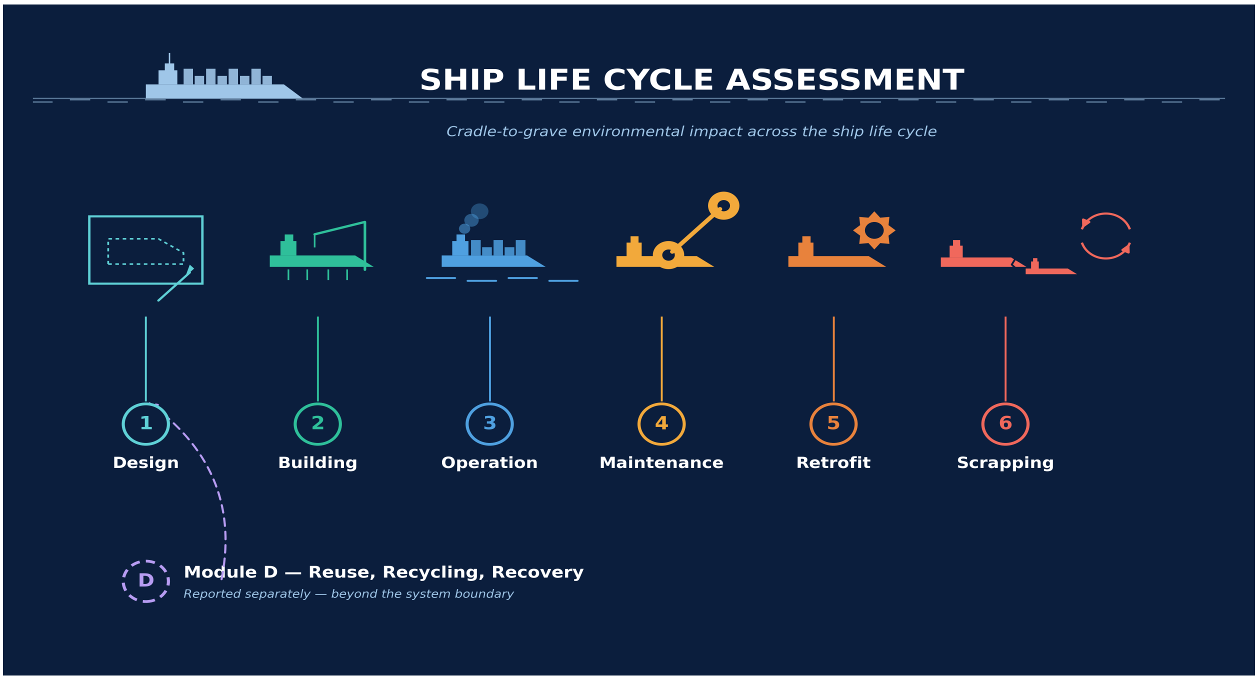
CHALMERS
UNIVERSITY OF TECHNOLOGY



Tool for life cycle assessment of ship material and structures

at the concept level stage using the industrial work breakdown structure.

Master's thesis in Marine Technology, Mobility Engineering Program

MALAKA MIHIRA GALAPPATHTHI

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

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

MASTER’S THESIS IN MARITIME TECHNOLOGY,
MOBILITY ENGINEERING PROGRAMME

Tool for life cycle assessment of ship material and structures at the concept level stage using the industrial work breakdown structure

MALAKA MIHIRA GALAPPATHTHI

Department of Mechanics and Maritime Sciences
Division of Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2026

Tool for life cycle assessment of ship material and structures at the concept level stage using the industrial work breakdown structure

MALAKA MIHIRA GALAPPATHTHI

Advisor: Ass. Prof. Remes Heikki, Mechanical Engineering Department, Aalto University
Supervisor: Prof. Jani Romanoff, Mechanical Engineering Department, Aalto University
Examiner: Prof. Jonas Ringsberg, Division of Marine Technology, Department of Mechanics and Maritime Sciences, Chalmers University of Technology

Department of Mechanics and Maritime Sciences
Division of Marine Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover: Stages of ship life cycle

Department of Mechanics and Maritime Sciences
Göteborg, Sweden 2026

Tool for life cycle assessment of ship material and structures at the concept level stage using the industrial work breakdown structure
Master's thesis in Marine Technology, Mobility Engineering Programme
MALAKA MIHIRA GALAPPATHTHI
Department of Mechanics and Maritime Sciences
Division of Marine Technology
Chalmers University of Technology

Abstract

The International Maritime Organisation (IMO) and EU have taken wider steps towards decarbonisation of maritime industry with new set targets, introducing tariffs and penalties to motivate the maritime sector. Therefore, Life Cycle Assessment (LCA) is important part of the early design stage of ship design to evaluate the carbon emission impact of the design, which supports the investors, and designers to take decisions at the early stage of ship design.

This thesis develops a tool for LCA of ship materials and structures at the concept level stage using the Industrial Work Breakdown Structure. The tool is developed based on the spreadsheet database with four main worksheets: SWBS, LCAI reference, LCA calculation, and result sheet. The tool follows cradle to grave LCA process including four stages: building, operation, maintenance, and scrapping. The tool presents the results as total global warming potential as carbon dioxide equivalent. The LCAI reference data base follows the EN 15804 module to store environmental impact data of the material.

The tool applied to a case study Ro-Pax vessel and validated against four published reference vessels. The tool verified through compliance check, formula verification test, consistency check following the ISO 14040/14044 standards. A sensitivity analysis was carried out for the case study Ro-Pax vessel for seven categories. The case study result shows the major contributor for GWP factor is the operational stage (96.5%) for conventional fuelled vessel, and GWP intensity factor lies within the reference vessels. The tool produced maximum gap is 3.1% for four validation case studies. The sensitivity analysis of the main case study vessel shows that operational stage assumptions are dominating and highly sensitive. The tool is complying to the ISO 14040/14044 standards following the formula verification test and consistency check confirming correctness and uniformity.

This study presents a generic LCA calculation tool to evaluate LCA at concept level stage for all commercial vessels. The tool is based on spreadsheet database, and it is incorporated with industrial work breakdown structure to organise material at concept level ship design. The tool has been verified and validated with independently published LCA studies. The Future work could focus on populating the LCAI reference database enabling automated import of material records to LCAI Reference database, program to direct import data from bill of materials.

Key words: Life cycle assessment (LCA), LCAI Reference, industrial work breakdown structure, Global Worming Potential, Concept Stage, Ship Design, Cradle to Grave, ship work breakdown structure, ISO

Contents

Preface and acknowledgements

This report presents a master’s thesis research study carried out as a part of the Nordic Master’s in Maritime Engineering at Aalto University and Chalmers University of Technology. In this study a life cycle assessment tool was designed to evaluate the environment impact of a ship at the conceptual design stage incorporating industrial work breakdown structure. The task was challenging and rewarding experience, where I gained deep knowledge and understanding in ship decarbonization assessment concepts and its practical impact.

I would like to express my heartful thanks to supervisors and advisors, Professor Jonas Ringsberg, Professor Jani Romanoff and Associate Professor Remes Heikki, for their guidance, valuable insights, continuous academic support and for the feedback throughout the work.

Finally, I would like to thank my friends for their continuous support extended to me during my studies. I wish to thank my parents, my spouse and my children for their endless love, patience and encouragement. Their patience, understanding and unwavering support during my studies has meant more than words can express.

Espoo July 2026-07-31

MALAKA MIHIRA GALAPPATHTHI

Symbols and abbreviations

Symbols

B	Breadth
CO_2	Carbon dioxide
C_o	Outfit weight coefficient
C_m	Machinery mass coefficient
E	Equipment numeral
GWP i, m	Global warming potential of material i for EN 15804 module m
Hi	Number of identical items
K	structural weight co-efficient
L	Length
Li	Total cradle to grave (A1-C4) Global Warming Potential factor of material
NOx	Nitrogen oxide
Ni	Quantity of material per item
Oi	Building stage total impact
Pi	Operational material consumption
Qi	Operation-stage total impact
Ri	Replacement quantity
Si	Maintenance stage total impact
SOx,	Sulphur oxide
Xi	Recycling credit
i	variable i
g/kWh	grams per kilowatt hour
kg CO2	kilogram carbon dioxide
kg CO2-e	kilogram carbon dioxide equivalent
kg CO2-e/kg	kilogram carbon dioxide equivalent per kilogram
Kg CO2-e/(kg lightship)	kilogram carbon dioxide equivalent per kilogram lightship
kg CO2-eq/kWh	kilogram carbon dioxide equivalent per kilowatt hour
kW	kilowatt
kWe	kilowatt electrical
m	variable m
mm	millimetre
rpm	rounds per minute
t	tonne
t CO2-e	Tons carbon dioxide equivalent

Operators

Σ_i	Sum over index i

Abbreviations

BF-BOF	Baseline blast furnace /basic oxygen furnace
BIM	Building information modelling
CBAM	Carbon border Adjustment mechanism
EAF	Electric-arc-furnace
EPD	Environmental product declarations
ESWBS	Expanded ship work breakdown structure
EUCBAM	European Union carbon border adjustment mechanism

GHG	Greenhouse gas emissions
GWP	Global warming potential
IMO	International maritime organization
ISO	International Organization for Standardization
IWBS	Industrial work breakdown structure
KPI	Key performance indicators
LCA	Life cycle assessment
LCAI	Life cycle assessment Inventory
LCC	Life cycle cost
LCPA	Life cycle performance assessment
LOD	Level of Development
MCR	Maximum continuous rating
PCTC	Pure car and truck carrier
RORO	Roll on roll off
Ro-Pax	Roll on roll off - Passenger
SBS	Ship breakdown structure
SWBS	Ship work breakdown structure
TRL	Technology readiness level

List of figures

List of tables

1 Introduction

1.1 Background

Shipping is responsible for approximately 1.076 billion tons of greenhouse gas emissions (GHG) in the year 2018, which is 2.9% of the global human-caused emissions, out of 98% being carbon dioxide (Albo-López et al., 2024). The Shipping industry's main regulatory body, the International Maritime Organization (IMO), has taken further steps in GHG emissions had set new targets to achieve net zero by or around year 2050 (International Maritime Organization, 2023) and the European Union has set new targets to achieve net-zero GHG emissions in 2050, with intermediate targets of 55% reduction at 2030 and 90% reduction at 2040 compared to year 1990 GHG emissions (European Commission, n.d.). These targets drive the maritime industry toward net-zero emissions, while the major emphasis is to reduce the operational phase emissions, which is accountable for 90% of the total lifetime emissions of combustion-linked pollutants such as CO2, SOx, NOx, and particulate matter (Chatzinikolaou and Ventikos, 2014).

With new technological developments and shipping industry governing bodies' guidelines, the maritime industry pursues decarbonization of propulsion and fuel systems, with the introduction of forward-looking, low-carbon fuel scenarios leading to a considerable reduction in operational phase emissions while substantially increasing the share of material and structures emissions up to 40% (Kwon et al., 2025). The regulatory bodies are enforcing the implementation of the carbon footprint of the products beyond their operation phase, which drives towards their material and structure. For example, the European Union's Carbon Border Adjustment Mechanism (EUCBAM) enforces the requirement of embedding the carbon footprint of the trading goods from 1st of January 2026 (Kwon et al., 2025). Evaluation of GHG emissions from all phases of a ship's lifetime becomes increasingly demanding in this new context, where cradle to grave life cycle assessment (LCA) is becoming more popular and important for shipbuilding (Kwon et al., 2025). This leads to material suppliers as well as ship builders focusing on LCA of new building ships. These developments point towards a credible, structured method for assessing the environmental impact of not only ship operational impact but also ship material and structures' impact on the carbon footprint.

The ship design process follows an iterative design process following the well-known ship design spiral introduced by J.H. Evans in 1959 (Papanikolaou, 2026). In 19050's commercial ship design process includes several design stages, concept design, preliminary design, contract design and detail design (Papanikolaou, 2026). The commercial ship design process evolved considerably with the introduction of computer-aided design technologies, at present, ship design process incorporates simulation driven design, parametric optimisation, digital twins, artificial intelligence and life cycle management (including life cycle sustainability) (Papanikolaou, 2026). Keiramo et al. (2018) had introduced a double spiral ship design concept, which demonstrate the high complexity and multidisciplinary nature of the modern ship design process. These evidence shows that the present design approach has given a higher consideration for ship LCA in its early stage of commercial ship design.

The conceptual design stage defines the ship's principal characteristics, including its mission, principal specifications, operating profile, and propulsion system (Trupper, 2013). Because these decisions determine many of the vessel's material, energy, and operational requirements, they have a significant influence on its lifetime carbon footprint and overall environmental performance (Gualeni & Maggioncalda, 2018).

International Organization of Standardization (ISO) has developed and published methodology to evaluate the LCA of product and systems. ISO 14040 (SFS, 2020a) defines the principle and framework, and ISO 14044 (SFS, 2020b) defines the requirements and guidelines for LCA of a product or a system, covering the full cradle-to-grave system boundary. However, applying LCA at the conceptual design stage of a ship yields specific difficulties due to certain factors, such as a lack of detailed drawings, a lack of material specification or take-off, and design changes during this stage. But at the conceptual design stage, the ship's major systems could be understood at a structural level. This understanding is typically organized through an established industrial work breakdown structure (IWBS), such as the SFI group system or the Expanded Ship Work Breakdown Structure (ESWBS), to classify the principal systems of the vessel. This thesis investigates whether such IWBS can serve as the material organizing structure of a concept-stage generic LCA tool, which enables environmental impact to be estimated and assigned to any kind of ship, while detailed design data is unavailable, and develops and tests such an LCA tool.

1.2 Problem statement

Existing applications of LCA in shipbuilding have tended to fail into one of the two categories, neither of which fully addresses the concept design stage problem this thesis targets. The first category includes detailed, later stages of the ship life cycle LCA studies of specific vessels or specific ship materials, which require a level of material and process details unavailable at the concept design stage. For example, Kown et al., (2025), on shipbuilding steel under EUCBAM exposure. The second category comprises broader maritime LCA methodology reviews (Chatzinikolaou and Ventikos, 2014) that establish the applicability of LCA to shipping in principle but do not provide an operational, structurally organized tool for concept stage ship design generic LCA tool for practical use.

A closely related precedent exists in Gualeni and Maggioncalda (2018), who developed an early-design stage Life Cycle Performance Assessment (LCPA) tool combining cost and environmental key performance indicators (KPIs) around a dedicated ship breakdown structure (SBS). The tool verified and validated via a Ro-Pax ship case study. Even though it built around a blended cost and environment KPI framework rather than EN 15804 (SFS, 2019) modular LCA structure, it demonstrates the feasibility and value of an IWBS-based concept stage ship LCA tool. Furthermore, the tool does not integrate with the existing industry recognized WBS standards, such as SFI or ESWBS, but with its own SBS. A gap, therefore, remains for a tool that is:

- organized around a recognizable, industry-relevant ship work breakdown structure (SWBS),
- capable of full cradle to grave environmental assessment aligned with EN 15804 (SFS, 2019) modular reporting, and
- usable with the level of information genuinely available at the concept design stage of a ship.

1.3 Research objectives and research questions

The problem statement outlined above provides the basis for the present research study. In response to the problem outlined above, the study aims to achieve its overall gaol through a set of specific research objectives. The following objectives define the key areas of investigation required to address the identified problem and provide direction to the study.

- To develop a generic ship IWBS (referred to throughout this thesis as the SWBS) suitable for organizing material and structural inventory at the conceptual design stage, independent of any single proprietary classification system.
- To design and implement a spreadsheet-based LCA calculation tool that links the SWBS to a material environmental impact database, supporting full EN 15084 modular reporting (A1-A5, B1-B7, C1-C4 and Module D) (SFS, 2019).
- To model the ship lifecycle explicitly across its building, operation, maintenance, and scrapping stages within the tool's calculation logic, including the treatment of periodic material renewal and whole unit component replacement.
- To populate the tool's material database using verified data sources such as manufacturer Environmental Product Declarations (EPDs) and industry / academic sources, and to apply and formally verify the LCA tool's calculation architecture.
- To validate the tool's outputs against independent published benchmarks for ship and shipbuilding material LCA and to critically discuss its capabilities, limitations, and appropriate scope of use at the concept design stage.

To guide the investigation towards achieving the above objectives, the study is guided by the following research questions.

RQ 1
How can an existing IWBS be adapted to develop an IWBS, which is suitable for organizing environmental impact data at the concept design stage, given that detailed material take-off information is not yet available?

RQ 2
What tool architecture and calculation logic are required to link such a work breakdown structure to a cradle to grave material impact database, while correctly representing the distinct ship lifecycle stages of Building, Operation, Maintenance, and Scrapping?

RQ 3
To what extent can such a tool be verified (in terms of calculation correctness) and validated (in terms of the credibility of its output against independent literature benchmarks)?

RQ 4
What are the practical benefits and limitations of a SWBS - based approach to concept stage ship LCA tool, compared with existing approaches in the literature?

1.4 Scope and limitations

This thesis is scoped to commercial vessels where the naval / combat-specific systems were excluded during the IWBS development stage, but those systems could be added to the SWBS as the end user requirement. The tool is specifically designed for the concept design stage for any commercial ship. It uses a simplified level of structural and material details, which is not sufficient for construction stage material take-offs. This difference is discussed further in Chapter 3 in relation to the Level of Development (LOD) used in early-stage ship design LCA. The environmental impact scope follows the EN 15804 international standard modular system (SFS, 2019, Clause 6.2.1). The EN 15804 (SFS, 2019) modular system considers all stages in the product life cycle, which includes the product stage (A1-A3) (SFS, 2019, Clause 6.2.2), construction stage (A4-A5) (SFS, 2019, Clause 6.2.3), Use Stage (B1-B7) (SFS, 2019, Clause 6.2.4 & Clause 6.2.5), End-of-Life stage (C1-C4) (SFS, 2019, Clause 6.2.6), and beyond the system boundary (Recycling/D) (SFS, 2019, Clause 6.2.7). The primary reported indicator is considered the Global Warming Potential (GWP, kg CO2-equivalent) for this study. Other indicators were not considered in this study. But the total environmental impact in terms of GWP is used. The data quality has three major components: the primary third-party certified EPD data, secondary data extracted from the literature, which are third-party certified, and the third is data extracted from literature, which are not third-party certified but verified and validated. This will be discussed explicitly in the validation and results chapter.

A further scope limitation, brought into focus by comparison with recent concept-phase LCA methodology (Javad, 2025), is that the tool does not currently distinguish materials or technologies by Technology Readiness Level (TRL). A structural steel record and a hybrid battery system record are treated identically as material database entries, despite representing technologies at materially different levels of maturity and data availability. The former technology is a well-established production process with reliable data, but the latter is still evolving and has less available data. This is not corrected within the scope of this thesis but is noted explicitly as a limitation relevant to interpreting any case study results involving emerging technology components.

1.5 Structure of the thesis

Chapter 2 reviews the literature underpinning the research. The LCA Principles and standards, LCA methodology and tools, LCA application in ship design and ship building, LCA application in other industries and material systems relevant to shipbuilding (notably steel, aluminium, copper, and marine batteries), IWBS practice in ship building: this means the shipbuilding industry's own classification system, such as SFI and ESWBS, instead of general project work breakdown structure; and existing tool for maritime LCA, concluding with a clear statement of the research gap this thesis addresses. The third chapter sets out the research methodology, including the framework for tool development, system boundary and functional unit definitions, data collection methods, and the approach to integrating the Industrial IWBS into the LCA framework. Chapter 4 describes the development of the tool itself. That is, tool architecture, the mapping of ship materials and structures to the IWBS, data inputs, calculation methods, and the implementation of the ship lifecycle stages.

The case study is presented in the chapter five, in which the tool is applied to a Ro-Pax ferry vessel, covering the full lightship weight breakdown into structural, machinery and outfit categories, the material decomposition of each, the estimation of operation fuel consumption, and the resulting lifecycle GWP results, and benchmarking against comparable published vessels. Chapter 6 includes the tool's verification and validation consists of: structural compliance with ISO 14040 (SFS, 2020a) and ISO 14044 (SFS, 2020b), formula and architecture testing with synthetic test cases, a data quality assessment of the material database, benchmark comparison against independent published literature, a consistency check of the tool's own method, and a sensitivity analysis. It is presented as a separate chapter from the results and discussion because it provides substantial evidence on its own. In Chapter 7, answers the thesis research questions based on the evidence, and a comparison with existing methods and the tools' benefits and limitations. Thesis conclusions, summarising contributions, practical implications, and recommendations for future work is presentedäösdv6y in the final chapter, Chapter 8.

2 Literature review

2.1 Life cycle assessment principles and standards

LCA is formally defined and standardized under ISO 14040 (principles and framework, (SFS, 2020a)) and ISO 14044 (requirements and guidelines, (SFS, 2020b)), which together establish the four-phase LCA structure. These are goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation, which are used throughout the thesis (ISO, 2006(a); ISO, 2006(b)). Of relevance to a tool development research, ISO 14044's interpretation phase explicitly defines three checks that any LCA study should be able to demonstrate, which are completeness check (ISO 14044, Clause 4.5.3.2), a consistency check (ISO 14044, Clause 4.5.3.4), and a sensitivity check (ISO 14044, Clause 4.5.3.3), (SFS, 2020 (b)). These three checks are adopted directly as the organising framework for this thesis's validation approach (in Chapter 6).

Within the European building and construction sector, EN 15804 extends the ISO 14040 and ISO 14044 frameworks into a standardised set of life cycle modules presented in the Table 2.1 (SFS, 2019). Although the standard is developed for construction products rather than ships, this modular structure has a practical advantage for the ship LCA tool as it is the reporting structure used by the overwhelming majority of Environmental Product Declarations manufacturers' (EPD's) available for structural materials, coatings, cables, and equipment. This is confirmed by the EPD-based material records compiled for the tool (Chapter 4). In addition, its separation of the use-stage submodules (B1-B7) aligns with the distinction made in this thesis between the building, operation, maintenance, and end-of-life stages of a ship's life cycle (SFS, 2019).

Table 2-1 EN 15804 (SFS, 2019) product life cycle module

Life Cycle Stage	Module	EN 15804 (SFS,2019)	Description
Product Stage	A1	Clause 6.2.2	Raw material supply
	A2	Clause 6.2.2	Raw Material Transport
	A3	Clause 6.2.2	Product Manufacturing
Construction stage	A4	Clause 6.2.3	Transport to Site
	A5	Clause 6.2.3	Installation
Use Stage	B1	Clause 6.2.4	Use
	B2	Clause 6.2.4	Maintenance
	B3	Clause 6.2.4	Repair
	B4	Clause 6.2.4	Replacement
	B5	Clause 6.2.4	Refurbishment
	B6	Clause 6.2.5	Operational Energy Use
	B7	Clause 6.2.5	Operational Water Use
End-of-Life Stage	C1	Clause 6.2.6	Deconstruction
	C2	Clause 6.2.6	Transport
	C3	Clause 6.2.6	Waste Processing
End-of-Life Stage	C4	Clause 6.2.6	Disposal
Benefits and Loads beyond the System Boundary	D	Clause 6.2.7	Reuse, Recycling, and Recovering

EN 15804 Product Life Cycle Stages and Modules

Module	Description
Product stage	
A1 Raw material extraction	Extraction and sourcing of raw materials and natural resources used to make the product, e.g. ore mining, quarrying, or harvesting of feedstock.
A2 Raw material transport	Transport of the extracted raw materials from the point of extraction to the manufacturing facility.
A3 Product manufacturing and storage	Processing and manufacturing of raw materials into the finished product, including on-site storage, packaging, and internal transport within the factory.
Construction stage	
A4 Transport to site	Transport of the finished product from the factory or distributor to the construction site.
A5 Installation	Installation or assembly of the product into the building or structure, including installation losses and associated waste.
Use stage	
B1 Use	Impacts arising directly from the installed product during normal use, e.g. off-gassing, wear, or leaching, over the reference study period.
B2 Maintenance	Planned, preventive actions to keep the product functioning as intended, e.g. cleaning, inspection, and servicing.
B3 Repair	Corrective actions restoring the product to working order after damage or failure, including repair materials and processes.
B4 Replacement	Replacing the product or a component once it reaches the end of its service life, including removal of the old unit and installation of the new one.
B5 Refurbishment	Larger-scale renovation or upgrade works carried out to extend the service life or improve performance of the product or building.
B6 Operational energy use	Energy consumed by the installed product or building during operation, e.g. heating, cooling, lighting, or equipment use.
B7 Operational water use	Water consumed by the installed product or building during normal operation.
End-of-life stage	
C1 Deconstruction / demolition	Demolition or deconstruction of the product or building at the end of its service life.
C2 Transport (waste)	Transport of the demolished/deconstructed materials from the site to a waste processing or disposal facility.
C3 Waste processing	Processing of waste materials for reuse, recovery, or recycling, e.g. sorting, crushing, or shredding.
C4 Disposal	Final disposal of waste that is not reused, recovered, or recycled, e.g. landfilling or incineration without energy recovery.
Beyond the system boundary	
D Reuse, recycling, recovery	Net benefits and loads from materials and energy leaving the product system for reuse, recycling, or energy recovery in another system. Reported separately, not summed into the A1–C4 result.

