	-11.81	-19.44
US	-1.27	-0.16	0.03	2.54	9.25	10.39
UK	0.11	0.00	0.05	0.41	0.95	1.52
NO	-0.08	0.01	0.08	-0.09	-0.40	-0.48
TT	-0.42	-0.02	0.00	-0.12	-3.66	-4.23
TW	-9.40	-0.03	0.00	-0.22	-0.61	-10.26
OFFSHORE	-22.92	-0.94	0.19	-3.85	-18.67	-46.20
SG	-7.47	-0.20	0.08	-2.13	-4.31	-14.04
MX	0.02	-0.02	0.00	0.00	-15.47	-15.48
Others	-5.83	-0.40	0.27	2.08	1.67	-2.21

Table 10: *Normalized net emissions benefit matrix (%). Columns correspond to the reverse logistics multiplier and rows correspond to the RTI life multiplier.*

RTI life multiplier	1.6	1.7	1.8	1.9	2.0
0.5	7%	2%	-3%	-9%	-14%
0.6	9%	3%	-2%	-7%	-12%
0.7	10%	4%	-1%	-6%	-11%
0.8	10%	5%	0%	-5%	-10%
0.9	11%	6%	1%	-5%	-10%
1.0	11%	6%	1%	-4%	-9%
1.1	12%	7%	1%	-4%	-9%
1.2	12%	7%	2%	-3%	-9%
1.3	12%	7%	2%	-3%	-8%
1.4	13%	7%	2%	-3%	-8%
1.5	13%	8%	2%	-3%	-8%

B

Case-Study Parameters

Listed below are the parameters used in the methodology section. They include the queries used in HMC's ERP INFOR, Package UOMs, Single Use and Reusable Transport Item specifications, Scenario Parameters and Assumptions.

B.1. Record Selection and Data Cleaning

Merged Package UOMs

Package types with similar functions were merged to simplify the analysis.

Measure	Selected Merged Unit	Alternate Units			
Liquids	DRM – Drum	BCK – Bucket	BTL – Bottle	IBC – IBC tank	BID – Bideon / CAN – Can
Collections	BND – Bundle	SET – Sets	LOT – Lots		
Wires	ROL – Roll	REEL – Reels	CL – Coil		

Table B.1: Measurement Units and Alternatives

Query and Data Cleaning Log

Transports Query: All transport records from 01-01-2012 to 01-01-2025, (all fields)
Final Size:[redacted]

Step	Description	Inclusion Criteria	Size Before	Removed Records	Size After
0	–	–	[redacted]	–	[redacted]
1	Only packages dispatched from key Dutch locations	Originating Store / From Address: HMCVL	[redacted]	[redacted]	[redacted]
2	Valid destination	Delivery Address / To HMC yard: $\neq$ <blank>, 0, ADMIN	[redacted]	[redacted]	[redacted]

Table B.2: Transport Cleaning Steps

Packages Query: All package records from 01-01-2012 to 01-01-2025, (all fields)
Final Size of Analytical Dataset: [redacted]

Step	Description	Inclusion Criteria	Size Before	Removed Records	Size After
0	–	–	[redacted]	–	[redacted]
1	Transport must be assigned	Transport: ≠ <blank>	[redacted]	[redacted]	[redacted]
2	Transport must be valid	TransportID ⊂ Transports	[redacted]	[redacted]	[redacted]
3	Discarded packages	Status: D	[redacted]	[redacted]	[redacted]

Table B.3: Package filtering steps used to construct the final analytical dataset

B.2. Packaging Specifications

Material Modeling

Type	Material	Description	Max Density	Grammage
CRT	C1	Carton – single	0.2	0.3
CRT	C2	Carton – single corrugation	1.5	0.54
CRT	C3	Carton – double corrugation	2	0.82
CRT	C4	Carton – triple corrugation	6	1.07
BOX	W1	Plywood – 10 mm	2	7
BOX	W2	Plywood – 20 mm	6	14
PAL	W3	Grade A wood – 10 mm	0	7
PAL	W4	Grade A wood – 20 mm	0	14
RTI	HDPE1	HDPE – 2.5 mm	6	2.4
RTI	HDPE2	HDPE – 5 mm	0	4.8
DRM	HDPE1	HDPE – 2.5 mm	6	2.4
DRM	HDPE2	HDPE – 5 mm	0	4.8
FOIL	LDPE1	LDPE – 0.1 mm	6	0.091
FOIL	LDPE2	LDPE – 0.2 mm	0	0.182
MIX	PP1	PP – 2.5 mm	0	2.2
MIX	PP2	PP – 5 mm	0	4.4
MIX	PM1	Mix plastic – 2 mm	0	2.2
MIX	PM2	Mix plastic – 5 mm	0	4.4