Figure 2-1 EN 15804 Product Life Cycle stages and modules

Figure 2-1 presents the EN 15804 product life cycle stages and modules applied within the LCAI Reference data sheet developed for this thesis, which underpins the evaluation of the total environmental impact of materials and structures.

Historically, data quality assessment in LCA has been dominated by the pedigree matrix approach originally developed by Weidema and Wesnæs (1996), which scores each data point against indicators of reliability, completeness, temporal assumptions, geographical, and technological representativeness before aggregating these into an overall quality classification. However, this expert judgement-based scoring has been shown to produce inconsistent results across practitioners. A multi-user test of the method found that consistency in indicator scoring was very poor, even among LCA practitioners with a similar level of experience, with deviations traced to unclear database documentation and differing interpretation of the scoring criteria (Edelen and Ingwersen, 2016).

More recent literature has instead pointed toward provenance-based data recording as a more traceable and reproducible alternative. Untraceable data sources remain a well-documented limitation in LCA practice, with secondary database frequently lacking explicit documentation of the technological, geographical, and temporal assumptions behind each data point, understanding reproducibility and making it difficult to verify whether a dataset is fit for purpose; in response, LCA data base are increasingly called to evolve toward architectures capable of storing Provenance-linked metadata alongside spatial and temporal detail, so that a data point's origin and context can be verified directly rather than inferred from an expert-assigned quality score (Xu et al., 2025). In parallel, assessing the completeness and comparability of EPD's has become a growing research focus given the increasing number of EPD's and their importance for building level life cycle assessment. With recent work proposing structured approaches to assess and assure EPD data quality directly from the declared metadata rather than through post-hoc expert scoring (Olanrewaju et al., 2025).

This thesis therefore does not adopt the pedigree matrix. Instead. It applies a set Provenance-based criteria for recording and assessing the quality of material records complied in its LCAI reference database (Chapter 4), drawn directly from the metadata reported within EPD's – including the manufacturing site, reference year, geographical scope, citation and underlying database or dataset version used to generate each declaration – anchoring data quality in traceable, independently verified provenance information rather than in subjective, expert-assigned scores.

2.2 Life cycle assessment methodologies and tools

Beyond the core ISO/EN standards, the practical conduct of LCA studies vary considerably in software platform, impact assessment method, and database used (Miranda Xicotencatl et al., 2023). Commercial software such as GaBi and SimaPro, paired with databases such as Ecoinvent, are widely used in both industry and academic LCA studies. For example, the World Steel (2017) global steel life cycle inventory study used GaBi 7.3 with data collected via a standardised web questionnaire from 109 sites across 28 countries, while Yadev et al. (2020) used SimaPro 9 with Ecoinvent 3.5 and the ReCiPe 2016 impact assessment method for a comparative bio-methanol production study. This variation in software, impact method, and database between studies is a recurring practical obstacle to direct comparability of LCA figures across sources (Miranda Xicotencatl et al., 2023). This is a challenge directly relevant to the compilation of a multi-source material database (Chapter 4), where records drawn from different manufacturers' EPDs may not share an identical underlying LCA software or database despite reporting to the same EN 15804 module structure.

For early design stage applications specifically, where detailed material and process information is not yet available, simplified, parametric, or top-down estimation approaches are more commonly used in place of a fully process-based bottom-up approach in LCA calculations (Roberts et al., 2020). This is analogous to the Level of Development (LOD) concept used in Building Information Modelling (BIM) based early design LCA tools for the construction sector, where progressively increasing LOD reflects the availability of design information. Early-stage assessment relies on generic or aggregate building elements, whereas fabrication and construction level details are represented only at the LOD 400 and above (Santos et al., 2020). This thesis adopts the same logic in justifying the granularity of its IWBS (Section 2.5, Chapter 3).

2.3 LCA in ship design and shipbuilding

As introduced in the Chapter 1, ship design process goes though iterative process of ship design spiral originally developed by J.H. Evans in 1959 in all four ship design stages for commercial ships (Papanikolaou, 2026). Ship design has evolved significantly pass few decades with the introduction of the computer-aided design into all four stages of ship design. Keiramo et al. (2018) extended the classical ship design singular spiral to double spiral ship design process for advanced modern cruise ship designs, incorporating complex architectural and technical system requirement. The paper introduces separate design spiral which focuses on defining the vessel's vision, operational requirements, and stake holder needs and the second spiral for technical and engineering solutions as in the classical spiral, while both spirals are interacting each other in the iterative process till it reaches a feasible solution (Keiramo et al., 2018).
This framework reflects the multidisciplinary nature and the high complexity of the modern commercial ship design process and the important role that the concept design stage plays in the ship building decision making process.

The Figure 2.1 illustrate the typical ship design process, which clearly showing how the concept design stage influences the ship building decisions. Papanikolaou (2026) highlights the influential effect of new IMO and other regulatory bodies guidelines towards net zero shipping, the importance of applying LCA at the conceptual stage, which helps designers and the investors to take right decision at early stage.

Chatzinkolaou and Ventikos (2014) provide an early and widely cited review of LCA application in shipping. Their study establishes the use of cradle to grave LCA for assessing ships and confirms that, for conventionally fuelled vessels, the operational phase has historically been the dominant contributor to combustion related emissions, consistent with the discussion in Chapter 1. Their review, however, does not present an operational software tool, leaving a gap between methodological validation and practical implementation.

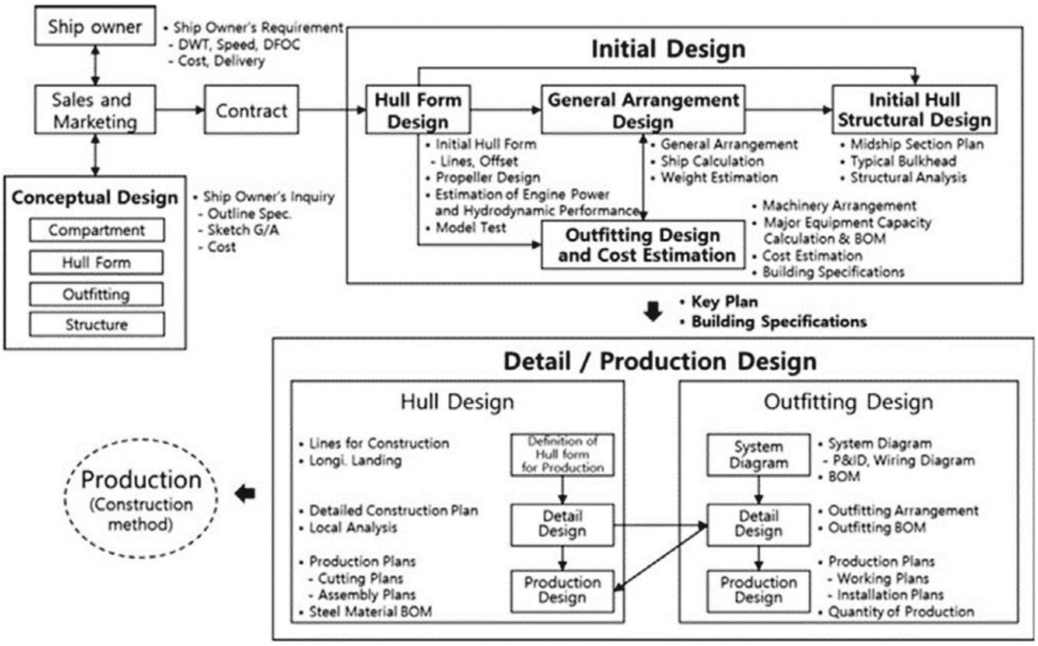


Fig. 1.21 Ship design procedure (Roh and Lee 2018)

Figure 2-2 Ship design process (Papanikolaou, 2026)

Gualeni and Maggioncalda (2018) address part of this gap by developing the (LCPA) tool for early-stage ship design. The tool integrates cost and environmental KPIs within a single assessment framework and is organised around a purpose-built SBS. The SBS is a three-level hierarchical decomposition of the vessel (e.g., 1.1.1 Hull, 1.1.2 Superstructure, and 1.2.1 Main Engine) that directly links design parameters to cost and environmental performance indicators. Importantly, the authors verify and validate the LCPA tool and its reliability through a Ro-Pax ship case study (Gualeni and Maggioncalda, 2018). This verify and validate approach, applied to a closely comparable problem, is also adopted in Chapter 6 of this thesis. The LCPA's SBS provides a valuable basis for comparison with the IWBS developed in this thesis (Chapter 3). Nevertheless, the two approaches differ in two important respects. The SBS is neither built around nor benchmarked against an existing industry-standard ship classification system, and it employs a blended cost-environment KPI structure rather than a full EN 15804 modular breakdown.

More recently, Kown et al. (2025), conducted a scenario-based LCA of shipbuilding materials specifically in the context of the EUCBAM, using GaBi software under ISO 14040/14044 compliance. Their findings are directly relevant to the validation work presented in Chapter 6 of this thesis. Under baseline blast furnace / basic oxygen furnace (BF-BOF) steelmaking assumptions, structural steel accounts for approximately 75-85% of a vessel's lightweight by mass but contributes 90-95% of cradle-to-gate embodied greenhouse gas emissions. This figure is highly sensitive to the steelmaking route, varying by more than 20% between BF-BOF and electric-arc-furnace (EAF) production. The study also confirms that the construction-phase share of total lifecycle emissions can rise towards 40% under forward-looking, lower-carbon operational fuel scenarios, reinforcing the motivation (Section 1.1) for a materials-focused, concept-stage LCA capability alongside the existing operational phase focus of maritime environmental research.

Hull maintenance strategy, a central component of the ship life cycle architecture developed in Chapter 4, has itself been the subject of dedicated LCA and life cycle costing (LCC) research. Wang et al. (2018) assessed the LCC and environmental impact of alternative hull maintenance strategies for a short-route hybrid ferry, establishing that hull steel is renewed on a scheduled basis (commonly associated with the roughly five-year classification society special survey cycle) rather than replaced as a single whole unit, which is directly supporting this thesis's choice to model hull steel renewal via a percentage-per-survey mechanism rather than a whole unit replacement mechanism (Chapter 4). Kim et al. (2025) extended this line of research with a Baltic Sea Ro-Pax hull maintenance case study, evaluating 93 maintenance scenarios using the HullMASTER decision-support tool, providing an additional, more recent literature source against which the illustrative renewal-rate parameters used in this thesis's tool can eventually be benchmarked or replaced with cited figures.

Ling-Chin and Roskilly (2016a, 2016b, 2016c) provides the most detailed published LCA case studies of ship power systems found in this review. Their work covers three configurations on the same Ro-Ro cargo ship. These are a conventional diesel-mechanical system, a retrofit system with added photovoltaic and battery technology, and a new-build all-electric hybrid system. Each study reports a full material inventory by mass. Each reports real component data. Each reports a single headline GWP figure. The hybrid system study reports 561,000 tons of CO2 equivalent over a 30-year life span. Diesel genset operation is found to dominate most impact categories. Disposal of metallic scrap is found to dominate ecotoxicity. This is the closest published precedent to a full system, multi-material ship LCA case study identified in this review. It is used as one of the principal references for the validation presented in Chapter 6 of this thesis.

Tuan and Wei (2019) present a cradle to gate LCA of a Panamax-size bulk carrier. Their case study is conducted using the ship MV Prabhu Yurikka, a 76,300 DWT vessel, where the study reports full material inventory. Hull steel accounts for 84.6% of lightship weight, 10.4% of outfitting weight, and the remaining 5% for machinery. A sensitivity analysis shows that a 55% change in the steel weight changes overall results by only 4.4% - 4.9%. This confirms that hull steel is the dominant, but not solely decisive, driver of embedded emissions. This weight split is used as a cross-check in this thesis case study (Chapter 5).

2.4 LCA in other industries, materials, and systems

2.4.1 Structural steel

The World Steel Association's 2017 Life Cycle Inventory study is the most authoritative and widely cited source of cradle to gate (production stage) steel LCA data available. Covering 16 steel products, 23 process stages (554 total unit processes), 109 sites, and 28 countries, and critically reviewed under ISO/TS 14071. The study reports cradle to gate Global Warming Potential of 1.5 kg CO2-equivalent per kg for steel sections, 2.2 kg CO2-equivalent per kg for hot-rolled coil, and at the 85% end of life recycling rate, approximately 1.0 - 1.4 kg CO2 - equivalent per kg (Worldsteel, 2018). The study further establishes that carbon dioxide and methane together account for over 98% of the steel industry's greenhouse gas emissions. In addition, applying system expansion to account for co-product credits (e.g., slag and process gases) increases the reported global warming potential by 3.4 % - 6.6% relative to an assessment that excludes these credits. This sensitivity analysis directly informs the treatment of Module D credits for steel in the tool presented in Chapter 4.

2.4.2 Aluminium

Aluminium alloys are widely used in shipbuilding for hull, lightweight structural components, superstructures, accommodation spaces, and equipment where weight reduction improves fuel efficiency and payload capacity (Hosseinabadi and Khedmati, 2021). Compared with steel, however, the LCA of aluminium is more sensitive to assumptions regarding recycled content and end-of-life allocation because of aluminium's high economic value and its ability to be recycled repeatedly with relatively little loss of material quality (Nuss and Eckelman, 2014; European Aluminium, 2018; International Aluminium Institute, 2023).

The International Aluminium Institute (2023) reviews the treatment of aluminium recycling across the principal standards governing carbon footprint and LCA calculation, including ISO 14044, ISO 14067, ISO 2193, and EN 1580+A2. The report concludes that these standards do not prescribe a single, universally applicable approach for allocating environmental burden associated with process scrap and recycled material. Instead, they permit different allocation methods, including cutoff, co-product allocation, and substitution (avoid burden), depending on the goal and scope of the assessment. Illustrative case studies demonstrate that, for the same production data, cradle to gate (production stage) greenhouse gas emissions can vary from 4.60 to 10.86 tCO2-eq. per tonne of aluminium product solely because of the allocation methodology applied.

These findings are consistent with broader LCA literature, which identifies recycling allocations as one of the principal methodological sources of variability in aluminium LCA (European Aluminium Association, 2013; European Aluminium, 2018). They are therefore directly relevant to the material modelling approach adopted in this thesis, where the cut-off approach is provisionally selected for end-of-life modelling because it provides a conservative treatment of recycled content while remaining compatible with the EN 15804 Module D (SFS, 2019) reporting framework implemented in Chapter 4.

2.4.3 Copper

Copper is an important engineering material in shipbuilding, primarily used in electrical power distribution, cabling, motors, transformers, and electronic systems because of its high electrical conductivity, corrosion resistance, and durability. Although copper represents a relatively small proportion of a vessel's structural mass compared with steel, its production is considerably more energy-intensive and therefore contributes disproportionately to embodied greenhouse gas emissions (Nuss and Eckelman, 2014). Consequently, accurate modelling of copper products is important in ship LCA, particularly for electrical systems represented within this thesis by an EPD for copper / XLPE power cable (Chapter 4).

LCA of copper production is complicated by the presence of multiple valuable co-products, including precious metals recovered during smelting and electrolytic refining. The International Copper Association (2022) provides harmonised guidance for calculating the carbon footprint of copper production across both pyrometallurgical and hydrometallurgical production routes. The guidance recommends economic allocation using a multi-year average metal price to distribute environmental burdens between copper cathode and co-products, thereby improving methodological consistency across studies. It also specifies data quality requirements, including a material balance tolerance of (+/-) 20% for individual unit processes, providing a useful benchmark for assessing the reliability of copper-related inventory data used in this thesis.

Previous LCA research further demonstrates that the environmental performance of copper (production stage) is strongly influenced by ore grade, mining practice, energy supply, recycling rates, and allocation methodology (Classen et al., 2009; Nuss and Eckelman, 2014). In particular, recycled copper production typically exhibits substantially lower greenhouse gas emissions and energy demand than primary production, making the recycled content and end-of-life recovery assumptions particularly important when interpreting embodied carbon results (Nuss and Eckelman, 2014). These findings reinforce the importance of transparent inventory selection and allocation procedures within the material database developed for this thesis.

2.4.4 Marine battery and onshore power systems

As hybrid and battery-electric propulsion and auxiliary power systems become more common on commercial vessels, their environmental assessment is an emerging but still limited area of the literature. Albo-López et al. (2024) evaluate onboard battery systems and onshore power supply as alternative strategies for reducing in-port emissions from Ro-Ro vessels, using a case study vessel on the Montori-Vigo route. Their findings quantify a standard marine emissions factor of 3,179 kg CO2 per ton of fuel consumed and demonstrate that shore-power cost alongside a 16.5% emissions reduction relative to auxiliary engine hotelling, while fuel onshore power supply can achieve up to an 81.7% emissions reduction. Even though the grid carbon intensity is low in onshore power supply, cost-effectiveness varies sharply by port depending on local electricity pricing. This body of work complements the battery-specific LCA literature reviewed separately for the hybrid battery system components included in this thesis. Independent peer-reviewed review studies report lithium-ion battery cradle to gate (production stage) global warming potential value typically ranging from approximately 58 to 140 kg CO2-eq/kWh, depending on chemistry and manufacturing assumptions (Peters et al., 2017). These findings are complemented by the dedicated marine battery LCA of Percic et al. (2022), which identifies lithium iron phosphate batteries as an environmentally favourable option for maritime applications.

2.4.5 Methodological transferability from other sectors

Beyond shipbuilding-specific materials, relevant methodological insights can be drawn from LCA studies in other sectors, particularly where similar modelling and inventory challenges are encountered. Yadev et al. (2020), assessing bio-methanol production from wood biomass as a potential marine alternative fuel feedstock, demonstrate the importance of sensitivity analysis in LCA. Their results show that changing the catalyst type increased the reported GWP by 348%, while changing the electricity grid source increased it by as much as 821%. These findings illustrate the extent to which LCA results can depend on the underlying modelling assumptions, many of which are not explicitly reported in summary results. The study provides a useful methodological reference for the sensitivity analysis presented in Chapter 6 of this thesis.

Rahman et al. (2026), reviewing the application of LCA and cradle to cradle approaches in textile wastewater treatment, and identify inconsistent system boundaries, unreliable inventory data, and unclear impact allocation between co-located facilities as recurring methodological challenges. Although the study concerns a different industrial sector, these findings demonstrate that such issues are common across LCA applications and support the emphasis placed in Chapter 6 on transparent boundary definitions and data quality assessment.

2.4.6 Marine fuels and operational-phase emissions

Since the ship operational life cycle stage depends on fuel emission factors, relevant literature was reviewed to identify representative values for the fuels considered in this thesis. Bengtsson et al. (2011) compare marine fuels including heavy oil, marine gas oil, and liquefied natural gas. They find that liquified natural gas offers only an 8 – 20% GWP advantage over heavy fuel oil. This advantage is highly sensitive to methane slip. Dong et al. (2023) evaluate the life cycle environmental performance of fossil, blue, and green hydrogen and ammonia fuels for tanker engines, demonstrating that the environmental benefits of these alternative fuels depend strongly on their production pathway. Green hydrogen gives the largest reduction, at 93% versus fossil baseline. blue ammonia gives only 35-38% reduction, despite being lower carbon in principle, because of a high upstream production burden. Zhang et al. (2025) review is the direct source for the marine diesel oil factor used in this thesis's tool (Chapter 4). Ahmed et al. (2023) model a full-life cycle, newly built, very large oil and chemical tanker case study. Green ammonia reduces whole ship GWP by more than 90% relative to a heavy fuel oil baseline, consistent with the other fuel-pathway studies reviewed here. Together, these studies confirm a consistent finding relevant to this thesis: a fuel's production route matters as much as its combustion chemistry when assessing true lifecycle emissions.

2.5 Industrial work breakdown structure (IWBS) in shipbuilding

Shipbuilding has a long-established tradition of organising design, procurement, and production information round standardised industrial work breakdown structures. The SFI Group System (originating form Skipsteknik Forskningsinstitutt in Norway) and the US Navy-derived Expanded Ship Work Breakdown Structure (ESWBS) are the two most widely referenced systems internationally. Both organising the ship into major functional groups (hull structure, propulsion, electrical systems, outfitting, and so on) with further numeric subdivision (Manchinu and McConnell, 1977; Naval Sea Systems Command, n.d.). This thesis's own Ship Breakdown Structure (SWBS) developed and refined over the course of this research (and documented in full in Chapter 3 and 4), was built using the SFI and ESWBS major group conventions as public domain structural basis and was subsequently consolidated and re-validated against literature and cross-industry equipment references data reach an appropriate for concept design stage assessment rather than construction stage material take-off.

Gualeni and Maggioncalda's (2018) ship breakdown structure, discussed in Section 2.3, represents closest published precedent for an IWBS purpose-built for early-design environmental/cost assessment, and its three-tier hierarchical numbering (Appendix A of that paper) provides a useful structural comparison point for the SWBS developed in this thesis. (Chapter 3, Section 3.5)

2.6 Existing tools and methods for LCA in the maritime sector

Drawing together Section 2.2-2.5, the maritime sector currently has:

a) Methodological reviews establishing the applicability of LCA to shipping (chatzinikolou and Ventikos, 2014);
b) detailed LCA studies focused on later design stages or individual materials (e.g., Known et al. (2025), for shipbuilding steel);
c) one closely comparable early design stage tool integrating cost and environmental key performance indicators (KPIs) within a dedicated Ship Breakdown Structure (Gualeni and Maggioncalda, 2018);
d) a growing, but fragmented, body of LCA data for individual materials and systems, including steel, aluminium, copper, marine batteries and hull structures.

However, this information has not yet been integrated into a single concept stage assessment tool based on an IWBS and aligned with the EN 15804 modular reporting framework (SFS, 2019) used by most manufacturer EPDs. No identified tool in the reviewed literature combines all of: (i) an industry recognised, non-proprietary industrial work breakdown structure; (ii) full EN 15804 modular (A1-A5, B1-B7, C1-C4, module D) reporting (SFS, 2019); and (iii) explicit modelling of the distinct ship lifecycle stages of building, operation, maintenance (including scheduled partial renewal, as distinct from whole unit replacement), and scrapping.

A further, more recent point of comparison is Javad (2025), who developed a concept-phase prospective LCA (pLCA) framework for net-zero emission ships, validated via a detailed openLCA/ecoinvent/premise case study of a cruise ship comparing marine gas oil and e-methanol fuel pathways projected forward from 2030 to 2064. This work provides a useful methodologically benchmark but differs from the tool developed in this thesis in several important respects. These differences are described explicitly below. First, it organises its case study directly as LCA software processes (separate process models for hotel area, machinery, hull equipment, and electrical systems within openLCA) rather than through an intermediate, reusable, industry-standard classification structure. Consequently, the primary output is a ship-specific LCA model rather than a general-purpose classification framework. Another notable difference is that, although presented as a concept phase methodology, the demonstrated case study is implemented at a relatively detailed process level and relies on specialist LCA software (openLCA) together with the licensed ecoinvent background database. In contrast, the tool developed in this thesis is deliberately coarse in its level of detail and is implemented as self-contained spreadsheet requiring neither specialist LCA software nor proprietary database. The approaches further differ in that the published methodology prospective, projecting future background-system changes using the premise tool, whereas the tool developed in this thesis provides a static, present-day assessment based on manufacturing EPDs.