Table B.4: Material Types, Descriptions, Permitted density (kg/l), Grammage (kg/m2)

Single Use Transport Items

Code	UOM	Material	Construction	Size class	Max. density (kg/l)	Dimensions (cm) L × W × H	Unit mass (kg)
C0	CRT	Cartonboard	Single wall	Full pallet	0.2	120 × 80 × 40	1.05
C1	CRT	Cartonboard	Single wall	Double pallet	0.2	240 × 80 × 80	2.70
C2	CRT	Cartonboard	Single wall	Double pallet low	0.2	240 × 80 × 40	1.92
C3	CRT	Cartonboard	Single wall	Large Euronorm	0.2	80 × 60 × 30	0.54
C4	CRT	Cartonboard	Single wall	Medium Euronorm	0.2	60 × 40 × 30	0.33
C5	CRT	Cartonboard	Single wall	Small Euronorm	0.2	40 × 30 × 20	0.15
C6	CRT	Cartonboard	Single wall	Tiny Euronorm	0.2	30 × 20 × 20	0.09
C10	CRT	Cartonboard	Single corrugation	Full pallet	1.2	120 × 80 × 40	1.89
C11	CRT	Cartonboard	Single corrugation	Double pallet	1.2	240 × 80 × 80	4.86
C12	CRT	Cartonboard	Single corrugation	Double pallet low	1.2	240 × 80 × 40	3.46
C13	CRT	Cartonboard	Single corrugation	Large Euronorm	1.2	80 × 60 × 30	0.97
C14	CRT	Cartonboard	Single corrugation	Medium Euronorm	1.2	60 × 40 × 30	0.59
C15	CRT	Cartonboard	Single corrugation	Small Euronorm	1.2	40 × 30 × 20	0.27
C16	CRT	Cartonboard	Single corrugation	Tiny Euronorm	1.2	30 × 20 × 20	0.16
C20	CRT	Cartonboard	Double corrugation	Full pallet	1.8	120 × 80 × 40	2.87
C21	CRT	Cartonboard	Double corrugation	Double pallet	1.8	240 × 80 × 80	7.38
C22	CRT	Cartonboard	Double corrugation	Double pallet low	1.8	240 × 80 × 40	5.25
C23	CRT	Cartonboard	Double corrugation	Large Euronorm	1.8	80 × 60 × 30	1.48
C24	CRT	Cartonboard	Double corrugation	Medium Euronorm	1.8	60 × 40 × 30	0.90
C25	CRT	Cartonboard	Double corrugation	Small Euronorm	1.8	40 × 30 × 20	0.41
C26	CRT	Cartonboard	Double corrugation	Tiny Euronorm	1.8	30 × 20 × 20	0.25
C30	CRT	Cartonboard	Triple corrugation	Full pallet	3.1	120 × 80 × 40	3.75
C31	CRT	Cartonboard	Triple corrugation	Double pallet	3.1	240 × 80 × 80	9.63
C32	CRT	Cartonboard	Triple corrugation	Double pallet low	3.1	240 × 80 × 40	6.85
C33	CRT	Cartonboard	Triple corrugation	Large Euronorm	3.1	80 × 60 × 30	1.93
C34	CRT	Cartonboard	Triple corrugation	Medium Euronorm	3.1	60 × 40 × 30	1.18
C35	CRT	Cartonboard	Triple corrugation	Small Euronorm	3.1	40 × 30 × 20	0.54
C36	CRT	Cartonboard	Triple corrugation	Tiny Euronorm	3.1	30 × 20 × 20	0.32
B0	BOX	Wood	Plywood, 10 mm	Full pallet	3.1	120 × 80 × 40	24.5
B1	BOX	Wood	Plywood, 10 mm	Double pallet	3.1	240 × 80 × 80	63.0
B2	BOX	Wood	Plywood, 10 mm	Double pallet low	3.1	240 × 80 × 40	44.8
B3	BOX	Wood	Plywood, 10 mm	Large Euronorm	3.1	80 × 60 × 30	12.6
B4	BOX	Wood	Plywood, 10 mm	Medium Euronorm	3.1	60 × 40 × 30	7.7
B5	BOX	Wood	Plywood, 10 mm	Small Euronorm	3.1	40 × 30 × 20	3.5
B6	BOX	Wood	Plywood, 10 mm	Tiny Euronorm	3.1	30 × 20 × 20	2.1
P0	PAL	Wood	Grade A wood	Full pallet	–	120 × 80 × 90	25.0
D0	DUN	Wood	Dunnage wood	Dunnage unit	–	–	1.0
F0	FOIL	LDPE	LDPE, 0.1 mm	N/A	–	–	0.02

Table B.5: Single-use packaging specifications used in the model

Reusable Transport Items

Code	UOM	Material	Construction	Size class	Max. density (kg/l)	Dimensions (cm) L × W × H	Baseline lifetime (uses)
C40	HD	HDPE	HDPE, 2.5 mm	Full pallet	3	120 × 80 × 40	100 [48]
C43	KLT	PP	PP, 2.5 mm	Large Euronorm	3	80 × 60 × 30	60 [49]
C44	KLT	PP	PP, 2.5 mm	Medium Euronorm	3	60 × 40 × 30	60
C45	KLT	PP	PP, 2.5 mm	Small Euronorm	3	40 × 30 × 20	60
C46	KLT	PP	PP, 2.5 mm	Tiny Euronorm	3	30 × 20 × 20	60
C50	HD	HDPE	HDPE, 2.5 mm	Full pallet	3	120 × 80 × 40	100
C51	HD	PP	PP, 5 mm	Double pallet	3	240 × 80 × 80	60
C53	CKLT	PP	PP, 5 mm	Large Euronorm	3	80 × 60 × 30	60
C54	CKLT	PP	PP, 5 mm	Small Euronorm	3	40 × 30 × 20	60
C56	CKLT	PP	PP, 5 mm	Tiny Euronorm	3	30 × 20 × 20	60
B10	UHD	Steel	Steel mesh	Full pallet	3	120 × 80 × 40	250 [50]
B11	UHD	Steel	Steel mesh	Double pallet	3	240 × 80 × 80	250
B12	UHD	Steel	Steel mesh	Double pallet low	3	240 × 80 × 40	250
P1	PAL	PP	Recycled PP	Full pallet	3	120 × 80 × 90	50 [51]
D1	DUN	Composite wood	Composite wood	Dunnage unit	–	–	25 [33]
F1	FOIL	Paper	Paper foil	N/A	–	–	1 [34]

Table B.6: Reusable transport item specifications used in the model

Density Values for carton and box estimation

Code	Category	Value	Unit	Examples
UL	Ultra Low	0.1	kg/l	foams, medical supplies, filters
LW	Low	0.2	kg/l	plastic parts, lubricants, wood, clothing
MD	Medium	0.5	kg/l	paint, crew provisions, electrical equipment, consumer appliances
HG	High	0.8	kg/l	kitchen equipment, heavy appliances, handheld tools
UH	Ultra High	0.9	kg/l	large equipment, workshop machines, grillages
MT	Metallic	1.2	kg/l	plumbing fittings, slings, cables, steel parts, raw stock, hull parts, workshop tools
PF	(Packing Factor)	0.8	–	for simulating realistic fill ratios

Table B.7: Final Density values used for approximating package density

Packaging Substitution Map

This table shows the mapping for substituting single use packaging with reusable transport item. Some single use cartons did not have an equivalent reusable counterpart and so were excluded (denoted by N/A)

SU code	SU UOM	SU material	RTI code	RTI UOM	RTI material
C0	CRT	C	C40	HD	HDPE
C1	CRT	C	N/A	N/A	N/A
C2	CRT	C	N/A	N/A	N/A
C3	CRT	C	C43	KLT	PP
C4	CRT	C	C44	KLT	PP
C5	CRT	C	C45	KLT	PP
C6	CRT	C	C46	KLT	PP
C10	CRT	C	C40	HD	HDPE
C11	CRT	C	N/A	N/A	N/A
C12	CRT	C	N/A	N/A	N/A
C13	CRT	C	C43	KLT	PP
C14	CRT	C	C44	KLT	PP
C15	CRT	C	C45	KLT	PP
C16	CRT	C	C46	KLT	PP
C20	CRT	C	C40	HD	HDPE
C21	CRT	C	N/A	N/A	N/A
C22	CRT	C	N/A	N/A	N/A
C23	CRT	C	C43	KLT	PP
C24	CRT	C	C44	KLT	PP
C25	CRT	C	C45	KLT	PP
C26	CRT	C	C46	KLT	PP
C30	CRT	C	C50	HD	HDPE
C31	CRT	C	C51	HD	PP
C32	CRT	C	N/A	N/A	N/A
C33	CRT	C	C53	CKLT	PP
C34	CRT	C	C54	CKLT	PP
C35	CRT	C	C54	CKLT	PP
C36	CRT	C	C56	CKLT	PP
B0	BOX	W	C50	HD	HDPE
B1	BOX	W	C51	HD	PP
B2	BOX	W	B12	UHT	ST
B3	BOX	W	C53	CKLT	PP
B4	BOX	W	C54	CKLT	PP
B5	BOX	W	C45	KLT	PP
B6	BOX	W	C56	CKLT	PP
P0	PAL	W	P1	PAL	PP
D0	DUN	W	D1	DUN	CW
F0	FOIL	LDPE	F1	FOIL	P

Table B.8: Substitution mapping between modelled single-use packaging classes and reusable transport items

B.3. Environmental Factors

Transportation Emission Factors

Mode	Value	Emission Unit	Note
ROAD	10.163×10^{-2}	kg CO_2e / ton km	HGV – average diesel truck, average loading
SEA	1.830×10^{-2}	kg CO_2e / ton km	Container/general vessel – average loading
AIR	89.939×10^{-2}	kg CO_2e / ton km	Flights – long-haul/international flights with indirect effects

Table B.9: Transport Mode Emission and Cost Factors

Production Emission Factors

The material factors here are cradle to gate i.e. for a procuring a finished product (in this case, a finished transport item). Composite Wood is assumed to be a 50-50 mix of recycled HDPE and Wood and emission factor has been calculated accordingly.