The case study findings are nevertheless directly relevant to the validation presented in Chapter 6 of this thesis. The authors found that the operational phase accounted for 83.2% of total life cycle GWP under the conventional-fuel baseline, consistent with the earlier findings of Chatzinkolaou and Ventikos (2014). Their comparison of alternative fuel pathways further showed that replacing marine gas oil with e-methanol reduces GWP by 21.8 %, but increase terrestrial acidification by 25%, ozone formation (human health) by approximately 10%, and water consumption by more than threefold (from 1414 m^3 to 4794 m^3). These results demonstrate that improvements in a single environmental indicator may be accompanied by adverse impacts in others, highlighting the importance of adopting a multi-indicator perspective when comparing alternative fuels or materials. This observation is directly relevant to the interpretation of the results present in Chapter 7 of this thesis

2.7 Research gap

Taken together, the literature reviewed in this chapter identifies the following research gaps, which provide the rational for the work presented in this thesis.

- Absence of an industry-standard organising structure: Existing concept stage LCA tools demonstrate the feasibility of early design assessment (Gualeni and Maggionstrate, 2018; Javed, 2025), but none adopts a reusable, non-proprietary, industry recognised IWBS. Consequently, no general-purpose concept stage assessment framework based on an industry standard IWBS has been identified in the literature.
- Fragmented and unintegrated material data: Although authoritative LCA data are available for key shipbuilding materials, including steel, aluminium and copper (Worlsteel, 2017; International Aluminium Institute, 2023; copper Association, 2022; kwon et al., 2025), these data remain material-specific and are not integrated within ship structural framework suitable for concept stage assessment.
- Insufficient treatment of scheduled maintenance and renewal: Existing studies recognise that hull maintenance is a process of scheduled renewal rather than whole-component replacement, with important implications for life cycle GWP calculations (Wang et al., 2018; Kim et al., 2025). However, no reviewed study incorporates this maintenance strategy into the calculation architecture of a general-purpose ship materials LCA tool.
- Limited treatment of uncertainty and data quality: uncertainty, data quality, and sensitivity analysis remain inconsistently addressed in maritime LCA studies. Javad (2025), drawing on the wider maritime LCA literature, reports that only around 16% of studies incorporate a formal uncertainty assessment. This gap motivates the explicit use of the pedigree matrix for data quality assessment (Section 2.1) together with the dedicated verification and validation framework presented in Chapter 6.
- Software and Licensing dependency: Existing concept stage methodologies rely on specialist LCA software and proprietary background database (Javad, 2025), reducing their accessibility for wider application in ship design. This thesis addresses this limitation through a self-contained, spreadsheet-based implementation.

This thesis addresses these gaps by developing a non-proprietary, EN 15804-aligned generic LCA tool based on an IWBS. The tool explicitly models the building, operational, maintenance (including partial renewal), and scrapping life cycle stages, integrates manufacturer EPD and literature-derived material data within a single assessment framework, and is implemented as a self-contained spreadsheet requiring no specialist LCA software. Its verification and validation presented in Chapter 6, follow the case study-based approach adopted in the closest comparable studies (Gualeni and Maggionstrate, 2018; Javed, 2025).

3 Methodology

3.1 Research approach

This thesis adopts a Design Science Research (DSR) methodology, in which the primary research contribution is a design artefact in the form of as SWBS-based conceptual-design LCA tool. The artefact is developed through an iterative process, verified throughout its internal consistency and functional correctness, and validated against published literature, recognised standards, and representative case studies. As demonstrated in Chapter 2, no directly equivalent concept stage assessment tool exists in the published literature. A designed science research approach is therefore appropriate, with the research question addressed through the iterative design, development, verification and validation of a new tool, rather than through hypothesis testing alone.

The research preceded through three explicit stages. Stage 1 (Chapter 2) comprised a literature review and a gap analysis, establishing the methodological basis, the material and system data available in the literature. The second stage of the research (Chapter3 3 and 4) focused on the development of the IWBS-based LCA tool, including its architecture, calculation logic, and material database. Third and final stage (Chapter 5 - 6) of the consisted of application of the tool to a case study vessel and its subsequent verification and validation against the framework set out in Chapter 6.

Consistent with the DSR approach, the tool was developed through a series of discrete documented stages rather than a single design-and-build process. These stages included establishing an IWBS, cross-checking it against an existing classification schemes and industry practices, refining it through criteria-based consolidation (Section 3.6). In parallel, a material impact database was structured and populated using cited data from EPDs and the published literature (Section 3.5). Throughout development, assumptions, design decisions, and limitations were systematically recorded in the tool’s Boundary and Limitations record. This document serves as primary source for defining the tool’s scope and is referred extensively through this chapter and Chapter 4.

3.2 Framework for LCA tool development

The tool is structure around four functionally distinct components, each implemented as a dedicated worksheet within a single spreadsheet workbook. This first worksheet, named SWBS within the tool, implements the IWBD developed in this thesis and lists every ship item or system that can be assessed during the conceptual design stage of the ship. The second worksheet is the LCAI Reference worksheet, contains the material and product impact database, listing every material, consumable, components or equipment with an associated environmental footprint. The third, the LCA calculation worksheet, links individual ship items to SWBS entries and assigns materials and total environmental impact (total GWP), product life span, product measuring unit from the LCAI Reference database. Finally, the Results sheet which aggregate the calculation sheet’s output as a total and by major ship system group. Although the tool does not explicitly calculate intervals or standard deviations. Nevertheless, it implicitly enables parameter sensitivity analysis by allowing input parameters to be varied within predefined uncertainty ranges. These uncertainty assumptions were subsequently used to conduct the sensitivity analysis and evaluate the influence of individual parameters on the resulting outputs.

A specific design requirement adopted during development was that the SWBS and LCAI Reference components should be independent. Users should be able to add a new ship system or material record directly into the relevant worksheet, and new entries become immediately available for selection and calculation in LCA Calculation worksheet, without any manual synchronisation step or modification of formulas. This was implemented by pre-extending the active row range up to 5000 rows of both the SWBS and LCAI Reference sheets, and the corresponding dropdown selection lists and lookup formulas in LCA calculation sheet. This functionality is verified by inserting test records near the upper limit of the predefined range and confirming that they were correctly recognised and processed in the calculations. This design reflects the methodological principal that a concept stage engineering tool intended for practical application should be extensible by end users without intervention from the original developer.

The calculation method behind LCA Calculation worksheet follows the same basic logic used in comparable published ship LCA studies. Quang et al. (2021) provide a clear published example, in which total life cycle emissions are obtained by aggregating the contribution from five distinct life cycle phases: row material production, shipbuilding, operation, maintenance and end-of-life cycle phases. Within each phase, physical inventory data (e.g. Electricity use, material consumption, painting activities, etc.) are multiplied by the corresponding emissions factors to quantify environmental impacts, which are then subsequently translated to environmental impact categories using the CML 200 characterisation method.

The calculation methodology adopted in this thesis differs from the conventional process-based approach. Rather than reconstructing the GHG emissions from detailed process inventory data, the tool adopts a material-based approach using GWP data derived from EN 15804+A2 EPDs. For each material, the cradle to grave GWP value is obtained by summing the GWP contribution reported for the Product stage (A1-A3) (SFS, 2019, Clause 6.2.2), Construction stage (A4-A5) (SFS, 2019, Clause 6.2.3), Use stage (B1-B7) (SFS, 2019, Clause 6.2.4/5), and End of life stage (C1-C4) (SFS, 2019, Clause 6.2.6) life cycle modules. This combined GWP value, expressed in kgCO2-eq per declared unit, is then used as the material impact factor throughout the assessment. Although EN 15804+A2 EPDs report additional environmental impact indicators, the present implementation considers only GWP. The main advantage of this material impact factor is that it could be applied to any industry universally as it considers all the relevant factors covering all the stages of a product life cycle.

This material impact factor is subsequently applied within the ship LCA framework developed in this thesis. The tool recognises four ship lifecycle stages: Building, Operation, Maintenance and Scrapping. Materials are introduced into the ship only during the building, Operation and Maintenance stages, and these are therefore the stages for which material quantities are entered and environmental impacts are calculated. For each of these stages, the cradle to grave material impact factor is multiplied by the quantity of material introduced. A separate Scrapping-stage calculation is not required because the End-of-Life (C1-C4) (SFS, 2019, Clause 6.2.6) impacts are already incorporated within the material's cradle to grave impact factor. Module D (SFS, 2019, Clause 6.2.7) is treated independently by multiplying the

Module D impact factor for each material by the cumulative quantity introduced throughout the ship's lifetime. The resulting recycling credits are reported separately in the assessment results, consistent with the EN 15804 reporting framework (SFS, 2019, Clause 7.5).

The calculation procedure described above is implemented using the following equations.

Material cradle-to-grave impact factor
For each material, the cradle to grave GWP factor is determined by summing the GWP values reported for the Product, Construction, Use and End-of-life stages of the corresponding EN 15804 modular framework EPD:

$$L_i = \sum_{m=A1}^{C4} GWP_{i,m}, \tag{3.1}$$

where:

L_i = cradle to grave GWP of material i (kg CO_2-eq per declared unit)
$GWP_{i,m}$ = Global Warming Potential of material i for EN 15804 module m.

Building stage
The Building-stage impact for material i (O_i) is calculated as:

$$O_i = N_i . H_i . L_i, \tag{3.2}$$

where:

N_i = Quantity of material per item
H_i = Number of identical items
L_i = cradle to grave GWP factor (A1-C4) per declared unit

Operation stage
The Operation-stage impact (Q_i) is:

$$Q_i = P_i . H_i . L_i, \tag{3.3}$$

where:

P_i = Operational material consumption
H_i = Number of identical items
L_i = cradle to grave GWP factor (A1-C4) per declared unit

The same calculation applied to all operational consumable represented in the LCAI Reference database, including fuels, lubricants, coatings and other materials.

Maintenance stage
The replacement quantity (R_i) is first determined.
when the service life is known:

$$R_i = N_i . H_i . \left[max\left(0, \left\lceil\frac{Design\ Life}{Item\ Life}\right\rceil - 1\right)\right] \tag{3.4}$$

Alternatively, where renewal percentage information is available:

$$R_i = N_i . H_i . \left(\frac{Renewal}{100}\right) . (Number\ of\ Surveys) \qquad (3.5)$$

The maintenance impact (S_i) is then:

$$S_i = R_i . L_i \qquad (3.6)$$

Each replacement is treated as a newly introduced material and therefore carries the same cradle to grave impact as the original installation.

Module D
The cumulative material quantity (V_i) introduced during the ship's lifetime is:

$$V_i = (N_i . H_i) + R_i \qquad (3.7)$$

The recycling credit (X_i) is:

$$X_i = V_i . D_i \qquad (3.8)$$

where:

D_i = Module D GWP value from the LCAI Reference database

Module D is reported separately from the cradle grave impacts accordance with EN 15804, Clause 7.5 (SFS, 2019).

Overall life cycle GWP and module D recycling credit
The total GWP of the ship is obtained by summing the Building, Operation and Maintenance impacts for all materials:

$$GWP_{Ship} = \sum_i (O_i + Q_i + S_i) \qquad (3.10)$$

The total module D recycling credit is calculated independently by summing the recycling credits for all materials introduced throughout the ship's lifetime:

$$GWP_{Module\ D} = \sum_i X_i \qquad (3.11)$$

3.3 Definition of system boundaries

The tool adopts two complementary system boundaries. The first follows the EN 15804 (SFS, 2019) modular framework introduced in Section 2.1, comprising the product stage (A1-A3) (SFS, 2019, Clause 6.2.2), Construction stage (A4-A5) (SFS, 2019, Clause 6.2.3), Use stage (B1-B7) (SFS, 2019, Clause 6.2.4/5), and End-of-life stage (C1-C4) (SFS, 2019, Clause 6.2.6) and module D (SFS, 2019, Clause 6.2.7) (benefits and loads beyond the system boundary). Consistent with EN 15804 (SFS, 2019, Clause 6.2.7 & Clause 7.5). Module D is calculated and reported separately from the cradle to grave results. The second boundary is specific to the ship life cycle and comprise four stages: Building, representing the initial installation of materials and components;

Operation, representing materials consumed during service (e.g., fuel, lube oil, etc…); Maintenance, representing scheduled renewal or replacement during the ship's design life; and Scrapping, representing the final disposal of all materials installed over the ship's lifetime.

These two boundaries are linked through the material impact factors stored in the LCAI references database. For each material, the cradle to grave GWP is obtained by summing the reported EN 15804 modular framework from A1 to C4. This single cradle to grave impact factor is applied whenever material is introduced into the vessel, whether during the Building, Operation, or Maintenance stage; only the material quantity differs between these stages. Consequently, the scrapping stage does not require a separate impact calculation because the end-of-life impacts (C1-C4) are already incorporated within the cradle to grave material impact factor. Module D is treated independently by multiplying the Module D value of each material by the cumulative quantity introduced over the ship's lifetime, including both the initial installation and all subsequent replacements. The resulting recycling credits are reported separately and are not included in the cradle to grave totals. The complete mathematical formulation of this methodology, together with its verification, is presented in Section 4.4.

3.4 Functional unit and assumptions

The functional unit adopted in this thesis is one vessel assessed over its complete cradle to grave life cycle. A default design life of 30 years is assumed, consistent with values adopted in previous maritime LCA studies, including Wang et al. (2018) for a short-route hybrid ferry and Ling-Chin and Roskilly et al. (2016b) for a Ro-Ro cargo vessel power system. The design life is user-adjustable, allowing the tool to be adapted to specific vessel types or case studies.

To improve transparency can minimise duplication, the ship design life and other project-level parameters, including project or vessel identification, the functional unit, the reporting framework (ISO 14040, (SFS, 2020a) / 14044, (SFS, 2020b) and, EN 15804 (SFS, 2019)), and the system boundary definitions are centralised within a dedicated Assumptions worksheet. This approach ensures that global parameters are defined only ones and are referenced automatically throughout the workbook. In particular, the ship design life is used directly in the Maintenance-stage whole-unit replacement calculations and partial replacement calculations during major classification society surveys described in Section 3.3 and Section 4.4.

3.5 Data collection methods

The environmental impact data used to populate the LCAI Reference database were obtained from two source categories, consistent with the data quality hierarchy described in Section 2.1. Primary data comprised third party verified manufacturer EPDs, while secondary data were obtained from peer-reviewed academic literature and authoritative industry publications where suitable EPDs were unavailable.

The primary data set includes EPDs covering a wide range of shipbuilding materials, equipment, and products. Representative examples include furniture products from Andreu World, structural and coated steel products from SSAB, gasketed plate heat exchangers from Alfa Laval, and marine paints and coating from Hempel A/S.

Secondary data were incorporated to supplement the database for materials and products lacking suitable EPDs. These include, among others, World steel Association's (2017) global steel life cycle inventory, the International Aluminium Institute's (2023) guidance on aluminium recycling allocation, the International Copper Association's (2022) guidance for copper carbon foot print calculations, an Environmental Product Declaration Norway record for copper/XLPE power cable, and published lithium-ion battery LCA studies and marine-specific battery assessment used to develop the hybrid battery system records. Additional literature sources were incorporated where required to provide material-specific environmental data not available through manufacturer EPDs.

Each record within the LCAI Reference database contains in addition to its environmental impact factors, dedicated data quality and data sources/citation fields. These provide complete traceability for every environmental value used in assessment and support the transparency and consistency principles of ISO 14044 (SFS, 2020b) (Section 2.1). The database structure has also been designed to support future application of the pedigree matrix method (Weidema and Wesnæs, 1996). Although a formal pedigree assessment has not yet been completed to facilitate future refinement of the tool's data quality reporting (Chapter 6).

The database development remains ongoing. While the current database contains more than 500 EPD based and literature derived records have been compiled, the database does not yet provide complete coverage of all material and equipment categories represented within the SWBS - including main machinery and components, electrical machinery and components, etc… This reflects the staged development strategy adopted for the tool rather than a limitation of its methodology. The calculation architecture and material database were intentionally developed as independent components, allowing the calculation logic to be verified and applied using the available data while enabling the database to be expanded continuously without modification of the underlying calculation framework.

Figure 3.1 summarised this data collection process. Every record entering the database passes through the same sequence: a source is verified against its publisher, journal, or EPD registry; the source is identified and its material category confirmed; every EN 15804 module that source reports is extracted, not only the production-stage figure; the record is structured with complete source and data quality information. Finally, the cradle to grave GWP impact factor is determined by summing all populated EN 15804 modules (A1-C4), producing the material impact factor subsequently used throughout the assessment (Section 3.2).

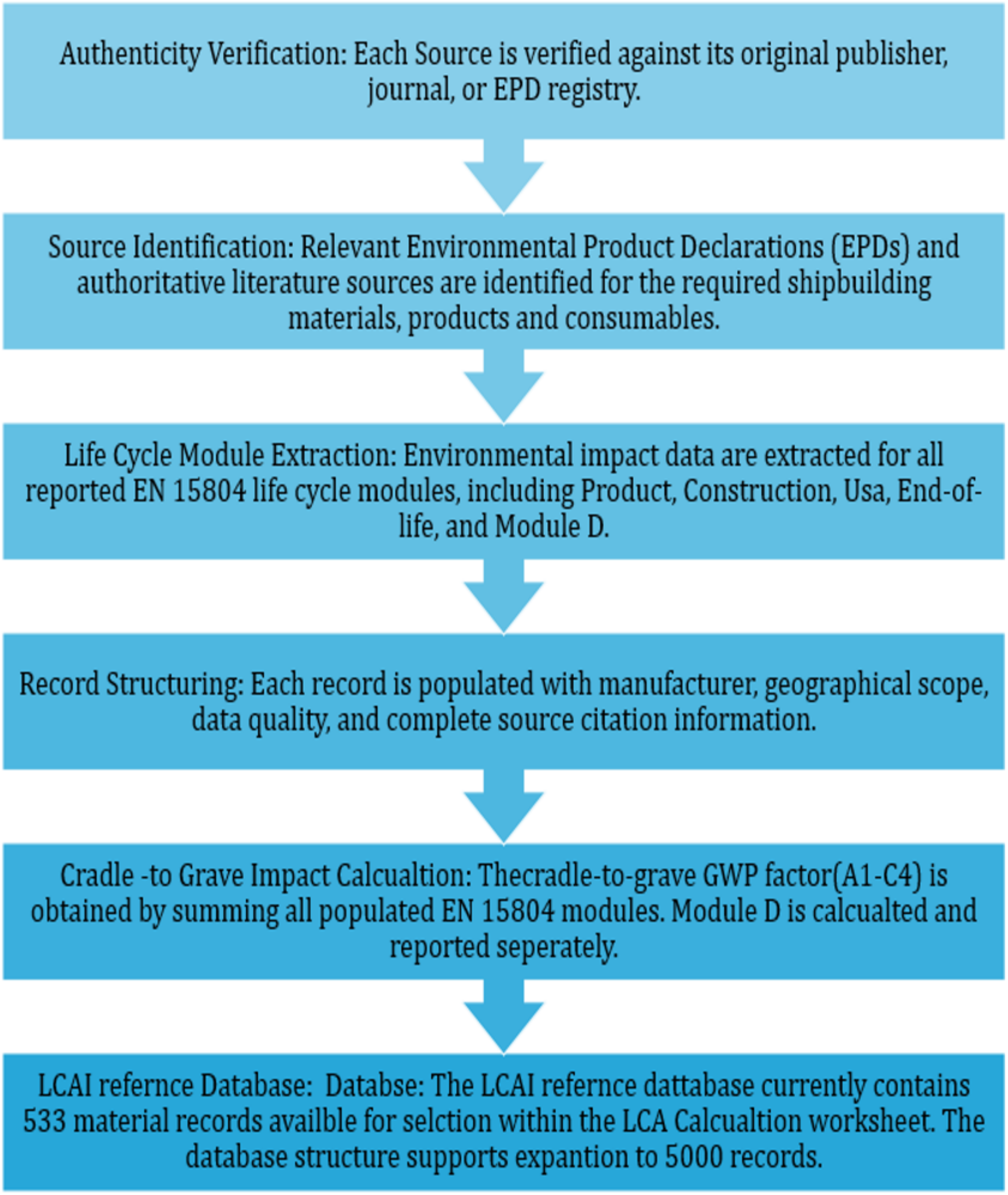


Figure 3-1 LCAI Reference database construction flow

This standardised workflow underpins the extensibility of the LCAI Reference database. Because every record is structured according to the same procedure, new material records can be incorporated either the original developer or future users without requiring any modification to the LCA Calculation worksheet or the underlying calculation methodology.

3.6 Development and integration of the SWBS for concept-stage ship life cycle assessment

3.6.1 Concept stage design requirement

The development of the ship work breakdown structure was driven by the specific information available during conceptual ship design and by the requirements of LCA at this stage of the design process. Unlike detailed design, conceptual design does not provide complete bills of materials, manufacturing specification, procurement information, or production sequences. Instead, designers typically define the principal characteristics of the vessel, including the hull form, main dimensions, propulsion system and arrangement, major onboard systems, preliminary equipment selection, and approximate material quantities. Consequently, any environmental assessment undertaken during concept design must operate using this limited but strategically important engineering information.

At the same time, a meaningful LCA requires environmental impacts to be associated with physical materials and products rather than with abstract engineering functions. EPDs and literature-based datasets quantify impacts for individual materials, products, and components. Therefore, concept stage assessment requires a structures method of linking the engineering description of the vessel with the environmental information available for those materials. Existing ship work breakdown structures were reviewed as part of this research to understand established methods of organising ship systems. However, these structures were primarily developed to support production planning, maintenance management, procurement, or cost estimation, rather than the systematic allocation of environmental data required for LCA. This identified the need for a dedicated work breakdown structure specifically designed to support concept stage LCA.

3.6.2 Development of the SWBS

The SWBS was developed to provide a practical organisational framework capable of representing the complete material inventory of a vessel while remaining consistent with the level of detail normally available during conceptual design. Development began with a review of commonly used shipbuilding terminology, including terminology contained within the SFI group system glossary (Manchinu and McConnell, 1977), together with publicly available ship work breakdown concepts. Rather than adopting an existing classification directly, individual terms were reviewed for their relevance to concept-stage environmental assessment and refined where necessary. The resulting set of terms was then consolidated to remove unnecessary complexity and reorganised into a new hierarchical structure developed specifically for this research.

The resulting SWBS adopts neither the numbering nor the hierarchical organisation of existing work breakdown structures. Instead, it groups ship systems according to their functional role and the materials expected to be associated with them during environmental assessment. Major ship systems, including hull structure, machinery, piping systems, electrical systems, accommodation, outfit, and consumables, are represented at a level considered appropriate for concept-stage design, while unnecessary production, maintenance, and non-material based specific subdivisions were omitted.

The principal objective of the SWBS is not to replicate an existing engineering classification but to provide a consistent farmwork for organising the materials that comprise the vessel. Every material, product, or consumable considered within the assessment can therefore be assigned to a logical engineering group, ensuring that material inventories remain organised, traceable, and suitable for subsequent environmental calculations.

3.6.3 Integration of the SWBS into the LCA framework

The SWBS forms the organisational backbone of the proposed lifecycle assessment methodology. Rather than treating environmental data as an independent collection of material records, the SWBS provides the structure through which those records are incorporated into the assessment. Each material or product used within the vessel is allocated to an SWBS element, establishing a direct relationship between the engineering representation of the ship and the environmental impacts data obtained from the LCAI Reference database.

This organization enables material to be systematically assigned during the Building, Operation and Maintenance stages of the vessel lifecycle, with each quantity linked to the corresponding cradle to grave environmental impact factor derived from EPDs or literature sources. Because every material is associated with an SWBS category, environmental impacts can subsequently be aggregated at multiple organisational levels, from individual materials to equipment items, subsystem groups, major ship systems, and ultimately the complete vessel. The SWBS therefore provides not only a consistent inventory structure but also the framework through which environmental impacts are calculated, interpreted, and reported.

The separation of the SWBS from the environmental database further supports the extensibility of the methodology. Additional materials, products, or ship components can be incorporated without altering the underlying calculation methodology, while the environmental database can continue to expand independently as new EPDs or literature sources become available. This modular architecture allows the tool to evolve over time while maintaining a consistent assessment framework for conceptual stage ship LCA.