Code	Material	Primary Production	Recycled	Unit	Note
C	Cartonboard	1200	1098	kg CO_2e / ton	–
P	Paper	1345	1050	kg CO_2e / ton	–
PP	Polypropylene	2578	1313	kg CO_2e / ton	–
HDPE	High Density Polyethylene	3095	1771	kg CO_2e / ton	–
LDPE	Low Density Polyethylene	2965	1098	kg CO_2e / ton	–
ST	Steel	3824	1639	kg CO_2e / ton	–
W	Wood	270	39	kg CO_2e / ton	–
CW	Composite Wood	905	905	kg CO_2e / ton	Recycled feedstock

Table B.10: Material production emission factors for primary and recycled material inputs

End of Life Emission Factors

Cut-off

Code	Material	Landfill	Incin.(Offshore)	WTE	Recycling Avg.	Unit
C	Cartonboard	1165	1660	5	5	kg CO_2e / ton
P	Paper	1165	1660	5	5	kg CO_2e / ton
PP	Polypropylene	9	2875	5	5	kg CO_2e / ton
HDPE	High Density Polyethylene	9	3064	5	5	kg CO_2e / ton
LDPE	Low Density Polyethylene	9	2505	5	5	kg CO_2e / ton
ST	Steel	9	18	5	5	kg CO_2e / ton
W	Wood	925	29	5	5	kg CO_2e / ton
CW	Composite Wood	463	1547	5	5	kg CO_2e / ton

Table B.11: End-of-life emission factors used for the cut-off model

System Expansion

Code	Material	Landfill	Incin. (Offshore)	WTE	Recycling Avg.	Unit
C	Cartonboard	1160	1660	-198	-57	kg CO_2e / ton
P	Paper	1160	1660	-194	-122	kg CO_2e / ton
PP	Polypropylene	9	2875	1905	-590	kg CO_2e / ton
HDPE	High Density Polyethylene	9	3064	2288	-709	kg CO_2e / ton
LDPE	Low Density Polyethylene	9	2505	1729	-722	kg CO_2e / ton
ST	Steel	9	18	18	-1127	kg CO_2e / ton
W	Wood	925	29	-318	-231	kg CO_2e / ton
CW	Composite Wood	463	1547	985	-470	kg CO_2e / ton

Table B.12: End-of-life emission factors used for the system expansion model

B.4. Waste EOL fractions

Code	Country	Material	Landfill	Incin. (off.)	WTE	Recycling
OFFSHORE	Ship	C	0.00	0.45	0.05	0.50
OFFSHORE	Ship	P	0.00	0.45	0.05	0.50
OFFSHORE	Ship	PP	0.00	0.00	0.10	0.90
OFFSHORE	Ship	HDPE	0.00	0.00	0.10	0.90
OFFSHORE	Ship	LDPE	0.00	0.00	0.10	0.90
OFFSHORE	Ship	ST	0.05	0.00	0.00	0.95
OFFSHORE	Ship	AL	0.05	0.00	0.00	0.95
OFFSHORE	Ship	W	0.00	0.00	0.10	0.90
OFFSHORE	Ship	CW	0.05	0.00	0.05	0.90

Table B.13: Offshore waste-treatment fractions used in the case study

Code	Country	Material	Landfill	Incin.	WTE	Recycling
AE	United Arab Emirates	all	0.78	0.00	0.00	0.22
AO	Angola	all	0.95	0.00	0.00	0.05
AR	Argentina	all	0.94	0.00	0.00	0.06
AT	Austria	all	0.95	0.00	0.00	0.05
AU	Australia	all	0.49	0.00	0.10	0.41
AW	Aruba	all	0.89	0.00	0.00	0.11
BE	Belgium	all	0.04	0.00	0.54	0.42
BR	Brazil	all	0.99	0.00	0.00	0.01
CA	Canada	all	0.75	0.00	0.04	0.21
CG	Congo	all	0.74	0.00	0.00	0.26
CI	Cote d’Ivoire	all	0.97	0.00	0.00	0.03
CM	Cameroon	all	1.00	0.00	0.00	0.00
CN	China	all	0.70	0.00	0.30	0.00
CW	Curaçao	all	0.98	0.00	0.00	0.02
CY	Cyprus	all	0.86	0.00	0.00	0.14
CZ	Czechia	all	0.55	0.00	0.18	0.27
DE	Germany	all	0.03	0.00	0.39	0.58
DK	Denmark	all	0.01	0.00	0.65	0.34
DO	Dominican Republic	all	0.92	0.00	0.00	0.08
ES	Spain	all	0.66	0.00	0.14	0.20
ET	Ethiopia	all	1.00	0.00	0.00	0.00
FI	Finland	all	0.13	0.00	0.55	0.32
FR	France	all	0.31	0.00	0.42	0.27
GI	Gibraltar	all	0.30	0.00	0.37	0.33
GN	Guinea	all	0.95	0.00	0.00	0.05
HK	Hong Kong	all	0.66	0.00	0.00	0.34
ID	Indonesia	all	0.90	0.00	0.00	0.10
IE	Ireland	all	0.45	0.00	0.18	0.37
IT	Italy	all	0.46	0.00	0.23	0.31
JE	Jersey	all	0.30	0.00	0.37	0.33
KR	South Korea	all	0.16	0.00	0.25	0.59
MX	Mexico	all	0.95	0.00	0.00	0.05
MY	Malaysia	all	0.82	0.00	0.00	0.18
NM	Namibia	all	0.96	1.00	0.00	0.04
NL	Netherlands	all	0.02	0.00	0.65	0.33
NO	Norway	all	0.06	0.00	0.63	0.31
OM	Oman	all	0.73	0.00	0.01	0.26
PL	Poland	all	0.53	0.00	0.16	0.31
PT	Portugal	all	0.57	0.00	0.24	0.19
QA	Qatar	all	0.93	0.00	0.04	0.03
SA	Saudi Arabia	all	0.85	0.00	0.00	0.15
SE	Sweden	all	0.01	0.00	0.61	0.38
SG	Singapore	all	0.02	0.00	0.37	0.61
TH	Thailand	all	0.81	0.00	0.00	0.19
TT	Trinidad and Tobago	all	1.00	0.00	0.00	0.00
TW	Taiwan	all	0.36	0.00	0.64	0.00
UK	United Kingdom	all	0.30	0.00	0.37	0.33
US	United States of America	all	0.86	0.00	0.00	0.14
VN	Viet Nam	all	0.73	0.00	0.00	0.27
ZA	South Africa	all	0.72	0.00	0.00	0.28

Table B.14: Country-level waste-treatment fractions used in the case study. Note that only countries observed in the dataset are included

B.5. Scenario Inputs

Parameter	Baseline	Tested values	Levels	Role in the model
RTI life multiplier	1.0	0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6	13	Scales the baseline lifetime assumptions assigned to reusable transport items.
Reverse logistics multiplier	1.8	1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0	7	Scales the total reusable transport burden relative to the forward transport burden.
End-of-life accounting treatment	Both methods	Cut-off; System expansion	2	Alternative accounting treatment evaluated alongside the numerical scenario inputs.

Table B.15: Scenario parameters used in the sensitivity and scenario analysis

Design component	Levels	Count
RTI life multiplier	0.5, 0.6, 0.7, 0.8, 0.9 1.0, 1.1, 1.2, 1.3, 1.4, 1.5	12
Reverse logistics multiplier	1.6, 1.7, 1.8, 1.9, 2.0	5
End-of-life accounting treatment	Cut-off / System expansion	2
Total scenario combinations	$(12 \times 5 \times 2)$	120

Table B.16: Factorial structure of the scenario design

C

Results Data

C.1. Single-use mass and emissions

Mass estimation

Table C.1: Estimated mass of single-use packaging by UOM and flow type

UOM	In-house (mt)	PO-receipt (mt)	Total (mt)
BAG	3	3	6
BND	40	58	98
BOX	27	49	76
CRT	1	13	14
DRM	3	7	10
EA	299	174	473
PAL	61	768	829
RACK	1	0	1
ROL	7	14	21
FOIL	2	18	20
Total	**444**	**1102**	**1546**

Emissions estimation

Table C.2: Emissions of single-use packaging by UOM under cut-off accounting

UOM	Production (mt CO_2eq)	Transportation (mt CO_2eq)	EOL (mt CO_2eq)	Total (mt CO_2eq)
BAG	2	1	0	3
BND	26	16	6	48
BOX	20	73	6	99
CRT	16	5	10	31
DRM	3	2	0	5
EA	127	160	39	326
PAL	223	296	62	581
RACK	0	0	0	0
ROL	6	3	1	10
FOIL	31	7	0	38
Grand Total	**455**	**562**	**123**	**1141**

Table C.3: Emissions of single-use packaging by UOM under system-expansion accounting

UOM	Production ($mt\ CO_2eq$)	Transportation ($mt\ CO_2eq$)	EOL ($mt\ CO_2eq$)	Total ($mt\ CO_2eq$)
BAG	2	1	-1	2
BND	26	16	-18	24
BOX	20	73	-12	81
CRT	16	5	9	30
DRM	3	2	-2	3
EA	127	160	-74	213
PAL	223	296	-129	390
RACK	0	0	0	0
ROL	6	3	-4	5
FOIL	31	7	-3	35
Grand Total	**455**	**562**	**-235**	**783**

C.2. Comparative results between single-use and reusable systems

Values in the comparative matrices are rounded to two decimal places.