The SWBS was developed through a structured methodology intended to transform general shipbuilding system terminology into a classification suitable for concept-stage environmental inventory development. Figure 3.2 illustrate this process, showing how the ship systems were functionally classified, decomposed into lower-level sub-systems, consolidated according to the material inventory requirements, screened for material relevance, and ultimately organised into the coded SWBS used throughout the LCA.

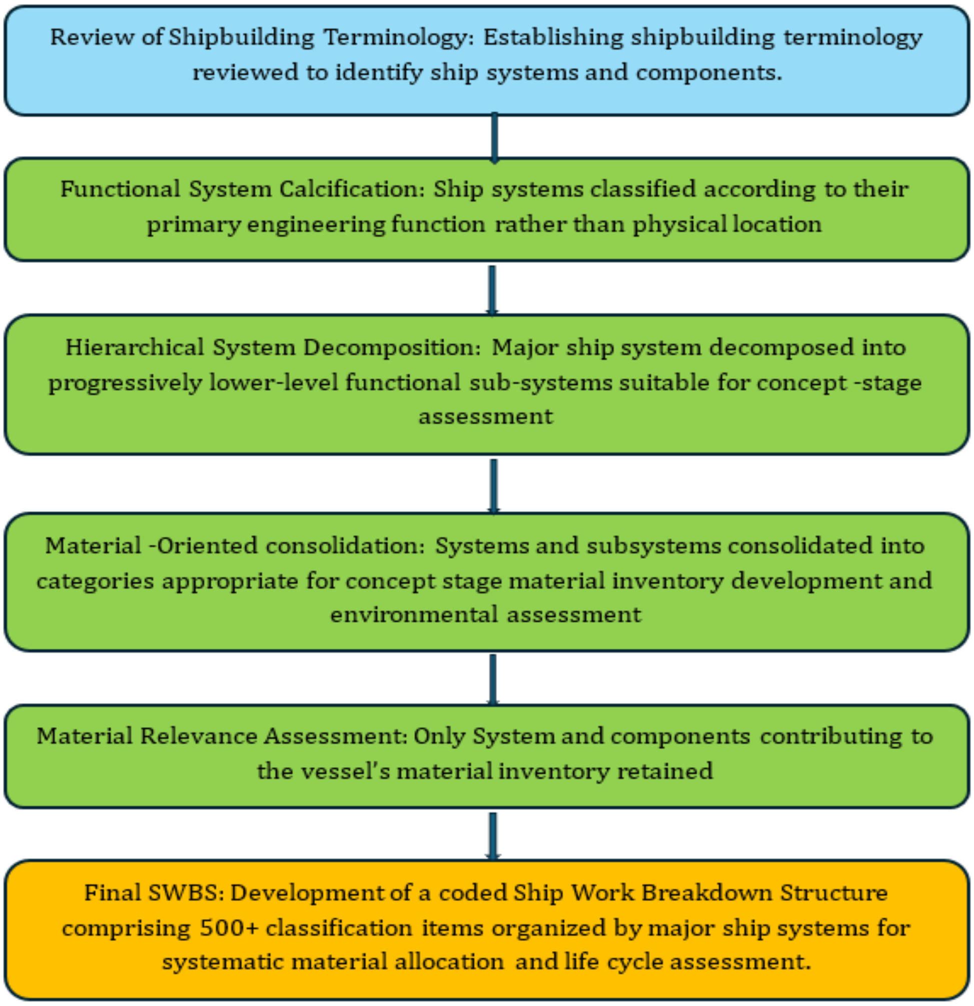


Figure 3-2 SWBS construction flow

Figure 3.3 illustrate the hierarchical organisation of the SWBS by tracing its decomposition form the vessel to the individual classification items used for material allocation. The vessel is first divided into eight principal ship systems, each represented by a dedicated major group within the SWBS. To demonstrate the hierarchical structure, the Main Machinery system (Group 400) is expanded further into its constituent sub-groups and representative SWBS items. The remaining major groups follow the same hierarchical organisation.

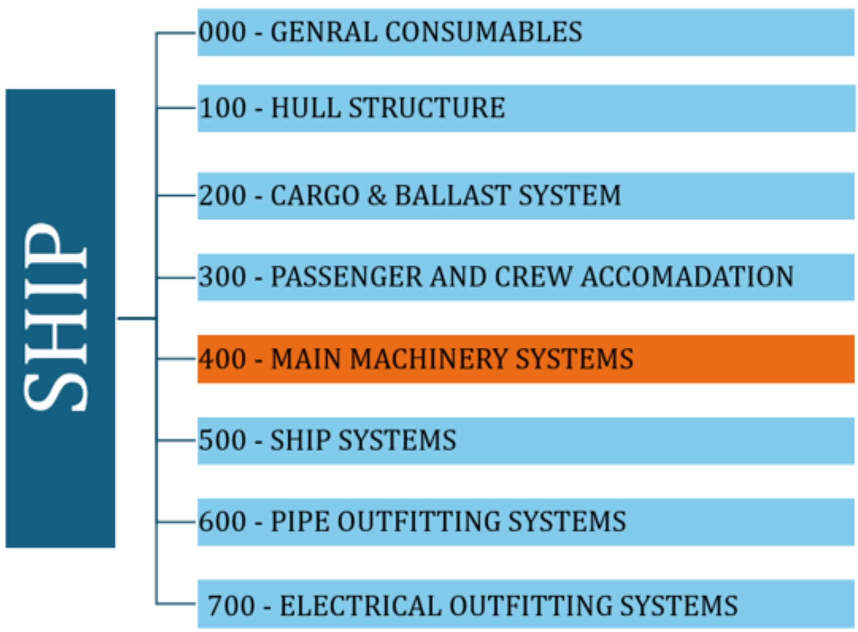


Figure 3-3 SWBS hierarchical structure

The SWBS adopts a hierarchical decomposition in which the vessel is organised into progressively lower levels of marine system detail. Major ship systems are divided into functional sub-groups, which are subsequently decomposed into SWBS sub-sub systems, representing the lowest of classification within the framework. These sub-sub systems provide the point at which materials are assigned during environmental impact calculation, allowing environmental impact to be continuously linked to the corresponding marine systems.

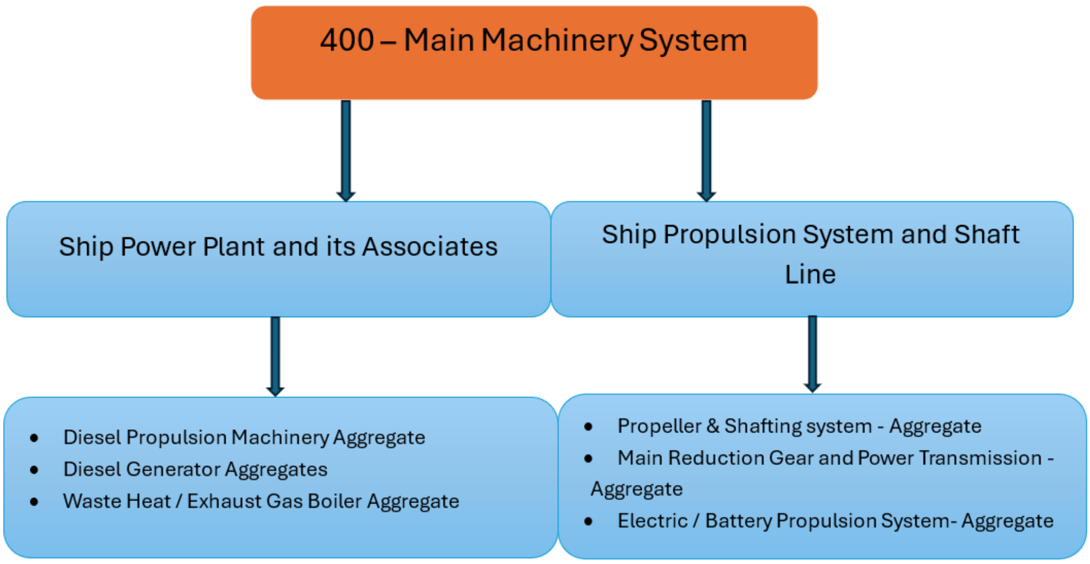


Figure 3-4 SWBS hierarchical decomposition - sub group level

Each SWBS item represents the lowest level of classification used within the proposed methodology. During LCA calculation for the functional unit, materials are allocated directly to these SWBS items, thereby establishing the relationship between the engineering description of the vessel and the environmental impact data contained within the LCAI Reference database. This hierarchical organisation enables material inventories to be aggregated consistently from individual components to subsystems, major-system, and whole-vessel levels during the subsequent LCA.

Together, Figures 3.2, 3.3 and 3.4 describes the methodology development of the SWBS. Figure 3.2 represents the systematic process through which the classification was developed, while Figure 3.3 illustrates its resulting hierarchical organisation. Combined, they demonstrate the SWBS provide a structured and repeatable framework for ongoing ship materials prior to their integration with the environmental impact database, thereby establishing the foundation of the proposed concept-stage LCA methodology.

3.7 Tool design approach

The tool is implemented as a single Microsoft Excel compatible spreadsheet workbook rather than as bespoke software or a web-based application. This implementation was selected for both practical and methodological reasons. From a practical point of view, spreadsheet software is widely available within shipbuilding design and engineering practice, requiring no specialist software, licensing, or programming expertise beyond general spreadsheet proficiency. It also allows user to inspect, modify, and extend the tool directly, avoiding the limitations associated with non-transparent or proprietary calculations platforms. From a methodological perspective, implementing the entire calculation methodology using spreadsheet formulas provide complete transparency of the assessment process. Every calculation can be traced directly from the reported results to the underlying input data and the corresponding formula, enabling systematic verification of the calculation logic and supporting the verification and validation activities presented in Chapter 6.

Several design principles were applied consistently throughout the development of the tool to improve its transparency, robustness, and long-term usability. Emphasis was given on ensuring that calculations remained independent of spreadsheet layout or record order, thereby avoiding dependencies that could introduce errors if the database were expanded, recorded, or modified during future use. Consequently, calculation and reporting functions were designed to operate independently of row sequence wherever possible, supporting both traceability and extensibility of the assessment methodology. These design decisions reflect the broader development philosophy that guided the development of the tool. Throughout the research, priority was given to the long-term robustness, reliability, and extensibility rather than implementation choices that provide short-term convenience but reduce flexibility during future application.

4 Development of the LCA tool

4.1 Tool architecture and structure

The tool comprises 7 worksheets and a result dashboard: Read Me, Assumptions, Boundary and Limitations, SWBS, LCAI Reference, LCA Calculation and Results. Four worksheets constitute the core assessment framework: SWBS, LCAI Reference, LCA Calculation, and Results. The remaining worksheets provide user guidance, global assessment assumptions, and documentation of the system boundary and scope decisions described in Chapter 3. The SWBS and LCAI reference worksheets independently supply classification and environmental impact data to the LCA Calculation worksheet through dropdown selection and lookup functions. The LCA Calculation worksheet performs the material-level life cycle calculations, while the Results worksheet aggregate and presents the calculated outputs without containing any independently entered assessment data. Figure 4-1 shows the LCA tool architecture.

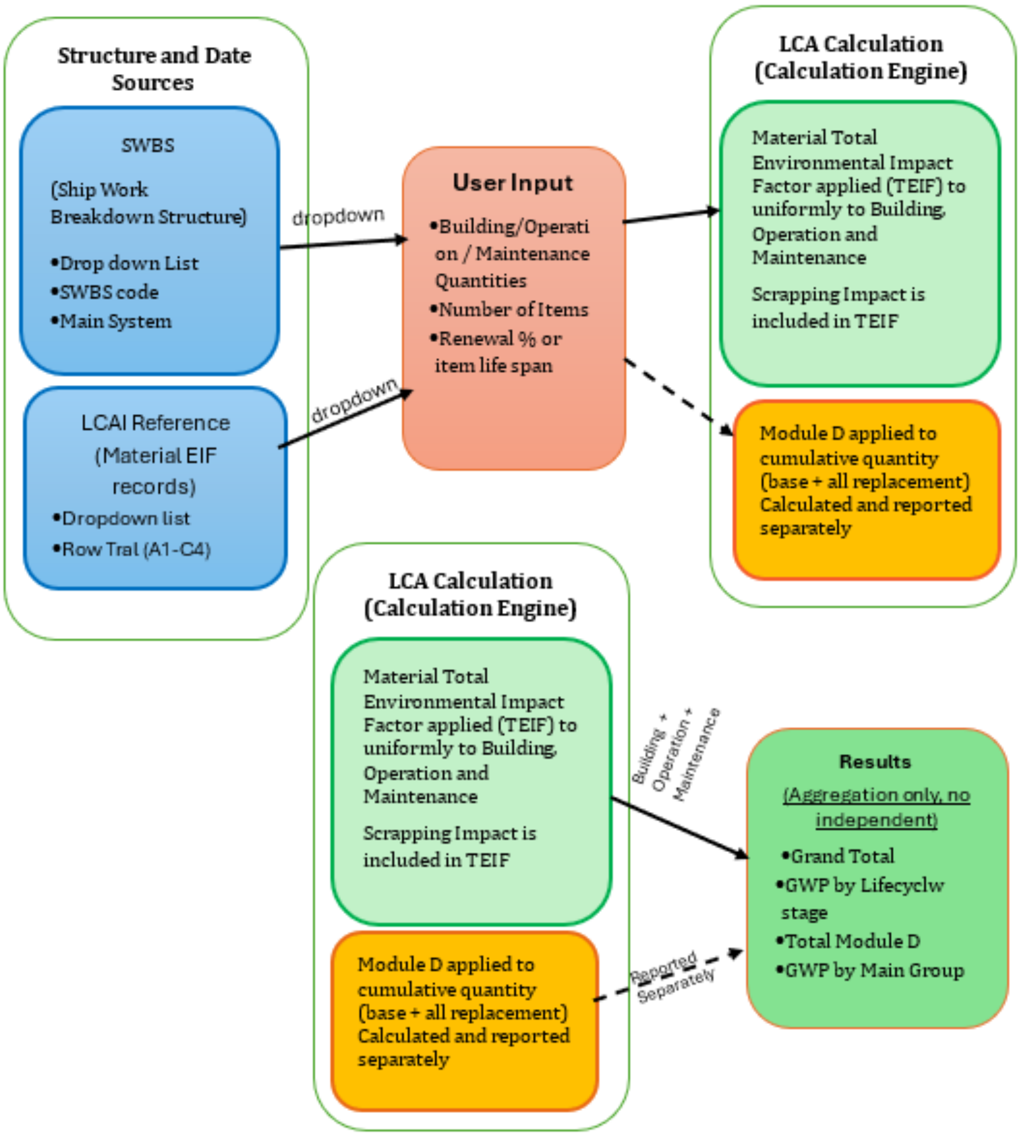


Figure 4-1 Tool architecture and LCAI Reference independently supply inputs to the calculation engine; Results aggregates its output without holding any independent-entered data

Figure 4-1 illustrates the flow of information through the assessment. The SWBS and LCAI Reference worksheets operate as two independent input sources. The SWBS provides the marine classification used to identify the relevant ship system, while the LCAI Reference supplies the corresponding environmental impact data. Following the user's selection of an SWBS item and a material record, lookup functions automatically retrieve the required classification and environmental impact data into the LCA Calculation worksheet. The user then enters the material quantities associated with the Building, Operation dn Maintenance stages, together with the appropriate maintenance or renewal information described in Section 4.4.

For each of these three stages, the calculation engine applies the material's cradle to grave impact factor (A1-C4 row total) (SFS, 2019) to the corresponding material quantity. A separate Scrapping stage calculation is not performed because the end-of-life impacts (C1-C4) (SFS, 2019, Clause 6.2.6) are already incorporated within the cradle to grave impact factor assigned to each material. Module D (SFS, 2019, Clause 6.2.7) is calculated separately using the cumulative quantity of material introduced over the vessel's life cycle comprising the initial installation and all subsequent replacements. The resulting recycling credits are transferred to the Results worksheet as a separate output and are not combined with the building, Operation and Maintenance impacts.

The Results worksheet contains on user entered data or independent calculations. Instead, all reported values are aggregated directly form the LCA Calculation worksheet, ensuring that the assessment maintains a single source of calculation data eliminating the risk of inconsistencies between the detailed calculations and reported results.

The architecture was deliberately designed to separate ship systems framework (SWBS), environmental data (LCAI Reference), and environmental impact calculation (LCA Calculation) into three distinct components rather than combining them within a single integrated dataset. This modular architecture allows each component to be updated without affecting the others. For example, the SWBS can be expanded or revised without modifying the environmental database or calculation methodology; additional material records can be incorporated into the LCAI Reference without altering the ship systems classification; and the same material record can be assigned to multiple SWBS items without data duplication. The separation of these components also supports independent verification of the classification structure, environmental database, and Environmental impact calculation methodology, as discussed in Section 4.4 and Chapter 6.

4.2 Mapping ship materials and structures to the industrial work breakdown structure

Each row within the LCA Calculation worksheet represent the LCA of a single material or resource allocated specific ship item. This row forms the fundamental assessment unit of the tool, linking the ship system calcification provided by the SWBS with the corresponding environmental impact data contained within the LCAI Reference database. The relevant ship system is selected from the SWBS hierarchy (see Figure 4.2), with the associated SWBS code and category retrieved automatically through lookup functions (see Figure 4-4). The material or resource is then selected independently from the LCAI Reference database (see Figure 4-3), form which the declared unit, size or dimensions (where applicable), environmental impact factors, and date quality classification are retrieved automatically (see Figure 4-4). Together, these linked records establish the engineering and environmental information required for the life cycle calculation described in Section 4.4.

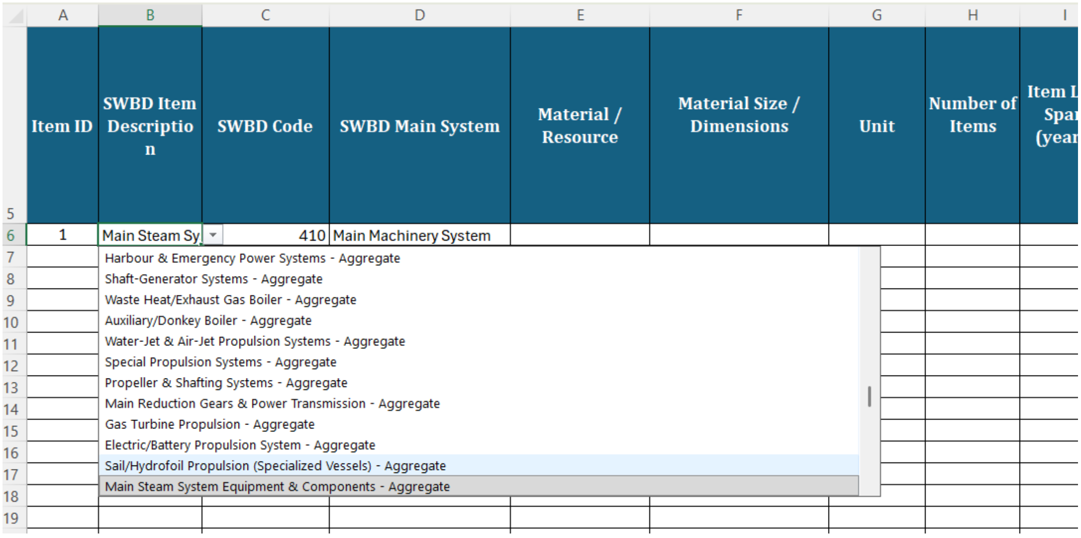


Figure 4-2 LCA calculation sheet - SWBD items selection from drop down list

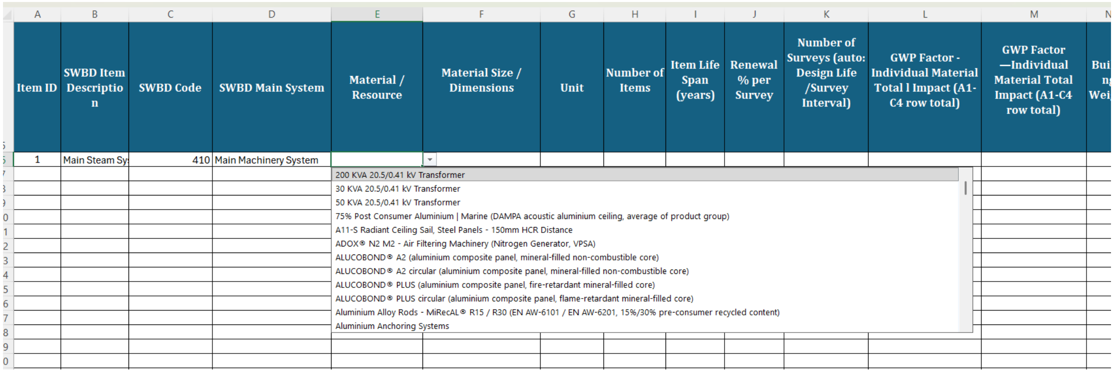


Figure 4-3 LCA calculation sheet - LCAI reference material selection from drop down list

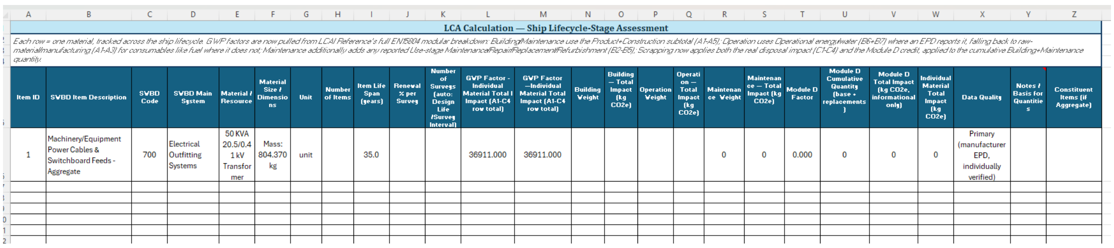


Figure 4-4 LCA calculation sheet - after retrieving SWBD and LCAI Reference data

A single ship system is typically associated with multiple materials and process inputs rather than a single material. Therefore, the relationship between SWBS items and LCA Calculation records is intentionally one-to-many. For example, a hull structural assembly is represented not only by its primary structural steel but also by the associated fabrication materials and resources required for its production, such as welding electrodes, welding flux, backing plates, material transportation, and electric energy. Each of these inputs is recorded as a separate assessment row while retaining the same SWBS item description, allowing all the contribution associated with the ship system to be aggregated automatically within the Results worksheet (Section 4.6). This approach preserves the detailed material inventory while ensuring that environmental impacts are reported at the appropriate ship system level.

To support accurate material allocation, the tool displays the selected material's size/dimensions information adjacent to the material selection field. This allows the user to verify that the selected database record is consistent with the physical characteristics of the material before material quantities are entered, thereby reducing the likelihood of incorrect material allocation and improving the reliability of the assessment.

4.3 Data inputs and parameters

The LCAI Reference database organises each material or product record into five column groups (see Table 4-1), matching the EN 15804 (SFS, 2019) modular reporting structure adopted in Chapter 3.

Table 4-1 LCAI reference database architecture

Column Group	Fields	Purpose
Identification	Material ID, Material Name, Size/Dimensions, Material Category, Service Life/Warranty, Declared unit	Identifies the record and the unit its impact factors are expressed per.
Product Stage (A1-A3)	A1 – Raw material supply, A2 – Transport to manufacturer, A3 - Manufacturer	Credle-to-gate production impact EN 15804, Clause 6.2.2
Construction Stage (A4-A5)	A4 – Transport to site, A5 – Installation	Trasport and installation impact, EN 15804, Clause 6.2.3
Usage Stage (B1-B7)	B1 – Use, B2 – Maintenance, B3 – Repair, B4 – Replacement, B5 – Refurbishment, B6 – Operational Energy Sue, B7 – Operational water use	Use impact EN 15804, Clause 6.2.4 & Clause 6.2.5
End-of Life Stage (C1-C4)	C1 – Deconstruction/Demolition, c2 – Transport to waste, C3 – Waste Processing, C4 – Disposal	Scrapping stage Impact EN 15804, Clause 6.2.6
Benefits and Loads	Module D	Net credit/burden from reuse, recovery or recycling, reported separately, EN

		15804, Clause 6.2.7 and Clause 7.5
Totals	TOTAL (exclude), Total (incl. D)	Self-Calculating summery field
Provenance	Manufacturer, Geography, Data Quality, Data Source/Citation, Notes	Traceability of every figure to its source

The LCAI Reference database currently contains 533 material records representing a broad range of shipbuilding materials, products, equipment and consumables, including structural and coated steel, aluminium, copper and brass, piping materials, marine coatings, machinery and outfitting equipment, marine fuels, passenger furniture and numerous other shipbuilding materials (Chapter 3, Section 3.5). Each database record contains the environmental impact factors extracted from its corresponding data source together with supporting information such as the declared unit, data quality classification, and source reference (see Figure 4-6). For use within the assessment, the environmental impacts reported for Product stage (A1-A3), Construction stage (A4-A5), Use stage (B1-B7), and End-of-Life stage (C1-C4) are combined to produce a single cradle to grave impact factor for each individual material (see Figure 4-5). This impact factor is subsequently applied by the LCA Calculation worksheet to the material quantity entered for the relevant ship life cycle stage, as described in Section 4.4.

nediately in LCA Calculation's dropdowns. Now expanded to the full EN15804 modular breakdown including B1-B7 (Use Stage). Range pre-extended to row 5000.