Cut-off results

Table C.4: Country × UOM net emissions benefit matrix under cut-off accounting

Country	BAG	BND	BOX	CRT	DRM	EA	PAL	RACK	ROL	FOIL	Grand Total
AE	0.00	0.00	0.02	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.06
AO	0.00	0.47	-0.54	-0.02	0.00	-1.65	1.68	0.00	0.00	0.01	-0.04
AR	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
AU	0.00	0.00	0.07	-0.14	0.00	0.01	-0.81	0.00	0.00	0.00	-0.87
AW	0.00	0.00	-0.19	0.00	0.00	0.00	0.13	0.00	0.00	0.01	-0.05
BE	0.00	0.00	0.01	0.00	0.00	0.09	0.01	0.00	0.00	0.00	0.11
CA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CI	0.00	0.00	-0.35	-0.02	0.00	-0.09	-0.03	0.00	0.00	0.00	-0.48
CM	0.00	0.00	0.03	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.52
CN	0.00	0.00	-1.79	-0.01	0.00	-0.22	-0.05	0.00	0.00	0.00	-2.08
CW	0.00	0.00	0.11	0.00	0.00	-0.09	0.00	0.00	0.00	0.00	0.03
CY	0.02	0.00	0.08	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.17
CZ	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.04
DE	0.00	0.01	0.02	0.00	0.00	0.61	0.07	0.00	0.00	0.01	0.72
DK	0.01	0.01	-0.01	0.00	0.00	0.10	0.05	0.00	0.00	0.00	0.17
ES	0.00	0.05	0.03	0.00	0.00	0.75	0.44	0.01	0.00	0.01	1.29
FR	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02
GI	0.00	0.05	0.03	0.00	0.00	0.01	0.14	0.00	0.00	0.01	0.23
HK	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
ID	0.02	0.24	-3.51	-0.22	0.02	3.18	1.85	0.00	0.00	0.02	1.61
IT	0.00	0.01	0.00	0.00	0.00	0.12	0.02	0.00	0.00	0.00	0.15
KR	0.00	0.00	0.06	-0.01	0.00	0.00	-0.61	0.00	0.00	0.00	-0.55
MX	0.00	0.00	0.02	-0.02	0.00	-15.44	0.00	0.00	0.00	0.00	-15.44
MY	0.00	0.00	0.16	-0.01	0.00	0.16	-0.05	0.00	0.00	0.00	0.26
NL	0.22	4.47	-4.35	0.02	0.05	31.63	2.90	0.15	0.36	0.32	35.77
NO	0.02	0.23	0.13	0.01	0.02	1.78	0.99	0.02	0.00	0.05	3.25
OFFSHORE	0.19	0.89	-20.47	-0.93	0.30	7.37	1.78	0.06	0.64	0.36	-9.82
PL	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.03
QA	0.00	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	-0.02
SA	0.00	0.00	0.04	-0.03	0.00	-0.24	-0.08	0.00	0.00	0.00	-0.31
SE	0.00	0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.03
SG	0.00	-0.14	-7.24	-0.20	-0.11	-2.99	-1.29	0.00	0.00	0.07	-11.91
TT	0.00	0.00	-0.17	-0.02	0.00	-3.64	-0.10	0.00	0.00	0.00	-3.93
TW	0.00	-0.20	-9.30	-0.03	0.00	1.64	-0.14	0.00	0.00	0.00	-8.04
UK	0.01	0.25	0.21	0.00	0.18	1.28	0.71	0.00	0.14	0.04	2.83
US	0.16	2.38	-1.23	-0.16	0.00	6.89	2.67	0.00	0.22	0.03	10.96
VN	0.00	0.00	0.00	0.00	0.00	0.00	-0.44	0.00	0.00	0.01	-0.43
ZA	0.00	0.00	0.13	-0.06	0.00	0.02	-0.11	0.00	0.00	0.01	-0.01
Grand Total	**0.65**	**8.72**	**-47.95**	**-1.86**	**0.45**	**31.88**	**9.80**	**0.23**	**1.37**	**0.96**	**4.26**

System-expansion results

Table C.5: Country × UOM net emissions benefit matrix under system-expansion accounting

Country	BAG	BND	BOX	CRT	DRM	EA	PAL	RACK	ROL	FOIL	Grand Total
AE	0.00	0.00	0.02	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.01
AO	0.00	0.47	-0.62	-0.02	0.00	-1.66	1.67	0.00	0.00	0.01	-0.16
AR	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	-0.01
AU	0.00	0.00	0.06	-0.14	0.00	0.01	-0.86	0.00	0.00	0.00	-0.93
AW	0.00	0.00	-0.30	0.00	0.00	0.00	-0.03	0.00	0.00	0.00	-0.33
BE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CA	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	-0.01
CI	0.00	0.00	-0.36	-0.02	0.00	-0.09	-0.03	0.00	0.00	0.00	-0.51
CM	0.00	0.00	0.03	0.00	0.00	0.49	0.00	0.00	0.00	0.00	0.52
CN	0.00	0.00	-1.80	-0.01	0.00	-1.01	-0.06	0.00	0.00	0.00	-2.89
CW	0.00	0.00	0.11	0.00	0.00	-0.09	0.00	0.00	0.00	0.00	0.03
CY	0.02	0.00	0.07	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.16
CZ	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.03
DE	0.00	0.00	0.00	0.00	0.00	-0.06	-0.01	0.00	0.00	0.01	-0.06
DK	0.00	-0.01	-0.03	0.00	0.00	-0.06	-0.02	0.00	0.00	0.00	-0.11
ES	0.00	0.01	0.01	0.00	0.00	0.60	0.24	0.00	0.00	0.01	0.86
FR	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
GI	0.00	-0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02
HK	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
ID	0.02	0.23	-3.53	-0.22	0.02	3.08	1.78	0.00	0.00	0.02	1.40
IT	0.00	0.01	0.00	0.00	0.00	0.09	0.01	0.00	0.00	0.00	0.11
KR	0.00	-0.01	0.05	-0.01	0.00	-0.02	-0.67	0.00	0.00	0.00	-0.66
MX	0.00	0.00	0.02	-0.02	0.00	-15.47	0.00	0.00	0.00	0.00	-15.48
MY	0.00	0.00	0.16	-0.01	0.00	0.15	-0.05	0.00	0.00	0.00	0.24
NL	-0.07	-0.87	-6.96	0.01	-0.02	-10.68	-1.10	-0.08	-0.09	0.41	-19.44
NO	0.00	-0.01	-0.08	0.01	0.00	-0.38	-0.09	0.00	0.00	0.08	-0.48
OFFSHORE	-0.21	-2.43	-22.92	-0.94	-0.24	-15.25	-3.85	-0.05	-0.49	0.19	-46.20
PL	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.02
QA	0.00	0.00	0.00	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	-0.02
SA	0.00	0.00	0.04	-0.03	0.00	-0.25	-0.10	0.00	0.00	0.00	-0.35
SE	0.00	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	0.01	-0.01
SG	-0.03	-0.29	-7.47	-0.20	-0.14	-3.86	-2.13	0.00	0.00	0.08	-14.04
TT	0.00	0.00	-0.42	-0.02	0.00	-3.66	-0.12	0.00	0.00	0.00	-4.23
TW	0.00	-0.21	-9.40	-0.03	0.00	-0.40	-0.22	0.00	0.00	0.00	-10.26
UK	0.00	0.14	0.11	0.00	0.09	0.64	0.41	0.00	0.08	0.05	1.52
US	0.15	2.29	-1.27	-0.16	0.00	6.59	2.54	0.00	0.21	0.03	10.39
VN	0.00	0.00	0.00	0.00	0.00	0.00	-0.46	0.00	0.00	0.01	-0.45
ZA	-0.01	0.00	0.11	-0.06	0.00	-0.05	-0.23	0.00	0.00	0.00	-0.23
Grand Total	**-0.12**	**-0.70**	**-54.34**	**-1.88**	**-0.29**	**-41.29**	**-3.38**	**-0.13**	**-0.29**	**0.92**	**-101.50**

Sensitivity analysis

Table C.6: Absolute net emissions benefit matrix (mt CO_2eq) as a function of RTI life multiplier and reverse logistics multiplier

Reverse Logistics Multiplier **RTI life multiplier**	**1.6**	**1.7**	**1.8**	**1.9**	**2.0**
0.5	23	6	-11	-28	-45
0.6	28	11	-6	-23	-40
0.7	31	14	-3	-20	-37
0.8	34	17	0	-17	-34
0.9	36	19	2	-15	-32
1.0	37	20	3	-14	-31
1.1	39	22	5	-12	-29
1.2	40	23	6	-11	-28
1.3	41	24	7	-10	-27
1.4	41	24	7	-10	-27
1.5	42	25	8	-9	-26