Product Stage (A1-A3)			Construction Stage (A4-A5)		Use Stage (B1-B7)							End of Life (C1-C4)				Benefits & Loads	Totals	
A1 Raw material supply	A2 Transport to manufacturer	A3 Manufacturing	A4 Transport to site	A5 Installation	B1 Use	B2 Maintenance	B3 Repair	B4 Replacement	B5 Refurbishment	B6 Operational energy use	B7 Operational water use	C1 Deconstruction/ demolition	C2 Transport to waste proc.	C3 Waste processing	C4 Disposal	Module D Reuse/Recovery/Recycling	TOTAL (excl. D)	TOTAL (incl. D)
7730.000		1120.000										89200.000					98050.000	98050.000
2340.000		365.000										27800.000					30505.000	30505.000
3270.000		441.000										33200.000					36911.000	36911.000
2.630	0.007	-0.364										0.004	0.024	0.553	0.373	-0.154	3.227	3.073
3.290	0.074	-0.062	0.094	0.250								0.003	0.040	0.019	0.004	-1.740	3.712	1.972
9370.000	246.000	190.000	471.000	559.000		102.000				396000.000			69.000	34.900	705.000		407746.900	407746.900
16.800	0.376	1.820										0.025	0.041	2.330	0.707	-18.200	22.099	3.899
5.430	0.300	0.314										0.027	0.115	2.350	1.050	-0.211	9.586	9.375
20.600	0.411	0.371										0.025	0.042	4.430	0.656	-17.900	26.536	8.636
8.290	0.330	-0.308										0.027	0.115	3.050	1.060	-0.297	12.564	12.267
		8740.000										23.700	8.630	52.400	2.570	-13100.000	8827.300	-4272.700
		14.300	0.011	0.122								0.000	0.008	0.344	0.000	-9.580	14.786	5.206

Figure 4-5 LCAI reference data base EN 15804 (SFS,2019) Modular items and total of (A1-C4)

Provenance				
Manufacturer	Geography	Data Quality	Data Source / Citation	Notes
Shirdi Sai Electricals Ltd. (50-55, 58-60, 45A, 45B, 137A, 137B, 137C, 13	India	Primary (manufacturer EPD, individually verified)	Shirdi Sai Electricals Ltd., "200 KVA 20.5/0.41 kV Transfo	No Module D disclosed in EPD; TOTAL(incl.D)=TOTAL(ex
Shirdi Sai Electricals Ltd. (50-55, 58-60, 45A, 45B, 137A, 137B, 137C, 13	India	Primary (manufacturer EPD, individually verified)	Shirdi Sai Electricals Ltd., "30 KVA 20.5/0.41 kV Transforn	No Module D disclosed in EPD; TOTAL(incl.D)=TOTAL(ex
Shirdi Sai Electricals Ltd. (50-55, 58-60, 45A, 45B, 137A, 137B, 137C, 13	India	Primary (manufacturer EPD, individually verified)	Shirdi Sai Electricals Ltd., "50 KVA 20.5/0.41 kV Transforn	No Module D disclosed in EPD; TOTAL(incl.D)=TOTAL(ex
DAMPA ApS (Højeløkkevej 4a, 5690 Tommerup, Denmark)	Denmark	Primary (manufacturer EPD, 3rd-party verified via EPD Hub)	DAMPA ApS EPD "75% Post Consumer Aluminium | Marir	A4-A5 and B1-B7 not covered (excluded from system bo
Swegon Group AB, J A Wettergrens gata 7, 421 30 Västra Frölunda, Swede	Germany	Primary (manufacturer EPD, 3rd-party externally verified by Imane Uald Lamkad	Swegon Group AB, EPD "A11-S, Steel panels - 150 mm HC	B1-B7 not covered (use stage not studied). Life span: 50
Isolcell S.p.A., Via A. Meucci 7, 39055 Laives (BZ), Italy	Italy	Primary (manufacturer EPD, 3rd-party externally verified by ICMQ S.p.A., Via Ga	Isolcell S.p.A., EPD "ADOX® N2" (Air filtering machinery), D	Module D not assessed; TOTAL(incl.D)=TOTAL(excl.D). L
3A Composites GmbH, Alusingenplatz 1, 78224 Singen, Germany (produ	Germany	Primary (manufacturer EPD, 3rd-party externally verified via EPD Hub). Third-pa	ALUCOBOND® A2, 3A Composites GmbH, EPD Hub regist	Cradle-to-gate + C1-C4, D; A4/A5/B1-B7 Not Declared. L
3A Composites GmbH, Alusingenplatz 1, 78224 Singen, Germany (produ	Germany	Primary (manufacturer EPD, 3rd-party externally verified)	3A Composites GmbH, EPD "ALUCOBOND® A2 circular", E	Life span: 60 years.
3A Composites GmbH, Alusingenplatz 1, 78224 Singen, Germany (produ	Germany	Primary (manufacturer EPD, 3rd-party externally verified via EPD Hub). Third-pa	ALUCOBOND® PLUS, 3A Composites GmbH, EPD Hub reg	Life span: 60 years.
3A Composites GmbH, Alusingenplatz 1, 78224 Singen, Germany (produ	Germany	Primary (manufacturer EPD, 3rd-party externally verified)	3A Composites GmbH, EPD "ALUCOBOND® PLUS circula	Life span: 60 years.
Midal Cables B.S.C. (Midal Bahrain) - Building No. 744, Road No. 5128, Blo	Bahrain	Primary (manufacturer EPD, 3rd-party verified); overall share of primary data fo	Midal Cables B.S.C. (Midal Bahrain) EPD "MiRecAL® Alumi	A4/A5/B1-B7 Not Declared. Life span: N/A (semi-finishe
Buhr Verankerungstechnik GmbH & Co. KG, In der Trift 10, 56743 Thür, Ge	Germany	Primary (manufacturer EPD, 3rd-party verified); verifier Manfred Russ, LCA-Cor	Buhr Verankerungstechnik GmbH & Co. KG "Aluminium a	B1-B7 excluded (permanently embedded, no use-phase
Buhr Verankerungstechnik GmbH & Co. KG, In der Trift 10, 56743 Thür, Ge	Germany	Primary (manufacturer EPD, 3rd-party verified); verifier Manfred Russ, LCA-Cor	Buhr Verankerungstechnik GmbH & Co. KG "Aluminium a	B1-B7 excluded (embedded, no use-phase impact). Life
Intals S.p.A., Viale Lombardia 3, 27020 Parona (PV), Italy	Italy	Primary (manufacturer EPD, 3rd-party verified via EPD Process Certification); v	Intals S.p.A. "Aluminium ingots, code 0533 (ingots for ste	Life span: N/A.
Somet S.p.A., Via J.K. Kennedy 18, Ambivere (BG), Italy	Italy	Primary (manufacturer EPD, 3rd-party verified via EPD Process Certification); v	Somet S.p.A. "Aluminium plates and billets in 6082 green	Cradle-to-gate only; no C1-C4/Module D. Life span: N/A.
Grupa Kęty S.A., Ul. Kościuszki 111, 32-650 Kęty, Poland; manufacturing	Poland	Primary (manufacturer EPD, 3rd-party externally verified by Ph.D. Eng. Halina P	Grupa Kęty S.A., 'Aluminium profiles from the 6xxx series',	C1 not assessed. Life span: N/A (semi-finished, applicat
Alumetal S.A., ul. Kościuszki 111, 32-650 Kęty, Poland	Poland	Primary (manufacturer EPD, 3rd-party externally verified per ISO 14025:2010)	Alumetal S.A., "Aluminium Recycled Foundry Alloy (RFA)" E	Cradle-to-gate + transport only; no B/C modules. Life sp

Figure 4-6 LCAI reference data base provenance data

4.4 Calculation methods and models

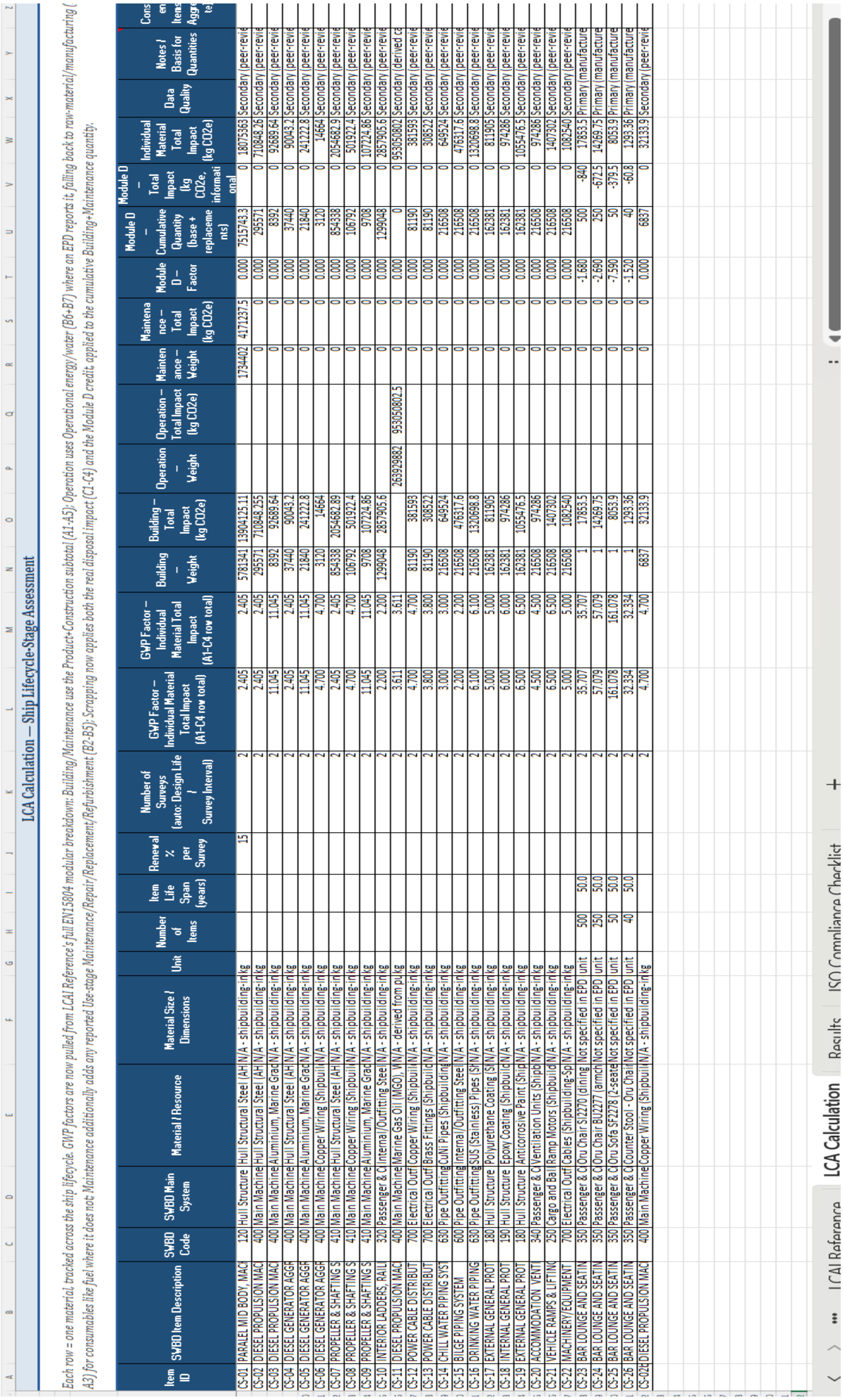
The LCA Calculation worksheet implements the calculation methodology established in Chapter 3 by applying a single cradle to grave environmental impact factor to each material record (See Figure 4-7, the LCA calculation sheet applied for case study). For every assessment row, the cradle to grave impact factor is retrieved automatically from the selected LCAI Reference record and applied consistently to the Building, Operational and Maintenance stages. The environmental impact factor remains unchanged across these three stages; only the material quantity associated with each life cycle stage differs. Accordingly, the Building, Operation, and Maintenance impacts are calculated by multiplying the same material environmental total impact factor (A1-C4) by their respective quantities. Operational consumables, such as marine fuels, follows the same calculation model. Their cradle to grave impact factor, as stored in the corresponding LCAI Reference record, is applied directly to the quantity consumed during operation. Consequently, no alternative calculation procedure is required for consumable materials, as their complete life cycle impacts are already represented within the environmental impact factor assigned to the selected record.

The maintenance-stage quantity is calculated independently of the environmental impact factor using one of two mutually exclusive maintenance models, depending on the renewal characteristics of the material or component. These models distinguish between items that are replace as complete units and materials that are renewed incrementally throughout the vessel's service life.

Whole-unit replacement model
For components with a defined item life span (number of years considered in the environmental impact assessment of the material), the number of replacements over the ship's design life is calculated by dividing the ship design life by the item life span, rounding the results up to the nearest whole number, and subtracting one to exclude the initial installation. The Maintenance quantity is then obtained by multiplying the building quantity by the calculated replacement count.

Scheduled partial renewal model.
For material with a defined renewal percentage per survey and number of surveys, the Maintenance quantity is calculated by multiplying the building quantity by the renewal percentage and the number of scheduled surveys. This model represents materials that are renewed progressively rather than replaces entirely. Hull structural steel is the principal example, reflecting the percentage-based renewal practices associated with classification society surveys cycles reported in the literature (Wang et al., 2018; Kim et al., 2025; Chapter 2).Where neither maintenance model is specified, the Maintenance quantity defaults to zero, representing materials or components that are installed once during construction and remain in service throughout the ship's design life cycle without scheduled renewal or replacement.

The partial renewal model has developed such that the user could defined how the partial renewal percentages are applied on the tool. The main objective is that the tool is a generic tool for LCA evaluation of ships, so the partial renewal percentages are depending on the ship type, operational profile, its main mission and its own characteristics. So, tool has given that flexibility to user to define those renewal percentages.



LCA Calculation — Ship Lifecycle-Stage Assessment

Each row = one material, tracked across the ship lifecycle. GWP factors are now pulled from LCAI Reference's full EN15804 modular breakdown: Building/Maintenance use the Product+Construction subtotal (A1-A5); Operation uses Operational energy/water (B6+B7) where an EPD reports it, falling back to raw-material/manufacturing (A3) for consumables like fuel where it does not; Maintenance additionally adds any reported Use-stage Maintenance/Repair/Replacement/Refurbishment (B2-B5); Scrapping now applies both the real disposal impact (C1-C4) and the Module D credit, applied to the cumulative Building+Maintenance quantity.

Item ID	SWBD Item Description	SWBD Code	SWBD Main System	Material / Resource	Material Size / Dimensions	Unit	Number of Items	Item Life Span (years)	Renewal % per Survey	Number of Surveys (auto: Design Life / Survey Interval)	GWP Factor – Individual Material Total Impact (A1-C4 row total)	GWP Factor – Individual Material Total Impact (A1-C4 row total)	Building – Weight	Building – Total Impact (kg CO2e)	Operation – Weight	Operation – Total Impact (kg CO2e)	Maintenance – Weight	Maintenance – Total Impact (kg CO2e)	Module D – Factor	Module D – Cumulative Quantity (base + replacements)	Module D – Total Impact (kg CO2e, informational)	Individual Material Total Impact (kg CO2e)	Data Quality	Notes / Basis for Quantities	Cons en Items Aggre te)
CS-01	PARALEL MID BODY, MACH	120	Hull Structure	Hull Structural Steel (AH	N/A - shipbuilding-in	kg			15	2	2.405	2.405	5781341	13904125.11			1734402	4171237.5	0.000	7515743.3	0	18075363	Secondary (peer-revie		
CS-02	DIESEL PROPULSION MAC	400	Main Machine	Hull Structural Steel (AH	N/A - shipbuilding-in	kg				2	2.405	2.405	295571	710848.255			0	0	0.000	295571	0	710848.26	Secondary (peer-revie		
CS-03	DIESEL PROPULSION MAC	400	Main Machine	Aluminium, Marine Grad	N/A - shipbuilding-in	kg				2	11.045	11.045	8392	92689.64			0	0	0.000	8392	0	92689.64	Secondary (peer-revie		
CS-04	DIESEL GENERATOR AGGR	400	Main Machine	Hull Structural Steel (AH	N/A - shipbuilding-in	kg				2	2.405	2.405	37440	90043.2			0	0	0.000	37440	0	90043.2	Secondary (peer-revie		
CS-05	DIESEL GENERATOR AGGR	400	Main Machine	Aluminium, Marine Grad	N/A - shipbuilding-in	kg				2	11.045	11.045	21840	241222.8			0	0	0.000	21840	0	241222.8	Secondary (peer-revie		
CS-06	DIESEL GENERATOR AGGR	400	Main Machine	Copper Wiring (Shipbuil	N/A - shipbuilding-in	kg				2	4.700	4.700	3120	14664			0	0	0.000	3120	0	14664	Secondary (peer-revie		
CS-07	PROPELLER & SHAFTING S	410	Main Machine	Hull Structural Steel (AH	N/A - shipbuilding-in	kg				2	2.405	2.405	854338	2054682.89			0	0	0.000	854338	0	2054682.9	Secondary (peer-revie		
CS-08	PROPELLER & SHAFTING S	410	Main Machine	Copper Wiring (Shipbuil	N/A - shipbuilding-in	kg				2	4.700	4.700	106792	501922.4			0	0	0.000	106792	0	501922.4	Secondary (peer-revie		
CS-09	PROPELLER & SHAFTING S	410	Main Machine	Aluminium, Marine Grad	N/A - shipbuilding-in	kg				2	11.045	11.045	9708	107224.86			0	0	0.000	9708	0	107224.86	Secondary (peer-revie		
CS-10	INTERIOR LADDERS, RAIL	320	Passenger & C	Internal/Outfitting Steel	N/A - shipbuilding-in	kg				2	2.200	2.200	1299048	2857905.6			0	0	0.000	1299048	0	2857905.6	Secondary (peer-revie		
CS-11	DIESEL PROPULSION MAC	400	Main Machine	Marine Gas Oil (MGO), W	N/A - derived from pu	kg				2	3.611	3.611			263929882	953050802.5	0	0	0.000	0	0	953050802	Secondary (derived ca		
CS-12	POWER CABLE DISTRIBUT	700	Electrical Outf	Copper Wiring (Shipbuil	N/A - shipbuilding-in	kg				2	4.700	4.700	81190	381593			0	0	0.000	81190	0	381593	Secondary (peer-revie		
CS-13	POWER CABLE DISTRIBUT	700	Electrical Outf	Brass Fittings (Shipbuild	N/A - shipbuilding-in	kg				2	3.800	3.800	81190	308522			0	0	0.000	81190	0	308522	Secondary (peer-revie		
CS-14	CHILL WATER PIPING SYST	630	Pipe Outfitting	CuNi Pipes (Shipbuilding	N/A - shipbuilding-in	kg				2	3.000	3.000	216508	649524			0	0	0.000	216508	0	649524	Secondary (peer-revie		
CS-15	BILGE PIPING SYSTEM	600	Pipe Outfitting	Internal/Outfitting Steel	N/A - shipbuilding-in	kg				2	2.200	2.200	216508	476317.6			0	0	0.000	216508	0	476317.6	Secondary (peer-revie		
CS-16	DRINKING WATER PIPING	630	Pipe Outfitting	SUS (Stainless) Pipes (Sh	N/A - shipbuilding-in	kg				2	6.100	6.100	216508	1320698.8			0	0	0.000	216508	0	1320698.8	Secondary (peer-revie		
CS-17	EXTERNAL GENERAL PROT	180	Hull Structure	Polyurethane Coating (Sh	N/A - shipbuilding-in	kg				2	5.000	5.000	162381	811905			0	0	0.000	162381	0	811905	Secondary (peer-revie		
CS-18	INTERNAL GENERAL PROT	190	Hull Structure	Epoxy Coating (Shipbuild	N/A - shipbuilding-in	kg				2	6.000	6.000	162381	974286			0	0	0.000	162381	0	974286	Secondary (peer-revie		
CS-19	EXTERNAL GENERAL PROT	180	Hull Structure	Anticorrosive Paint (Ship	N/A - shipbuilding-in	kg				2	6.500	6.500	162381	1055476.5			0	0	0.000	162381	0	1055476.5	Secondary (peer-revie		
CS-20	ACCOMMODATION VENTI	340	Passenger & C	Ventilation Units (Shipb	N/A - shipbuilding-in	kg				2	4.500	4.500	216508	974286			0	0	0.000	216508	0	974286	Secondary (peer-revie		
CS-21	VEHICLE RAMPS & LIFTING	250	Cargo and Bal	Ramp Motors (Shipbuild	N/A - shipbuilding-in	kg				2	6.500	6.500	216508	1407302			0	0	0.000	216508	0	1407302	Secondary (peer-revie		
CS-22	MACHINERY/EQUIPMENT	700	Electrical Outf	Cables (Shipbuilding-Sp	N/A - shipbuilding-in	kg				2	5.000	5.000	216508	1082540			0	0	0.000	216508	0	1082540	Secondary (peer-revie		
CS-23	BAR LOUNGE AND SEATIN	350	Passenger & C	Oru Chair SI2270 (dining	Not specified in EPD	unit	500	50.0		2	35.707	35.707	1	17853.5			0	0	-1.680	500	-840	17853.5	Primary (manufacture		
CS-24	BAR LOUNGE AND SEATIN	350	Passenger & C	Oru Chair BU2277 (armch	Not specified in EPD	unit	250	50.0		2	57.079	57.079	1	14269.75			0	0	-2.690	250	-672.5	14269.75	Primary (manufacture		
CS-25	BAR LOUNGE AND SEATIN	350	Passenger & C	Oru Sofa SF2278 (2-seate	Not specified in EPD	unit	50	50.0		2	161.078	161.078	1	8053.9			0	0	-7.590	50	-379.5	8053.9	Primary (manufacture		
CS-26	BAR LOUNGE AND SEATIN	350	Passenger & C	Counter Stool - Oru Chair	Not specified in EPD	unit	40	50.0		2	32.334	32.334	1	1293.36			0	0	-1.520	40	-60.8	1293.36	Primary (manufacture		
CS-02b	DIESEL PROPULSION MAC	400	Main Machine	Copper Wiring (Shipbuil	N/A - shipbuilding-in	kg				2	4.700	4.700	6837	32133.9			0	0	0.000	6837	0	32133.9	Secondary (peer-revie		

Figure 4-7 LCA calculation sheet - case study Ro-Pax vessel LCA calculation

End-of-Life impacts (C1-C4) are not calculated as a Scrapping-stage multiplication. Instead, where these modules are reported in the source data, they are already incorporated within the cradle to grave environmental impact factor retrieved from the LCAI Reference database and are therefore included automatically in the building, Operation, and Maintenance calculations. A separate Scrapping-stage calculation would therefore duplicates impacts already accounted for within the material-specific environmental impact factor.

The individual material total impact for each assessment row is calculated as the sum of the Building, Operation, and Maintenance impacts. Since each of these stages are calculated using the material's cradle to grave environmental impact factor, the reported total already includes the associated end-of-life (C1-C4) impacts wherever these are available within the source data.

The Module D calculation uses a cumulative material quantity equal to the sum of the Building quantity and the calculated Maintenance quantity. This represents the total quantity of material introduces into the vessel throughout its design life, including both the initial installation and subsequent replacement. The Module D environmental impact factor is applied to this cumulative quantity to determine the end-of-life recycling credit. Consistent with the methodology established in Chapter 3, Module D is reported separately in the Results worksheet and is not included within the grand total. Because it represents the potential benefits beyond the system boundary rather than part of the cradle to grave environmental impact of the considered ship.

4.5 Implementation of the life cycle stages.

Table 4-2 demonstrates the calculation approach described in Section 4.4 using a worked example based on a structural steel record. The selected material has a cradle to grave environmental impact factor of 0.7158 kg CO_2-equvivelent per kg, comprising a production-stage contribution of 0.702 kg CO_2-equvivelent per kg, and an end-of-life contribution of 0.0138 kg CO_2-equvivelent per kg, together with a Module D factor of -0.285 kg CO_2-equvivelent per kg. The material is assigned a schedule partial renewal profile of 15% per survey over four scheduled surveys during the ship's design life.

The worked example illustrates the complete calculation sequence implemented within the tool, including the calculation of the Building, Maintenance, and cumulative material quantities, the calculation of the corresponding impacts, and the separate reporting of the Module D recycling credit. As described in Section 4.4, the cradle to grave environmental impact factor already incorporates the reported end-of-life (C1-C4) impacts. Therefore, the same material-specific impact factor is applied consistently to both the Building and Maintenance quantities without performing a separate Scrapping-stage calculation. The individual material total impact is therefore obtained by summing the Building, Operation and Maintenance impacts, while Module D is reported independently.

Table 4-2 Example of tool calculation method

Stage	Quantity (kg)	Impact (kg CO_2-e)	Basis
Building	85,000	60,843	Building quantity x material total impact (A-C4) (0.7158 kgCO_2-e/kg)
Operation	0 (not applicable)	0	No operational stage consumption for a structural material
Maintenance	51,000 (85 000 x 0.15 x 4)	36,506	Maintenance quantity x material total impact (A-C4) (0.7158 kgCO2-e/kg)
Individual material total impact	-	97,349	Sum of Building, Operation and Maintenance impacts

4.6 User interface and usability features

Beyond the core calculation functions, several user interface and usability features were incorporated to improve the accessibility, reliability and ease of use the tool. Dropdown-based selection, described in Section 4.2, restricts user inputs to predefined SWBS items and LCAI Reference records, reducing the likelihood of errors associated with the manual text entry while ensuring consistency in material and systems classification. A dedicated Read Me worksheet provides guidance for first-time users, explaining the purpose of each worksheet, the function of the principal input fields, and the procedure for adding new SWBS items and LCAI Reference records. The guidance was intentionally written in straightforward, user-oriented language so that the tool can be understood and extended without requiring familiarity with its development history or underlying calculation methodology.

Further usability feature, discussed in Section 3.7, is the deliberate omission of row-by-row running total with in the LCA Calculation worksheet. Instead, all summery values are generated independently in the Results worksheet. Although a running total could provide immediate results and it will propagate with the row order. If the rows are reordered or sorted it could miss lead the results. The adopted approach ensures robustness and reliability while maintaining a clear separation between data entry and results presentation.

Further to this the SDBD could be replaced with separate user developed SWBD without affecting the LCA calculation methodology, which is one of the main advantages of spreadsheet-based tool. There for the tool can be directly use by the industry with present SWBD or their custom made SWBD.

5 Case study

5.1 Case study vessel selection

This chapter applies the tool developed in Chapter 4 to a representative case study vessel. No real vessel weight and material data set was available for this research (Chapter 3, Section 3.5). Therefore, representative vessel was needed for the cases study.

The case study vessel is the Ro-Pax Ferry preliminary design reported by Antoniadis (2021), a diploma thesis from the National Technical University of Athens. This design was chosen for three reasons. First, it is a published, fully specified naval architecture design, not an invented vessel. Second, it uses manufacturer identified machinery (Wärtsilä engines), giving genuine component masses rather than estimated ones. Third, its principal particulars sit within the range of vessels already surveyed in Chapter 2, allowing direct comparison with existing literature.

The vessel's main particulars are length between perpendiculars 166.5m, beam 25.9 m, depth 9.27m, scantling draft 6.54m, block coefficient 0.586, passenger capacity of 1668 passengers, lightship weight 10373 tons, and deadweight 6430 tons. It operates the Piraeus-Chania route (165 nautical miles each leg) at a service speed of 24 knots, completing 168 round trips per year. Propulsion is provided by four Wärtzilä 12V31DF main engines (77.7 tons each, total of 310.8 tons) and three Wärtzilä 8L20DF generator sets (20.8 tons each, 62.4 tons total), both real, named, dual fuel machinery items with manufacturer-stated masses (Antoniadis, 2021).

Table 5-1 summarises the principal particulars and named machinery items adopted from Antoniadis (2021) for the representative vessel used in this case study, providing a consolidated reference for the source data used throughout this chapter.

Table 5-1 Principal particulars, operational profile, and main machinery items of the representative Ro-Pax vessel used in the case study

Category	Parameter	Value
Principal particulars	Length between perpendiculars (LPP)	166.5 m
Principal particulars	Beam (B)	25.9 m
Principal particulars	Block coefficient (CB)	0.586
Principal particulars	Depth (D)	9.27 m
Principal particulars	Scantling draft	6.54 m
Principal particulars	Passenger capacity	1,688
Principal particulars	Lane metres, trucks	1,805.7 m
Principal particulars	Lane metres, private cars	371.8 m
Principal particulars	Lightship weight	10,373 tons
Principal particulars	Deadweight (DWT)	6,430 tons
Principal particulars	Shaft horsepower (SHP)	20,565.6 kW
Route and operating profile	Route	Piraeus-Chania

Route and operating profile	Route distance	165 nautical miles (one way)
Route and operating profile	Service speed	24 knots
Route and operating profile	Service condition	80% MCR, calm sea, clean hull
Route and operating profile	Propulsion arrangement	Twin-screw, mechanical propulsion
Route and operating profile	Deck arrangement	One main deck, one upper trailer deck, two lower holds, hoistable deck, two stern ramps
Main engines	Make and model	Wärtzilä 12V31DF (4-stroke, dual-fuel)
Main engines	Number of units	4
Main engines	Nominal power per engine	7,200 kW
Main engines	MCR per engine	6,600 kW
Main engines	Engine speed	750 rpm
Main engines	Dry weight per engine	77.7 tons (310.8 tons total)
Reduction gears	Make and model	Wärtzilä TCH350
Reduction gears	Number of units	2 (one per engine room, each connecting two main engines)
Propellers	Type	Controllable pitch, twin-screw
Propellers	Diameter	5.224 m
Generating sets	Make and model	Wärtzilä 8L20DF (Tier II)
Generating sets	Number of units	3
Generating sets	Engine power per unit	1,480 kW
Generating sets	Electrical power per unit	1,420 kW
Generating sets	Genset speed	1,200 rpm
Generating sets	Dry weight per unit	20.8 tons (62.4 tons total)
Electrical power demand	Manoeuvring	2,592.4 kW
Electrical power demand	At sea	1,812.3 kW
Electrical power demand	In port	1,119.6 kW
Shafting	Intermediate shaft diameter / length	385 mm / 18 m
Shafting	Stern tube shaft diameter / length	470 mm / 27.17 m

Source: Antoniadis (2021). Preliminary Design of Ro-Pax Ferry (Diploma thesis, National Technical University of Athens, School of Naval Architecture and Marine Engineering, Tables 2-4, 3-1 to 3-4, and 3-6, and 3-7.

5.2 Structural steel weight estimation

The Antoniadis (2021) does not have a weight break down for steel, outfitting and machinery separately and only the total lightship weight is available. This gap was identified during the literature review (Chapter 2) and could not be closed using Ro-Pax specific source.

Hull steel weight was estimated using the parametric formula used by Wang et al. (2018), which applies the empirical weight estimation approach originally developed by Garbatov et al. (2017). The weight estimation method divides the total hull steel into five components: the main hull structure, bulkheads, decks and platform, superstructure and foundations. Each expressed as a function of the vessel's principal dimensions, block coefficient, and number of superstructure decks.

Applying the parametric formulation to the case study vessel produced an estimate hull steel weight of 578.3 tons, comprising 3938.2 tons for the hull structure, 439.7 tons for bulkheads, 791.5 tons for decks and platforms, 502.0 tons for the superstructure, and 109.9 tons for foundations. This estimate should be interpreted within the limitations and assumptions of the underlying empirical model. Wang et al. (2018) developed the formulation using data from the 43.5 m ferry MV Hallaig, whereas the case study vessel considered here is 166.5 m long with lightship weight of 10,373 tons. The application therefore extends the model beyond the size range for which it was originally developed, and the calculated steel weight should be considered as an engineering estimate rather than an exact representation of the vessel's structural weight.

A comparison with published structural weight fractions provides a qualitative assessment of the results. The estimated steel weight corresponds to 55.7% of the vessel's lightship weight, which is lower than the 75–85% range reported for cargo vessels (Known et al., 2025; Tuan and Wei, 2019). This difference is consistent with the configuration of Ro-Pax vessels, where accommodation spaces, passenger facilities, machinery, and outfitting account for a larger proportion of the lightship weight than in conventional cargo ships. Although this comparison indicated that the estimate is reasonable, it does not constitute validation on the absence of measured structural weight data for a comparable Ro-Pax vessel.

The uncertainty associated with applying the steel weight estimation method reported by Wang et al. (2018) to a vessel considerably larger than its original case study was further assessed using an independent structural weight estimation method presented by Parsons (2004). Parsons reproduces the original regression model developed by Watson and Gilfillan (1976), and importantly, includes the complete ship-type coefficient table together with the corresponding calibration ranges for each coefficient. Unlike secondary sources referred earlier in this research, Parsons (2004) provides the calibration ranges for each ship-type coefficient. This makes it possible to determine whether the case study vessel falls within the intended range of application of the empirical model. Structural weight is estimated using the equipment numeral, an empirical parameter calculated from the vessel's principal dimensions together with superstructure and deckhouse geometry, combined with a corrected block coefficient, and a ship-type coefficient.

Using the case study vessels hull dimensions alone, while excluding superstructure and deckhouse contributions to provide a conservative lower-bound estimate requiring no additional geometric assumptions. The equipment numeral was calculated as $E = 5787.6$. The value falls within Parson's published calibration range for passenger ships ($500 < E < 15\,000$; $k = 0.038$), while exceeding the range specified for Ro-Pax ferries ($2000 < E < 5000$; $k = 0.031$). The case study vessel is therefore more appropriately classified using the passenger ship coefficient and, lies within the calibrated range of the regression model rather than requiring extrapolation beyond its intended application.

Applying the passenger ship coefficient produced a lower-bound structural weight estimation of 4,737 tons. To provide a more realistic estimate, an illustrative allowance was included for the vessel's three superstructure decks, represented as a single equivalent profile, as the details of the superstructure decks were not available. This increased the estimated structural weight to approximately 5,698 tons, differing by only 1.4% from the 5781.3 tons estimated using the estimation method by Wang et al. (2018). The similarity of the estimates obtained from these two independently developed empirical methods provides additional confidence in the structural steel weight used for the LCA. Therefore, the estimated steel weight of 5,781 tons. T using the Wang et al. (2018) is used in the case study CAL calculations.

5.3 Machinery weight estimation

The weights of the main propulsion engines and generator sets were available in the case study vessel data reported in the Table 5.1, which contributes 373.2 tons (310.8 tons + 62.4 tons). The remaining machinery weights were not available; therefore, the unknown machinery weight was estimated using the classical parametric method of Watson and Gilfillan (1976). The method estimates the remaining machinery weight as a function of the total installed propulsion power (MCR) and the ship type. The ship-type coefficient is used to account for different ship types such as Cargo, Passenger, container, etc…. Parsons (2003/2004) reproduces the original coefficient table, confirming that the appropriate coefficient for passenger vessel and ferries is $C_m = 0.83$. The total propulsion power of the case study vessel is 26,400 kW corresponding to four main engines contributing 6,600 kW each. Applying the Watson & Gilfillian (1976) parametric formula gives an estimation for remaining machinery wight of 1033.2 tons. Since the generator sets weight is also included in the this estimated weight, the remaining machinery mass except generator sets is 970.8 tons. The total machinery weight used in the case study LCA calculation is 1,344.0 tons.

5.4 Outfitting weight

The outfitting weight was determined by deducting the hull and machinery weights from the lightship weight.

Outfitting weight = Lightship weight - (Steel Weight + Machinery Weight)
Outfitting weight = 10373 tons – (5781.3 tons + 1344.0 tons) = 3,247.6 tons

The residual approach was initially used in calculating the outfitting weight as it ensures consistency with the vessel's published lightship weight rather than relying on an additional empirical outfitting weight estimation method. However, the classical outfitting weight calculation was carried out based on Watson and Gilfillan (1976), reproduced by Parsons (2004) as an independent comparison. Using the appropriate coefficient for passenger vessel ($C_o = 1.25$) and the main dimensions of the case study vessel (L = 166.5m, and B = 25.9 m), the calculated outfit weight is 5,392.4 tons.

This estimation from the empirical method is approximately 66% greater than the residual method value of 3,247.6 tons. When combined with the independently estimated structural steel and machinery weights, the total lightship weight is 12,515.7 tons. This exceeds the published lightship weight by 20.7 %. This difference highlights the cumulative uncertainty associated with the independently verified parametric weight estimation models, rather than an error in calculation. As noted by Aasen and

Bjørhovde (2010), the accuracy of the parametric weight estimation depends on the similarity between the target vessel and the source data used to develop the empirical relationships, and uncertainties in individual estimates accumulate when multiple independent models are applied together.

Therefore, the residual outfitting weight of 3247.6 tons was used as the Building-stage eight input to the LCA tool. This approach ensures consistency with the vessels original lightweight ship, which represents the most reliable weight reference available. The Watson & Gilfillan (1976) estimate is reported as an independent comparison, showing the level of uncertainty that may arise when empirical weight estimation methods are applied during the conceptual design stage.

The resulting lightship weight comprises approximately 55.7% of structural steel, 13% of machinery and 31.3% outfitting. The outfitting weight component is higher than the 10-15% typically reported for cargo vessels (Known at al., 2025; Tuan and Wei, 2019), reflecting the greater contribution of passenger accommodation, outfitting and super structure characteristic of Ro-Pax vessels.

5.5 Material breakdown of machinery and outfitting

The weight estimated in Sections 5.2 to 5.4 give total weights for ship system groups rather than individual materials. However, The LCA tool described in Chapter 4 requires every input to be linked to a specific material record in the LCAI References database, so that the LCA calculation sheet could use the corresponding cradle to grave environmental impact factor for the LCA calculation. Therefore, the estimated machinery and outfitting weights were breakdown into their constituent materials using literature-based material composition data.

The main propulsion engines and generating sets were allocated according to the material composition of a marine generator set reported by Ling-Chin and Roskilly (2016b), comprising 69.5% cast iron, 21.3% steel, 2.7% aluminium and 2.2% carbon and remaining 1.4% chromium and tin. The remaining machinery weight (970.8 tons; Section 5.3), representing all other machinery items such as propellers, shafting, pumps, motors, and other auxiliary machinery, was allocated using the electrical motor material composition reported by Lin-Chin and Roskilly (2016b): 82% steel, 11% copper, 3 % cast iron, 1% aluminium, and 2% plastic. Although this composition does not represent every component within the machinery group, it was considered the closest available published data. Even though, this case study uses material breakdown for machinery and outfitting, the real design teams could use the actual manufacturer EPD data and weight values, where material breakdown is not necessary.

The estimated outfitting weight of 3,247.6 tons was distributed across twelve material categories using the percentage reported by Kwon et al. (2025). These categories are outfitting steel, copper wiring, brass fittings, three piping materials (copper-nickel, carbon steel and stainless steel), three coating materials (polyurethane, epoxy, and anticorrosive paints) and three machinery and outfitting items (ventilation units, ramp motors and cables). Where the total was divided equally among those materials, following the method used in the literature.

The outfit material allocation shows the greatest uncertainty within the material breakdown. The dataset reported by Kwon et al. (2025) was derived from cargo vessels, including a RORO vessel, a bulk carrier and a container ship, none of which includes passenger accommodation. In contrast, the Ro-Pax vessel (considered in this case study) includes accommodation and public spaces for 1688 passengers. Where the substantial outfitting weight includes equipment and components related to passenger facilities and lifesaving systems, which are not explicitly represented in the available material composition data. This limitation is acknowledged explicitly and remains outside the scope of this research study.

5.5.1 Passenger accommodation furniture

Considering the substantial passenger capacity of the case study vessel (1688 passengers; Section 5.1), a limited passenger furniture inventory was included within the case study. Consistent with the scope defined in Chapter 1 (Section 1.5), furniture items were included only where a published EPD was available within the tool's material database. The inclusion of each furniture category was based on the availability of EPD data, while the number of items assigned to the vessel was treated as an engineering estimate.

Four furniture products with published EPD issued by Andreu World S.L. (November 2025) were selected within the database: a dining chair (Oru Cahir SI2270), a lounge armchair (Oru Cahir BU2277), a two-seater sofa (Oru Sofa SF 2278), and a bar stool (Counter Stool – Oru Chair BQ2275). Each declaration reports environmental impacts across the full life cycle, including production, installation, and end-of-life stages, allowing the complete cradle to grave impact factor to be applied directly within the LCA tool in accordance with its calculation methodology (Chapter 3, Section 3.2; Chapter 4, Section 4.4)

The quantities assigned to the cases study vessel includes 500 dining chairs, which can accommodate 30% of passenger in dining areas, 250 lounge armchairs and 50 two-seater sofas, providing setting for approximately 350 passengers in public lounge spaces and 40 bar stools. These quantities are engineering estimates derived from the vessel's passenger capacity rather than published design data. No relevant EPD data were available within the LCAI Reference database for beds, mattress and other cabin furnishing items. Therefore, these items were excluded from the case study. Although the combined contribution of the four furniture items is relatively small (approximately 41.5 tons CO2-equivelent; Section 5.7), their inclusion improves the completeness of the passenger area inventory while maintaining the requirement that every material entered into the tool is supported by verifiable EPD data.

5.6 Operational fuel consumption estimation.

The Operational stage of the LCA tool (Chapter 3, Section 3.2) requires the total fuel consumption and the environmental impact factor for the relevant fuel type to evaluate the total environmental impact of the case study vessel during the ship life span. There were no published data for lifetime fuel consumption, therefore the fuel consumption quantity was estimated from the vessel's operating characteristics and the engine manufacturer published engine performance data.

The vessel operates at a service speed of 24 knots, corresponding to 80% of the maximum continuous rating (MCR), as specified by Antoniadis (2021). This gives a service power demand of 21120 kW. Based on the operating schedule established in

Section 5.1, the vessel completes approximately 168 round trips per year, totalling to an estimated 2436 operating hours annually.

A specific fuel consumption of 171g/kWh was adopted based on manufacturer data for the Wäartzilä 31 engine platform. The 12V31DF engine model consumption rages from 169.7 to 174.0 g/kWh between 75% and 100% engine load for diesel-mode operation (Wärtzilä, 2019). Extrapolating to the 80% MCR gives an estimated specific fuel consumption of 171 g/kWh. The calculated annual fuel consumption is approximately 8,798 tons and for lifespan of 30 years (Chapter 3, Section 3.4), total fuel consumption is 263930 tons.

The environmental impact of the marine gas oil was calculated form cradle to grave from the data published by Bengtsson et al. (2011). The GWP of 3.611 kg CO_2-equivelent per kilogram, of well-to-propeller basis was calculated from the well-to-tank and tank-to-propeller data reported in the paper. The original publication reports impact per ton-kilometre rather than unit mass of fuel. The calculation was carried out using the energy demand together with lower heating value of marine gas oil reported in the literature. The resulting factor (3.611 kg CO_2-e/kg) applied throughout the operation stage calculation. The same calculation was carried out for heavy fuel oil and liquified natural gas resulting 3.545 and 3.508 kg CO_2-e per kilogram respectively, which gives a useful consistency check on the derivation.

5.7 Case study results

Table 5.2 summarised the case study's calculated GWP, for ship life cycle stages in the LCA calculation tool. The study considered functional unit as one ship cradle to grave, and the life span of 30 years. The LCA tool calculation details are in Appendix A.

Table 5-2 Summery of GWP contribution of ship lifecycle stages for case study ship

Lifecycle stage	GWP (t CO_2e)	Share of total
Building	30091	3.05%
Operation	953051	96.53%
Maintenance	4171	0.42%
Total	987313	100%

Module D, the recycling credit potential associated with every material installed in the vessel during its life span (includes replacement) is - 1.95 tCO_2-e. This is reported separately and it is not part of the total GWP of the ship tabulated in Table 5.2, which is consistent with the EN 15804, Clause 7.5 convention of reporting Module D.

As Figure 5.1 shows, Operation stage dominates the total GWP of the case study ship. Which is aligning with the reported maritime LCA litterateur reviewed in Chapter 2. Chatzinikolaou and Ventikos (2014) report operational emissions exceeding 90% of total lifecycle output for conventional-fuel ships. Javad (2025) reports an 83.2% operational share for concept-phase cruise vessel case study. Ling-Chin and Roskilly (2016b) similarly find diesel genset operation is the dominant contributor across most impact categories for a comparable RORO power system.

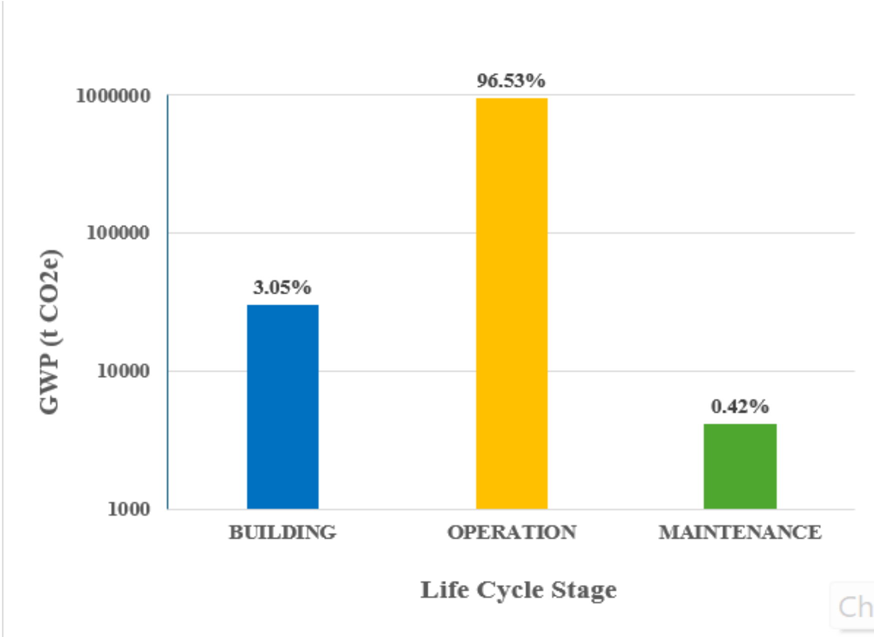


Figure 5-1 Case study GWP by life cycle stages (log scale)

The case study results for Operational stage are in the upper end of the range reported in the literature, which accounts for 96.53% of the total lifecycle GWP. One possible explanation is that the fuel consumption estimate (Section 5.6) may overestimate the actual fuel consumption as it is calculated based on the constant power consumption in the service-speed without considering the full operational profile, which includes slow steaming, port manoeuvring and other operational variations. This limitation is recognised as an opportunity for future refinement and is discussed further in Chapter 6 and 7.

The total Building and Maintenance stages contribution is 3.47 % of the total lifecycle GWP of the case study vessel. This is consistent with previous studies showing that construction related emissions currently represents a relatively small proposition of the lifecycle emissions for conventionally fuelled vessels (Kwon et al., 2025). Kwon et al. (2025) also state that this proportion could increase significantly even up to 40% with the decarbonised marine fuel pathways. Therefore, the low construction stage contribution resulted in this case study should be considered as being specific to conventionally fuelled vessel under current fuel consumption assumptions rather than as a general characteristic of ship construction.