Table C.7: Normalized net emissions benefit matrix (%) as a function of RTI life multiplier and reverse logistics multiplier

Reverse Logistics Multiplier **RTI life multiplier**	**1.6**	**1.7**	**1.8**	**1.9**	**2.0**
0.5	7%	2%	-3%	-9%	-14%
0.6	9%	3%	-2%	-7%	-12%
0.7	10%	4%	-1%	-6%	-11%
0.8	10%	5%	0%	-5%	-10%
0.9	11%	6%	1%	-5%	-10%
1.0	11%	6%	1%	-4%	-9%
1.1	12%	7%	1%	-4%	-9%
1.2	12%	7%	2%	-3%	-9%
1.3	12%	7%	2%	-3%	-8%
1.4	13%	7%	2%	-3%	-8%
1.5	13%	8%	2%	-3%	-8%

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Meeting Minutes

Kickoff Meeting - 13/10/2025

Attendees: Dr Alessia Napoleone
Agenda: Introduction and problem statement of the project
Summary:

- Presentation given introducing the host company, Heerema Marine Contractors and the background for the project. The motivation to reduce packaging waste produced was introduced.
- The preliminary planning of the project was presented, with tentative planning of the Mid-term meeting in Week 2, Greenlight meeting in Week 7 and Finalisation in Week 11 of 2026.
- Feedback was requested to formulate the research question and the proposed research methods to address the challenges for the project

Action Items:

- Conduct a literature review on the principles of circular economy
- Conduct research to understand company operations and logistics systems
- Propose a formal research question and subgoals to answer it

Thesis Update Meeting - 05/11/2025

Attendees: Dr Alessia Napoleone
Agenda: Presentation of research question, results of literature review
Summary:

- Research question and subgoals formulated. Primary goal of the project is to evaluate reusable packaging systems to reduce environmental footprint.
- Preliminary scope of project defined
- High level process diagram for decision support framework presented.
- Results of literature review presented, diverse research exists on circular economy however, there are no published works for circular packaging specific to the offshore sector
- HMC logistics data is limited, instead requiring estimation of packaging waste
- Proposal of generating synthetic data to test model

Action Items:

- Research methods to generate synthetic data.
- Continue developing package estimation method

Thesis Update Meeting - 17/12/2025

Attendees: Dr Alessia Napoleone, Daniel Biegel
Agenda: Project update presentation, Discussion of further work, University and Company supervisor introduction
Summary:

- Introduction of Daniel and Alessia and discussion of university requirements and grading rubric
- Project update presentation for implemented modules for data processing, geocoding and logistics, package estimation and synthetic data generation
- Question and Answer session for methodology and future planning

Feedback and Action items:

- Package estimation method has many assumptions that will require validation
- Plan a yard visit for data collection to validate assumptions
- Provide Daniel with the TU Delft ME-MME grading rubric for clarity
- Create partially complete first draft of report before scheduling mid-term meeting
- Continue developing the decision model

Midterm Update Meeting - 03/02/2025

Attendees: Dr Alessia Napoleone, Dr Frederik Schulte
Agenda: Progress Check, Project update presentation, Formulation of model, Discussion of future work
Summary:

- Reintroduced project for Dr Frederik
- Presented methods for route selection of RTIs
- Presented design for validation study for package mass estimation
- Discussed project planning and fulfilling TU Delft requirements

Action Items:

- Prioritize obtaining results
- Revise research goals to accurately reflect project goals
- Revise literature review to be more coherent
- Delay green light meeting to have a better outcome

Results Update Meeting - 09/03/2025

Attendees: Dr Alessia Napoleone, Dr Frederik Schulte, Ir. Daniel Biegel
Agenda: Update on scope and content, Presentation of preliminary results and conclusion
Summary:

- Introduced updated research questions
- Presented finding from yard visit to HMC Vlissingen
- Presented validated assumptions for mass estimation
- Compared LCA methods and justified chosen methods
- Presented preliminary results and conclusion

Action Items:

- Document in detail methods, assumptions and results in the project

- Revise and complete thesis report draft for feedback
- Create tentative planning for greenlight meeting and finalization

Greenlight Meeting - 02/04/2025

Attendees: Dr Alessia Napoleone, Ir. Daniel Biegel, Ir. Nandini Suresh. Dr Frederik Schulte were unable to attend and have submitted written feedback on the greenlight deliverables

Agenda: Review of greenlight deliverables, Greenlight decisions, Practical matters for Finalization phase

Summary:

- Presented a summary presentation of the research process
- QnA session with attendees
- Received feedback to improve thesis report
- Greenlight decision confirmed
- Discussed assessment committee composition and tentative dates for thesis defense

Action Items:

- Implement feedback into report and presentation
- Send assessment committee composition and presentation details to faculty
- Send diploma application to faculty