5.8 Benchmark comparison against reference vessels.

The Building-stage GWP results were evaluated by comparing the case study's embedded carbon intensity (GWP per unit of lightship weight) with those reported for the reference vessels presented in Chapter 2.

The Resulting value of 2.90 kg CO_2-equivelent per kilogram of lightship weight is comparable with those reported for the reference vessels (see Table 5.3). The case study vessel LCA tool result falls within the same order of magnitude as the reference vessel GWP intensity figures, where the case study results are lies closer to the RORO vessel designed for PCTC. The other two cargo vessels intensity factors are below the case study vessel intensity figure which is meaningful as the machinery and outfitting's in bulk carriers and container vessels are much lesser than Ro-Pax vessels. This comparison provides a quantitative validation that the estimated Building-stage impact is consistent with values reported in the literature and does not appear as an outlier.

Table 5-3 Benchmark GWP intensity factor results for case study vessel and reference vessels

Vessel	Lightship Weight (t)	Building Stage GWP (t CO_2e)	Intensity (kg CO_2e/kg lightship)
Case study Ro-Pax – (this study)	10373	30091	2.90
PCTC – 7000 CEU (Kwon et al., 2025) (approx.)	24500	72500	2.96
Bulk Carrier, 200k DWT (approx.)	28906	75000	2.59
Container Carrier, 20,000 TEU (approx.)	33535	88000	2.62

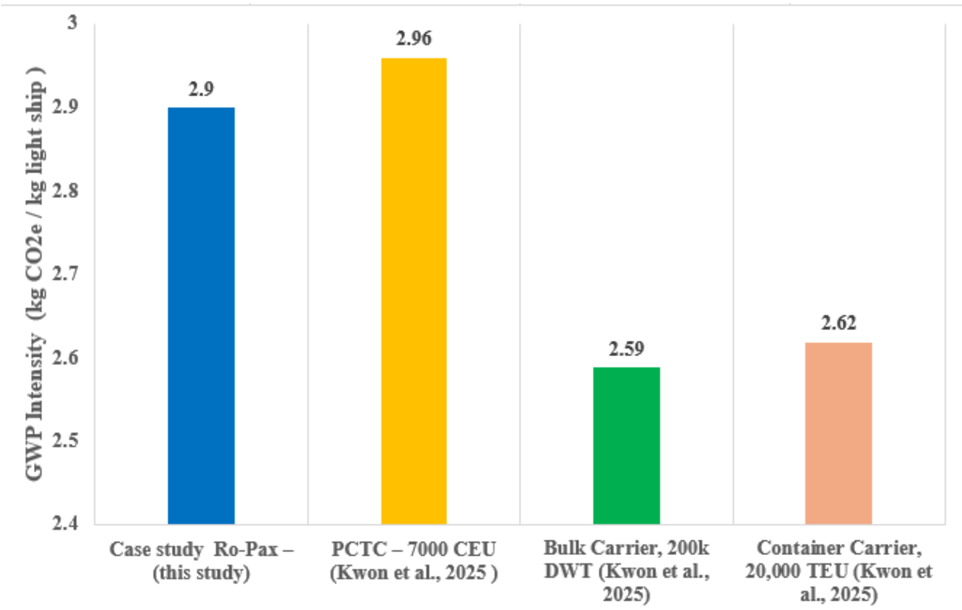


Figure 5-2 Benchmark of Building-stage GWP intensity (kgCO_2-e / kg lightship) against cargo vessels comparators from Kwon et al. (2025)

As Figure 5.2 illustrates, case study Building stage GWP intensity factor and all three Kwon et al. (2025) Building-stage intensity factor results calculated based on the approximated total GWP values at Building stage extracted from the paper's Figure 6 stacked bar chart, where the exact figure is not printed and the values are not published elsewhere in the paper. In addition to that the Figure 6 in the paper only uses the values which are higher than 1% of the total, therefore few material items didn't present in the Figure 6 of the reference paper.

6 Verification and validation

6.1 Verification and validation framework.

This chapter evaluates the developed LCA tool through separate verification and validation methods, which are commonly used in engineering model assessment. Verification addresses whether the tool has been implemented correctly by examining it internal correctness, including whether the calculation procedures perform as intended and does the implementation confirms to the methodological framework developed (Chapter 3)? Validation addresses a different question. Is the tool being appropriate for its intended purpose or not? This is assessed by examining the credibility of the tool's outputs through comparison with independent reference data and established engineering knowledge.

The evaluation is structured according to the three interpretation checks defined in ISO 14044, Section 4.5.3 (SFS, 2020b): completeness (ISO 14044, Section 4.5.3.2), consistency (ISO 14044, Section 4.5.3.4), and sensitivity (ISO 14044, Section 4.5.3.3). Although these checks are specified for LCA studies, they are applied here to assess the performance and reliability of the developed LCA tool.

The verification and validation process comprises of methodological, computational, and external evaluations, followed by sensitivity analysis. Section 6.2 assesses the methodological compliance with ISO 14040 (SFS, 2020a) and ISO 14044 (SFS, 2020b). This section also addresses the completeness check required by interpretation phase of ISO 14044, Section 4.5.3.2. The provenance fields associated with each material record, together with the Boundary & Limitation worksheet, are reviewed to confirm that all information necessary to interpret the results is explicitly documented rather than assumed or omitted. Section 6.3 verifies the correctness of the implementation calculated using synthetic test cases. The external validation of the tool is covered in Section 6.4 by reproducing published reference case studies and comparing the resulting outputs with the corresponding published results. Section 6.5 addresses the tools consistency check named in ISO 14044, Section 4.5.3.4, checking the tool's own methods and assumptions were applied uniformly throughout its application. Section 6.6 completes the evaluation through a sensitivity analysis (ISO 14044, Section 4.5.3.3), examining the influence of the uncertain input assumptions on the case study results.

6.2 ISO 14040 / 14044 compliance verification

Compliance with ISO 14040 (SFS, 2020a) and ISO 14044 (SFS, 2020b) was verified by mapping eighteen individual clauses to the corresponding locations where they are implemented within the tool. This assessment confirms that the tool has been developed in accordance with the internationally recognised standard structure. The full mapping is carried out in separate worksheet as the ISO Compliance Checklist worksheet, while representative examples are shown in Table 6.1. The detailed ISO Compliance Checklist is in Appendix A.

Table 6-1 Compliance checklist - sample list (full list in Appendix A)

ISO Clause	Requirement	Implemented Where
ISO 14044, Section 4.2.3.2	Functional unit	Assumption worksheet: 1 Vessel, cradle to grave
ISO 14044, Section 4.2.3.6	Data quality requirement	LCAI Reference: Manufacturer, Geography, Data quality, and Citation columns, for every material record.
ISO 14044, Section 4.4.2.4	Characterisation	LCA Calculation worksheet's Building, Operation, and Maintenance formulas (each incorporating scrapping impact through total GWP value)
ISO 14044, Section 4.5.3.2	Completeness check	Boundary and limitations worksheet, documenting known gaps.
ISO 14044, Section 4.5.3.4	Consistency check	Uniform column structure across all LCAI Reference records; verified by the formula test in Section 6.3

All the cluses are implemented somewhere in the tool. No gaps were identified in this structural review. This verification confirms compliance with the standard structural requirements, and it doesn't imply that every material record or case study input is of the highest available data quality.

6.3 Formula verification tests

Structural compliance (Section 6.2) does not confirm that the tool's formulas compute correctly according to the methodology described in the Chapter 3. Therefore, a separate set of isolated tests was used for this purpose. In this test, mock materials with clean, round number impact factors were used rather than tool's real case study data. The expected results could be derived independently by hand and checked against the tools' own formula output.

Nine test cases were carried out, each isolating a different calculation pathway. Those are as follows: a building-only item with no renewal, no operation, and with Module D; a whole-unit replacement mechanism using an item life span; a scheduled partial renewal mechanism using renewal percentage and survey period; an operation-only material; a multiplied item using the number of items input; a full combination of building, operation, maintenance and module D in a single calculation; testing a life span that does not divide the ship life span evenly; a life span longer than the design life of the ship; and a priority check confirming that when both replacement mechanisms are populated on the same row, the item life span mechanisms takes precedence over the scheduled renewal mechanism.

Table 6-2 LCA tool formula verification test results

Test No.	Pathway Tested	Results
1	Building only, with Module D	Pass
2	Maintenance via Item life span	Pass
3	Maintenance via renewal percentage per survey	Pass
4	Operation only	Pass
5	Number of items multiplier	Pass
6	Fully combined (Building, Operation, Maintenance and Module D)	Pass
7	Life span edge case 1: Ship life span doesn't divide evenly	Pass
8	Life span edge case 2: Material life span greater than ship life span	Pass
9	Both material life span and renewal percentage recorded in same row	Pass

Results of all nine cases are matching independently with the hand calculated expected values exactly. Because every calculation is implemented using deterministic spreadsheet formulas, with no random or volatile function anywhere in the tool. Where identical inputs always produce identical outputs, regardless of any recalculations or number of calculations caried out in the tool.

Section 6.2 and Section 6.3 together, constitute the LCA tool completeness check. Section 6.2 confirms that every structural element is present somewhere in the tool as required by the ISO 14040/14044 standards and the Section 6.3 confirms every calculation pathway that structure enables computes correctly.

Both Section 6.3 and 6.4 constitute the correctness check of the LCA tool presented in this thesis. The synthetic tests in Section 6.3 verify the underlying formulas in isolation, while the independent reconstruction described in Section 6.4 provides a second, validation using real-world data.

6.4 Validation against published reference case studies

Section 6.2 and 6.3 verifies that the tool has been built correctly. This section presents its external validation. The objective is to determine whether the tool reproduces the same published results of independent reference studies when provided with the related input data. This gives more rigorous validation than comparison with a general literature range, as it evaluates the calculation mechanism directly against an independent verified and validated published results.

The validation procedure applied throughout this section is as follows. Each reference study provides a material inventory as absolute masses or as percentage share of stated total mass. These weight inventory values are entered into the tool's calculation engine. The LCAI Reference material impact factors are then used, where these material impact factors extracted from the same reference study (otherwise tool's own material impact factors were used). The validation isolates the correctness of the calculation mechanism itself, independent of the differences in input data. The tool calculated results are then compared with the published values reported by the references study. Any variation is examined against both the published methodology and the documented scope of the tool. The specific reasons identified for the deviations are reported rather than leaving an unexplained difference.

Only reference studies that report a published quantitative results suitable for direct comparison are treated as validation cases. Four case studies found in the literature were used in this validation procedure, which covers structural materials, machinery and electrical systems and a complete real vessel. Three cases use vessels reported by Kwon et al. (2025): a PCTC (RORO ship), a bulk carrier and a container carrier. The fourth case uses a real oil tanker reported by Quang et al. (2021).

6.4.1 Kwon et al. (2025): (PCTC)

The PCTC has a reported lightweight of 25,000 tons. Kown et al. (2025) adjust this to 24,500 tons, 98% of the total, to define the LCA boundary. This excludes items such as main engines and furnishings. The paper's Table 1 gives the percentage share of each material category within this adjusted lightweight, Table 2 gives an GWP impact factor for every material within each category. Multiplying these together (weight x GWP impact factor) and summing up, gives a total material GWP for the vessel. Kwon et al. (2025) Figure 6 shows this total GWP as a stacked bar chart, by reading the chart the PCTC building stage total GWP factor is approximately 72,500 tons of CO_2-equvelent.

The tool reproduces this calculation using the same individual material weights and the same material GWP impact factors, resulting in 73,349.3 tons of CO_2-equvelent, this is a difference of plus 1.17%. Two factors explain this small difference. First, Kwon et al. (2025) chart explicitly state that it excludes the material categories contributing less than 1% of the total. And the other reason is that a bar chart without printed data labels carries some visual imprecisions. Both these factors would contribute to this small change in the results, which is the direction observed here.

6.4.2 Kwon et al. (2025): bulk carrier

The 200,000 DWT bulk carrier has a lightweight of 29,800 tons, which adjust to 28,906 tons, which is 97 % of the total lightweight by Kwon et al. (2025) to meet the LCA boundary condition. The same method is applied as in the PCTC study, where the Table 1 and Table 2 data were extracted and entered to the LCA tool.

The Figure 6 reading for the bulk carrier was approximately 75,000 tons CO_2-equvelent. The tool's results corresponding to the Bulk carrier's input data is 75,769.4 tons CO_2-equvelent. This is a difference of 1.03 percent, explained by the same two factors in Section 6.4.1.

6.4.3 Kwon et al. (2025): container carrier

The container carrier has a capacity of 20,000TEU and its reported lightweight is 35,500 tons. The author adjusts this to 33,535 tons, 95 % of the total weight, for the LCA boundary.

Following the same method as in in previous two vessels and reading the Figure 6 container vessel bar gives approximately 88,000 tons CO_2-equvelent. The tool reproduction gives 75,769.4 tons CO_2-equvelent. This is a difference of +1.03 percent, explained by the same two factors described in Section 6.4.1.

6.4.4 Quang, Dong and Hai (2021): Panamax oil tanker

Quang et al. (2021) report a complete cradle to grave LCA of a real, named Panamax oil tanker, built in 2009 in South Korea. The study uses CML2001 method across six life cycle phases: material consumption, shipbuilding, operation, maintenance, end-of-life and material transportation. The paper reports a life cycle GWP of 1,790,000 tons of CO_2-equivelant in the Table 11 entire life cycle environmental impact results.

The paper's Table 1 gives a steel weight of 12,022 tons. This is a single standalone figure, not a sum of components. The paper also gives a 25-year total fuel consumption of 472,000 tones, obtained by adding the annual consumption figures presented in the Table 4 of the case study paper.

Table 1 of the reference paper also reports the main engine (368 tons) and generator (59.1 tons) weights separately form the structural steel weight. These weights are presented as vessel specifications rather than as material inputs to the construction-phase assessments. The paper explicitly states that the engine and equipment production lies outside its system boundary. For consistency with the material breakdown approach used throughout the thesis (Chapter 5, Section 5.5), the reported engine weights were included and decomposed using the Ling-Chin and Roskilly (2016b) marine genset composition. Although this extends the calculation marginally beyond the original paper system boundary, the resulting contribution is less than 0.1% of the total lifecycle impact and therefore has no material influence on the validation outcome.

The tools results, including the main engine and genset weight breakdown, and fuel consumption, gives a total of 1,734,432 tons of CO_2-equivelent. This is a difference of minus 3.1% against the paper's published figure. The gap is well within a defensible margin. The main reason is that the tool uses a material emission factor derived from another literature source, as the paper did not publish the material impact factors used in its own calculation.

6.5 Consistency check

ISO 14044, Clause 4.5.3.4 (SFS, 2020b), defines a consistency check as an assessment of whether assumptions, methods, and data have been applied uniformly throughout the study, relative to its own goal and scope. This section checks the tool itself against this requirement, across the case study and all four validation cases.

Table 6-3 Consistency check criteria

Consistency Aspect	Description
System boundary consistency	Every case in this thesis uses the same system boundary. Building, Operation, and Maintenance stages are calculated using materials total environmental impact factor which includes the scrapping impact, hence scrapping stage is not separately reported. Module D is calculated and reported separately, never summed into the headline total. This

	boundary is applied identically to the case study and to every validation case.
Functional unit consistency	The same functional unit, which is one vessel, assessed cradle to grave was used for every case studies. Every case reports its results using the same indicator, Global Warming Potential (GWP), in kilogram of CO2-equivelent. No case study substitutes a different functional unit or a different indicator.
Characterization method consistency	All the material records in the tool used in the case study or in validation case studies, draws its environmental impact factor from the LCAI Reference database structure. Every impact factor represents a GWP100 characterisation. None of the cases employs a different impact assessment method or characterisation horizon.
Data quality documentation consistency	Each material record carries the same four traceability fields: manufacturer, geography, data quality and citation. This applies equally to case study materials and to validate materials.
Calculation logic consistency	Every row in the tool, uses the same Building, Operation, Maintenance, and Module D formulas. These formulas were verified directly in Section 6.3. No case uses a modified or case specific version of any formula.

The case study and all four validation cases apply the same system boundary, functional unit, characterisation method, data quality and calculation logic. No case specific exceptions were found. The tool's methods and assumptions are consistent throughout this thesis.

6.6 Sensitivity analysis

ISO 14044 Section 4.5.3.3 (SFS, 2020b) requires a sensitivity check as part of an LCA study's interpretation phase (Section 6.1). Several inputs to the Chapter 5 case study are subjected to uncertainty, including the specific fuel consumptions, the estimated hull steel weight, and the selected fuel type. This section test how these uncertainties effect the study's final results, rather than treating them as qualitative limitations.

Seven sensitivity scenarios were carried out, each varying a single input while holding all other at their Chapter 5 base line values, using the tool's own calculation engine. Table 6.3 presents the resulting change in the case study vessel's GWP, ranked from largest to the smallest effect.

Table 6-4 Results of sensitivity analysis of case study vessel Ro-PAX for uncertainty assumptions - organised in desending order

Scenario	Change in Total GWP
Design life: 25 years (vs. 30 years baseline)	-16.30%
Fuel type: LNG fuel oil instead of marine gas oil (both well to propeller)	-12.52%
Specific fuel consumption: +10%	+9.65%
Specific fuel consumption: -10%	-9.65%

Fuel type: Heavy fuel oil instead of marine gas oil (both well to propeller)	+4.33
Hull steel weight: +20%	+0.37%
Hull steel weight: -20%	-0.37%

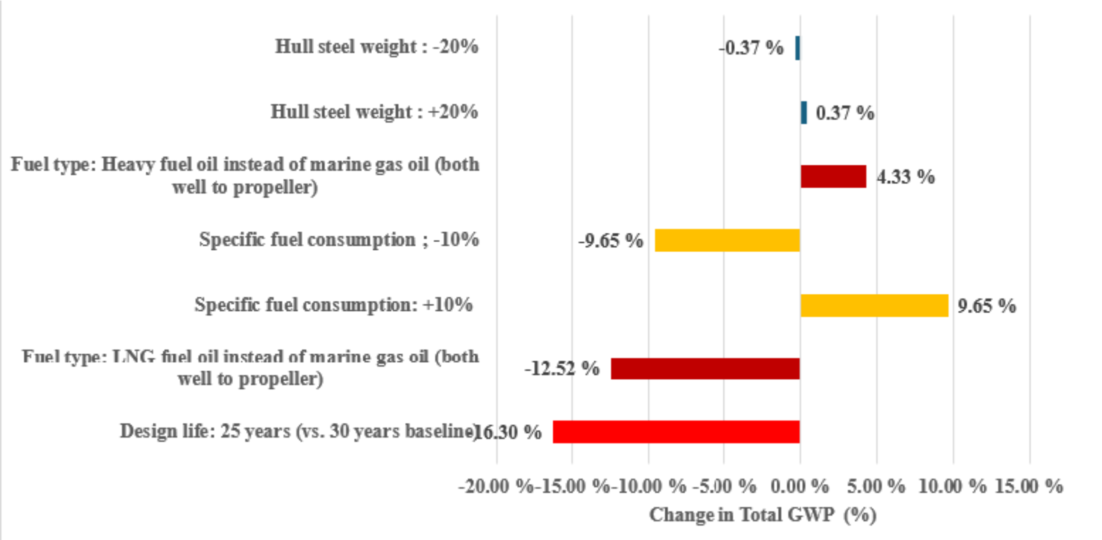


Figure 6-1 Results of sensitivity analysis for case study vessel Ro-Pax for four uncertainty assumptions

Figure 6.1 Presents sensitivity results visually, ranked by magnitude for the main case study. Three findings follow from this ranking. The case study's results are far more sensitive to Operational stage assumptions than to Building stage assumptions. Varying the hull steel weight estimate by plus or minus 20 %, which is a wide margin, reflecting the concern raised in Chapter 5, Section 5.2- changes the vessel's total GWP results by only about 0.4%. This is a direct consequence of the building stage's small share of the total (3.05%, Chapter 5, Section 5.7). This shows, even a large error in a Building-stage estimates has a small effect on the end results, for a conventionally fuelled vessel of this kind.

Second finding is the choice between two different fuel types. The fuel mass is correctly scaled to energy content for each new fuel types, and both fuel type environmental impact factor was correctly derived on a well-to-propeller basis form the same source (Bengtsson et al., 2011). Switching to LNG reduces the total GWP results by 12.52%, the second largest effect of all seven scenarios. Switching to HFO increase the total results by 4.33%. The fuel type selection is one of the most consequential assumption this tool's case study results depend on.

The third finding is design life and specific fuel consumption are also important and consequential assumption among all others. Both scale the operational-stage GWP results, where the operational stage accounts for 96.53% of total GWP impact of the case study (Chapter 5, Section 5.7). Design life has a secondary effect on the Maintenance stage GWP impact as the number of material or component renewal is changes with the change of the design life, because the design life is directly divided by the material life or by the major survey interval (Chapter3, Section 3.4; Chapter 4, Section 4.4), so reducing design life from 30 years to 25 years reduces the number of surveys lowering the maintenance impact alongside the larger Operational-stage reduction.

6.7 Synthesis of validation results

The validation of the tool was conducted in Section 6.4 using published LCA studies covering four different ship types. The results and synthesis of these case studies are presented in this section. The Table 6-5 compares the GWP values reported in the published studies with the corresponding GWP values reproduced using the tool. The table also presents the percentage difference between the reference and tool reproduced results. The largest deviation was observed for the case study by Quang et al. (2021), with a difference of -3.1%.

Figure 6-2 presents a bar chart comparing the GWP values reported in the reference studies with those reproduced by the tool, plotted on a logarithmic scala. The Figure 6-3 shows the percentage differences between the reference and tool reproduced results for each case study. Overall, the results demonstrate the validity and accuracy of the tool in reproducing the GWP results reported in the published LCA studies.

Table 6-5 Total GWP factors for validation case studies - published results, tool reproduced results and the gap as a percentage of reference value

Case	Comparator (t CO_2-e)	Reproduced (t CO_2-e)	Difference	Role
Kwon et al. (2025), PCTC	72,500	73,349.3	+1.17%	Validation
Kwon et al. (2025), Bulk Carrier	75,000	75,769.4	+1.03%	Validation
Kwon et al. (2025), Container Carrier	88,000	89,113.9	+1.27%	Validation
Quang et al. (2021), Oil Tanker	1,790,000	1,734,431.7	-3.1%	Validation

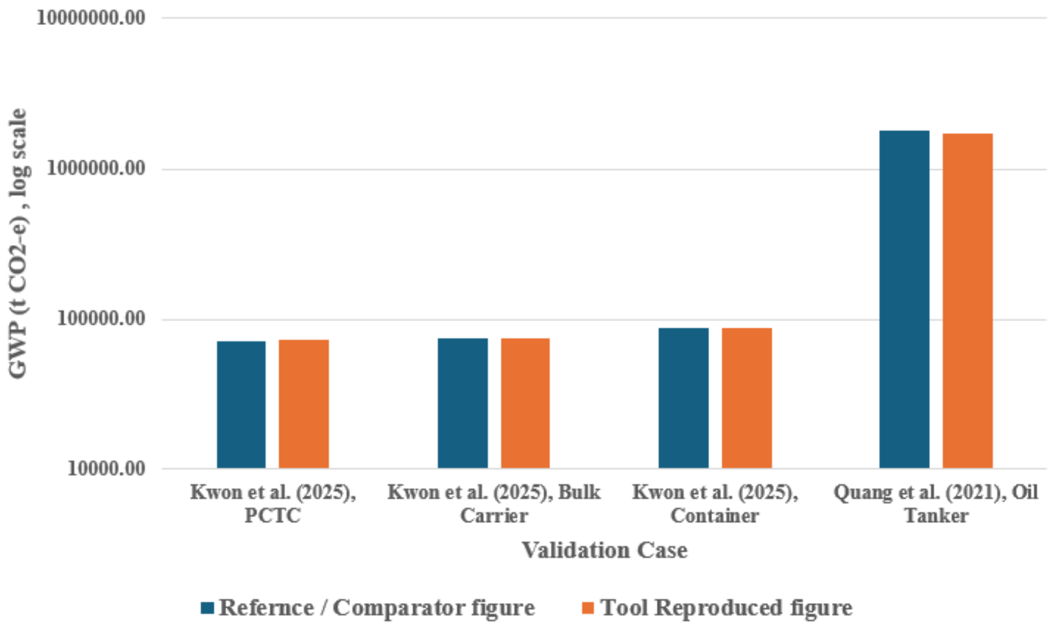


Figure 6-2 Reference/comparator vessels total GWP factors verses LCA tool reproduced total GWP factors for all validation case studies

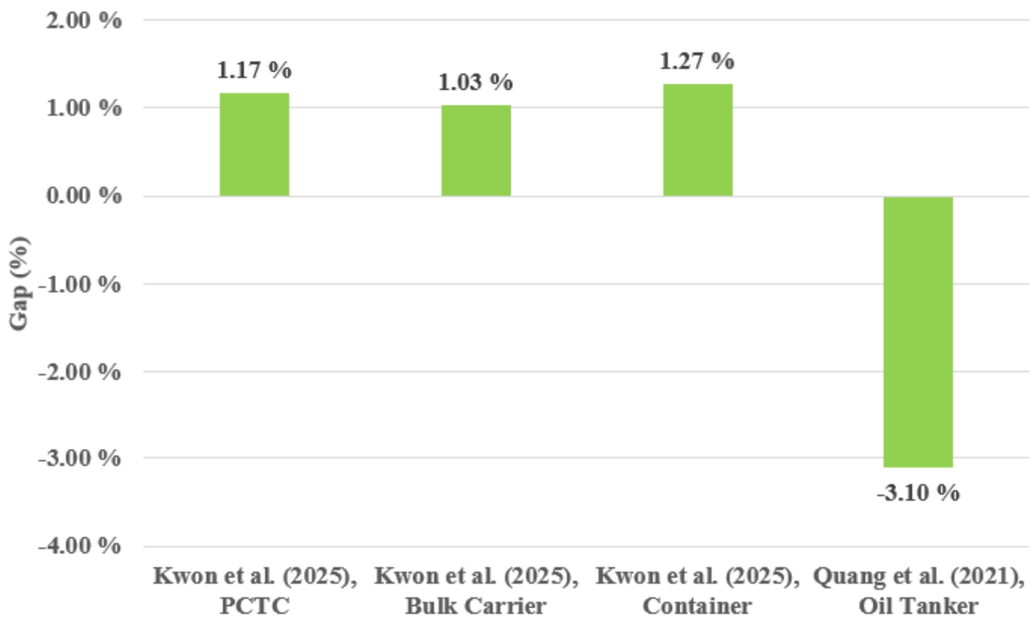


Figure 6-3 Percentage gap for all validation case study vessels

Following are the three key findings identified form the results of four validation cases collectively.

- The tools core calculation mechanism is confirmed correct and consistent. Across two independent source papers, four vessel types, and two different comparison bases, all reproduced results were within 3.1 % (Figure 6.3) of its respective reference figures. This finding was further supported by the formula verification tests in Section 3.1, which confirm the underlying formula produce the expected results when tested independently using synthetic data.

- The smallest gaps observed for the three Kwon et al. (2025) cases are explained by two specific reasons. The Figure 6 of the source paper excludes any material category which GWP impact is less than 1% of the total GWP impact. Other reason is that the total GWP value was taken by visually reading the bar chart as the real value was not in the data labels or not mentioned in the source paper elsewhere. Which may carry visual imprecisions.
- The magnitude of the variation is more strongly associated with the origin of the emission factors than with the uncertainty of the input data alone. The three Kwon et al. (2025) cases, where this tool uses the source's own published impact factors. The results show gaps under 1.3 %. But in the oil tanker case, LCA tool substitutes its own material impact factors as the source paper does not publish data related to emission factors which were used in its own evaluation. This resulted the largest gap of 3.1 %, even though the source paper stated mass and total GWP impact figure.

6.8 Chapter summery

The verification and validation process demonstrated that the developed tool performs reliably at multiple levels. Methodologically, the tool adheres to the requirement of ISO 14040 (SFS, 2020a) and ISO 14044 (SFS, 2020b) (Section 6.2). Formula verification in Section 6.3 confirms the tool's calculation engine produces correct, repeatable results on isolated test data. Empirically, the tool reproduces LCA results with deviation of no more than 3.1%, with each gap is explained by known differences in modelling assumptions or data sources (Section 6.4). Finally, the consistency check (Section 6.5) confirms the tool applies the same system boundary, functional unit, characterisation method, and calculation logic throughout. Together, these findings establish the credibility of the tool and support the validity of the case study results presented in Chapter 5.

7 Results and discussion

This chapter draws the Chapter 5 case study results and the Chapter 6 validation and verification results to answer four research questions set out in Chapter 1 and to discuss the LCA tool's practical benefits and the limitations in relation to the wider literature review in Chapter 2. Each of these research questions are addresses in Section 7.1 to Section 7.4. In Section 7.5 case study findings are discussed.

7.1 Adopting an industrial work breakdown structure into a concept stage ship work break down structure.

The RQ1 asked how an existing Industrial Work Breakdown Structure can could be adopted to a suitable work breakdown structure to organize the environmental impact data at the conceptual design stage when the detail material take-off information is not available.

This thesis answered this question by developing an independent ship SWBS suitable for concept design stage ship LCA calculation. The SWBS structure is consisting of three major levels. The main system level defines the main ship systems based on their functionality and application where the group of systems are consolidated based on their similarity and industrial identification. The second level further subdivides the main system based on the difference in the functionality of those sub systems, and the third level has individual or group of sub-sub systems that had been consolidate based on their functionality. The SWBS does not goes into individual material level breakdown as the conceptual stage detailed material take-off information are not available.

The user can easily allocate the material based on the main system and subsystem to the LCA tool by selecting the relevant item form the dropdown list in the LCA Calculation tool. The tool allows the multiple material allocation for single SWBS category, where most of the ship systems include multiple materials, equipment, components, consumables. So, the SWBS allows user to include all relevant material to relevant SWBS item to evaluate the LCA impact. The SWBS is independent of other worksheets, and it only serves the LCA Calculation sheet.

Another feature is that the user can add SWBS items based on the requirement. So, the SWBS structure is flexible to certain level, and the tool can accommodate those newly added SWBS items to its calculation engine without any formulation or synchronisation. Another feature is that the SWBS cover all the vessel scopes except naval armament systems (which is out of this thesis scope), and it serves all types of commercial ships. Even though this SWBS is dedicated to conceptual stage LCA calculation, it could be easily expanded to evaluate the detail ship design level LCA calculation by expanding the SWBS.

7.2 Tool architecture and calculation logic

The RQ2 question is, what tool architecture and calculation logic are required to link a work breakdown structure to a cradle to grave material impact database, while correctly representing the distinct Building, Operation, Maintenance, and Scrapping lifecycle stages?

The tool architecture is set out formally in the Chapter 3 (Section 3.2) and implemented in the Chapter 4. The LCA tool consists of 4 worksheets which are linked together, and a calculation logic in which every life cycle stage draws on the same EN 15804-modular material impact factor, rather than being calculated as an independent process from raw activity data, in contrast to the approach taken by Quang et al. (2021) discussed in Chapter 3, Section 3.2.

The case study (Chapter 5) exercised every part of this tool architecture. The Building, Operation, and Maintenance stage impact assessment. In the Maintenance-stage assessment it considered both whole-unit replacement (used for machinery, on the basis of a known item life span), scheduled partial renewal (used for hull steel, based on a renewal percentage and survey interval). The fuel was accounted for the Operational-stage assessment. The scrapping is treated by including the scrapping impact in the own material impact factor, which correctly accounts for all the material mass used in other three stages. This method simplified the tool calculation architecture and avoided double accounting. The module D is calculated separately and the all the material weights used in three stages were summed and multiplied by the material module D factor to calculate the total module D credit. The formula verification test carried out in Chapter 6, Section 6.3 independently confirm that the tool calculation logic works correctly on synthetic data, in isolation form any question about the case study's own input data quality.

The thesis has successfully answered the research question 2 by developing a tested and verified tool architecture which link the ship work breakdown structure to cradle to grave material impact database, while representing all four stages of the ship lifecycle stages.

7.3 Extent of verification and validation achieved.

RQ 3 questions the extent the tool can be verified, in terms of calculation correctness and validated, in terms of the credibility of its output against and independent literature results.

The tool was verified based on two bases, that is structurally and computationally. The structure of the tool was verified in the Chapter 6, Section 1, with eighteen reviewed clauses of ISO 14040 and ISO 14044 were found to be implemented somewhere in the tool. Chater 6, Section 6.3 verified the tool using nine isolated formula tests, the results were matched with the independently hand calculated expected value. Which were matched exactly without any discrepancy. Both these verifications support a high degree of confidence that the tool computes what it is intended to compute.

The validation of tool is present in the Section 6.4, and the validation results were synthesized in the Chapter 6.7. The tool was validated against four published reference figures. Three form the Kwon et al. (2025): a pure car and truck carrier, a bulk carrier and a container vessel. The other one form Quang et al. (2021): a real oil tanker. The tool calculated results for all four cases were withing 3.1% of the reference case results. Every gap resulted was traced to specific reason and clearly stated with each case results in Chapter 6, Section 6.5.

Therefore, the thesis has answered the research question 3, where the tool is verified to a high degree of confidence and it is validated against four independent, four different commercial ship types.

7.4 Practical benefits and limitations relative to existing approaches

The RQ 4 ask what the practical benefits and limitations of an industrial work breakdown structure-based approach, compared with existing approaches identifies in the literature review.

Three main practical benefits were identified following this approach in this thesis. The IWBS are widely incorporated in the shipbuilding industry specially based on the project management. Which facilitates to identify different systems and allocate resources as ship has a highly complex integrated material structure. Applying same system breakdown structure and incorporating it to the LCA calculation tool helps the user to allocate relevant materials to the correct system which is familiar to them. Another advantage is that the present industrial management inventory systems can be incorporated to the LCA tool easily through the SWBS. Specially, when making material weight estimates for new ship designs, industry uses its own previous material usages, which could easily ink to the LCA tool through SWBS. Further this could be expanded easily for detail design stage LCA as the SWBS is independently developed and it is expandable.

Other three main advantages were identified relative to the LCA tool been developed in Excel based worksheets. Tool is transparent, because tool is implemented as an auditable spreadsheet rather than compiled software. All reported figures can be traced back to its input data and formula cell by cell. This kind of transparency do not offer software tools revied in the Chapter 2, Section 2. Since those software's underlying calculation engines were not made available even where their outputs are published. Another advantage is that, not only SWBS but also the LCAI Reference database is extendable. Presently they have pre-extended range of 5000. Which could be further extend by the user as required with small changes in the excel formulas, addressing a stated limitation of several earlier ship LCA software tools that required original developer's involvement to extend. Third advantage is that the explicit lifecycle-stage and EN 15804 (SFS, 2019) module integration. This tool architecture requires every material impact record to carry values across full EN 15804 modular range (A1-Module D) (SFS, 2019), in a single worksheet. This simplifies the tool functionality and helps the user to independently work on the LCA inventory database.

The main limitation of this tool is that it only evaluates the global warming penitential, which is inherent with the scope of the thesis. The tool only processes one ship at a time and it neither evaluate multiple ships nor compare them. This tool could not access other industry EPD source database, where all the material impact data must be manually entered to the database. Where the industry software's such as GaBi operates with other EPD inventory databases. Also, the tool does not have the capability extract the data form the bill of materials that industry process. All these data need to be manually entered to the tool calculation engine. Each of these limitations are room for further improvement and development of the tool.

7.5 Discussion of case study findings

While the case study results presented in Chapter 5 directly address the four research questions, they also have a brooder implication for two key aspects identified in the literature.

The first is the balance between contribution of Building-stage and Operational stage GWP impact to the total GWP impact. The case study results show the operational stage GWP contributes 96.53% of total lifecycle GWP (Chapter 5, Section 5.7). This result is consistent with the wide pattern reported by Chatzinikolaou and Ventikos (2014), Javad (2025), and Ling-Chin and Roskilly (2016b). Kwon et al. (2025) reported that this trade-off changes with the marine fuel decarbonisation. It states that the Building stage contribution can expand up to 40% of the total GWP impact with decarbonised fuel systems. Therefore, the cases study results should be interpreted as specific to conventionally fuelled vessel under current fuel pathway assumptions. This finding has an important implication for future applications of the developed tool. The tool facilitates the detail level of modelling in the building and maintenance stages. Even though, it contributes to smaller portion of total GWP impact. With the present IMO and EU regulations and the sustainability targets (IMO, 2023; European Commission, 2026), the shipping industry is moving rapidly toward decarbonised fuels and structures as deeply discussed in Chapter 2. Which ultimately change the balance between the Operational stage and Building stage contributions, where the building stage detail LCA analysis become important aspects of future ship LCA studies.

Another important fact to be highlight here is that the material decomposition of the machinery has been carried out in the case study (Chapter 5), mainly because of the inability to find the machinery EPD data from the manufacturer or other publicly available sources. In industry application of the tool, these data gaps could be covered as those EPD data could be requested form the manufacturer.

Other key theme is the main findings of the sensitivity analysis. The results of the sensitivity analysis show that the case study result is highly sensitive to operation related assumptions rather than Building stage assumptions. The change in the service life, change of fuel type to decarbonise fuel and improvement of the engine efficiencies shows a reasonable variation in the total GWP impact, whereas the significant variation in the Building stage material only have minor effect on the total GWP impact. This gives an indication why much higher effort needed to develop the decarbonisation fuel and improve the present engine efficiencies to achieve the set sustainability targets in shipping industry by the IMO and other regulatory bodies.

Another key feature of the tool is that the tool could be utilised easily for sensitivity analysis of LCA studies which is a compulsory requirement under ISO 14044, Section 4.5.2.3 (SFS, 2020b). The only limitation is that the sensitivity analysis should be carried out individually for each scenario. Where tool does not support multiple scenarios.

8 Conclusions

This thesis set out to develop a concept stage life cycle assessment tool for all types of commercial ships, and the work presented across the preceding chapters has achieved this aim through several interconnected contributions.

An independent SWBS was developed, capable of organizing ship material and structures in a form suitable for concept stage LCA evaluation. Building on this structure, a spreadsheet-based LCA evaluation tool was implemented, incorporating the EN 15804 module framework and capable of assessing the cradle to grave GWP impact of a ship. It can be found that the tool calculation methodology successfully incorporates ship life cycles stages; Building, Operation, Maintenance and Scrapping, within its calculation logic.

To support the thesis methodology, LCAI Reference worksheet was prepared, populating material environmental impact data in alignment with the EN 15804 (SFS, 2019) module structure. The resulting database comprises 533 material impact records, extracted from EPDs and published literature sources. The LCAI Reference worksheet demonstrate that it provides cradle to grave material impact factor, with a traceable and structured foundation for the tool's calculation.

Finally, it could be concluded that the tool was verified and validated against independent published literature. Verification confirmed the tool's compliance with the structural, formulaic, and internal consistency requirements set out in the ISO 14040/14044 methodology, while validation was carried out by reproducing reference figures from independent published sources. Together, these steps confirm the tool performs reliably within its intended scope, while also clarifying its capabilities, limitations and appropriate scope of use for concept stage LCA evaluation.

These contributions demonstrate that a SWBS based LCA tool can be developed and reliably applied to ship materials and structures at the concept design stage, providing a verified and structurally consistent method for evaluating cradle to grave environmental impact early in the shipbuilding design process. Which offers a practical and verifiable basis for early-stage environmental decision-making in shipbuilding

8.1 Recommendation for future work

Future work should first expand the LCAI Reference data base with manufacturers EPDs and third party verified EPDs. The present data base consists of 533 material impact data. The data base should be further populated with the environmental impact data of ship main machinery and systems, cargo handling equipment's and systems, electrical equipment's, deck machinery and systems, navigation equipment's and systems, piping and its accessories, etc…

The present tool scope evaluates single environment impact assessment criteria, which is GWP. This scope has to be further expanded to assess other environmental impact criteria such as acidification potential, ozone depletion potential, eutrophication potential, and water deprivation. Evaluating the other environmental impacts will give wider understanding to the decision makers to make much accurate decisions related to ship building design selections.

Another limitation of the tool is that the LCAI Reference database is populated through manual entry of material records, including their associated environmental impact factors and traceability fields. While this approach ensured close control over data quality during development, it is time consuming and does not scale well as the database grows or as new EPDs become available. Future work should develop an automated import capability, allowing material records to be parsed directly from structured EPD documents and populated into the LCAI Reference database with minimal manual intervention. Such automation would reduce the time and effort required to expand and maintain the database. This will also help to minimize the risk transcription errors associated with manual data entry, and up to date EPD records.

The material quantities must be entered manually to the LCA Calculation worksheet for each material. This manual transfer step introduces additional effort and time. In shipbuilding industry, the bill of materials or previous material consumptions are recorded in its own management system under its own industrial work breakdown structure. So, the future development of the tool should support the direct import of these material quantity data into the LCA Calculation work sheet when relevant material is selected. This will reduce the manual workload involved and support faster, more consistent evaluation of multiple design alternatives at the concept stage.

8.2 Practical implications and concluding remarks.

Thesis has demonstrated the feasibility of a transparent, spreadsheet-base, industrial work breakdown structure driven framework enables cradle to grave generic ship LCA at the concept design stage, which can be verified and validated. As a result, naval architects and ship designers can produce meaningful cradle to grave life cycle GWP impact estimation during the conceptual design process using the LCA tool developed in this research study.

9 References

Aasen, R., & Bjørhovde, S. (2010). Early-stage weight and CoG estimation using parametric formulas and regression on historical data. In Proceedings of the 69th Annual Conference of the Society of Allied Weight Engineers (SAWE) (Paper No. 3505). Virginia Beach, VA, United States, 23–26 May 2010. Society of Allied Weight Engineers. https://shipweight.com/wp-content/uploads/2024/04/SAWE%202010%20-%20Paper%203505%20Early%20Stage%20Weight%20and%20CoG%20Estimation%20using%20Parametric%20Formulas%20and%20Regression%20on%20Historical%20Data.pdf

Ahmed, S., Li, T., Yi, P., & Chen, R. (2023). Environmental impact assessment of green ammonia-powered very large tanker ship for decarbonized future shipping operations. Renewable and Sustainable Energy Reviews, 188, Article 113774. https://doi.org/10.1016/j.rser.2023.113774

Albo-López, A. B., Carrillo, C., & Díaz-Dorado, E. (2024). Contribution of onshore power supply (OPS) and batteries in reducing emissions from Ro-Ro ships in ports. Journal of Marine Science and Engineering, 12, 1833. https://doi.org/10.3390/jmse12101833

Andreu World S.L. (2025). Environmental Product Declarations: Oru Chair SI2270, Oru Chair BU2277, Oru Sofa SF2278, and Counter Stool - Oru Chair BQ2275 (EPD Hub Core PCR v1.2, EN 15804+A2:2019, ISO 14025, cradle-to-grave, ecoinvent 3.10.1). Published 3 November 2025, valid until 3 November 2030. EPD Hub.

Antoniadis, P. (2021). Preliminary Design of Ro-Pax Ferry. Diploma Thesis. School of Naval Architecture and Marine Engineering, National Technical University of Athens, Athens, Greece. Available at: https://dspace.lib.ntua.gr/xmlui/bitstream/handle/123456789/54266/Antoniadis%20Panagiotis_Diploma%20Thesis.pdf?sequence=1

Bengtsson, S., Andersson, K., & Fridell, E. (2011). A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 225(2), 97–110. https://doi.org/10.1177/1475090211402136

Chatzinikolaou, S. D., & Ventikos, N. P. (2014). Applications of Life Cycle Assessment in Shipping. In Proceedings of the 2nd International Symposium on Naval Architecture and Maritime (INT-NAM 2014), Istanbul, Turkey, 23–24 October 2014, pp. 723–732. Yıldız Technical University. ISBN 978-605-4123-32-2.

Classen, M., Althaus, H.-J., Blaser, S., Tuchschmid, M., Jungbluth, N., Doka, G., Faist Emmenegger, M., & Scharnhorst, W. (2009). Life Cycle Inventories of Metals. Final report ecoinvent data v2.1, No. 10. Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories.

Dong, D. T., Schönborn, A., Christodoulou, A., Ölcer, A. I., & González-Celis, J. (2023). Life cycle assessment of ammonia/hydrogen-driven marine propulsion. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 238(3), 531-542. https://doi.org/10.1177/14750902231207159

Edelen, A., & Ingwersen, W. (2016). Guidance on data quality assessment for life cycle inventory data (EPA/600/R-16/096). U.S. Environmental Protection Agency. https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=528687

European Aluminium Association (EAA). (2013). Aluminium recycling in LCA: A survey of common allocation methodologies for recycling and their application to aluminium. European Aluminium Association, Brussels, Belgium

European Aluminium. (2018). Environmental Profile Report: Life Cycle Inventory Data for Aluminium Production and Transformation Processes in Europe. European Aluminium.

European Commission. (2026, April 20). European Climate Law. European Union. https://climate.ec.europa.eu/eu-action/european-climate-law_en

European Commission. (n.d.). EU climate, energy and environmental targets. https://commission.europa.eu/topics/climate-action/eu-climate-energy-and-environmental-targets_en

Gualeni, P., & Maggioncalda, M. (2018). Life cycle ship performance assessment (LCPA): A blended formulation between costs and environmental aspects for early design stage. International Shipbuilding Progress, 65(2), 127–147. https://doi.org/10.3233/ISP-180144

Hosseinabadi, O. F., & Khedmati, M. R. (2021). A review on ultimate strength of aluminium structural elements and systems for marine applications. Ocean Engineering, 232, 109153. https://doi.org/10.1016/j.oceaneng.2021.109153

International Aluminium Institute. (2023). Reference document on how to treat scrap flows in carbon footprint calculations for aluminium products: Draft for public review, prepared by Solinnen, Contract SOL 21-101.4.

International Copper Association. (2022). The carbon footprint of copper: Methodology and 2018 benchmark results. International Copper Association.

International Maritime Organization. (2023, July 7). Revised GHG reduction strategy for global shipping adopted. https://www.imo.org/en/mediacentre/pressbriefings/pages/revised-ghg-reduction-strategy-for-global-shipping-adopted-.aspx

Javed, M. M. (2025). Development of a life cycle assessment framework for early-stage ship design: Methodological guidelines and case study application of prospective life cycle assessment for concept-phase cruise vessels (Master's thesis, Aalto University and Chalmers University of Technology). Aaltodoc. https://urn.fi/URN:NBN:fi:aalto-202601201620

Keiramo, M., Heikkilä, E. K., Jokinen, M. L., & Romanoff, J. (2018). A concept for collaborative and integrative process for cruise ship concept design: From vision to design by using double design spiral. In P. Kujala & L. Lu (Eds.), Marine Design XIII: Proceedings of the 13th International Marine Design Conference (Vol. 1, pp. 193–202). Taylor & Francis. https://research.aalto.fi/en/publications/a-concept-for-collaborative-and-integrative-process-for-cruise-sh

Kim, Y., Lagerström, M., Granhag, L., & Ytreberg, E. (2025). Sustainable hull maintenance strategies in Baltic Sea region through case studies of RoPax vessels. Marine Pollution Bulletin, 211, 117453. https://doi.org/10.1016/j.marpolbul.2024.117453

Kwon, B., Oh, S., Jeong, B., Park, Y., & Shin, S. (2025). Life Cycle Assessment of Shipbuilding Materials and Potential Exposure Under the EU CBAM: Scenario-Based Assessment and Strategic Responses. Journal of Marine Science and Engineering, 13(10), 1938. https://doi.org/10.3390/jmse13101938

Ling-Chin, J., & Roskilly, A. P. (2016a). Investigating a conventional and retrofit power plant on-board a Roll-on/Roll-off cargo ship from a sustainability perspective - A life cycle assessment case study. Energy Conversion and Management, 117, 305-318. https://doi.org/10.1016/j.enconman.2016.03.032

Ling-Chin, J., & Roskilly, A. P. (2016b). Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective - A life cycle assessment case study. Applied Energy, 181, 416-434. https://doi.org/10.1016/j.apenergy.2016.08.065

Ling-Chin, J., & Roskilly, A. P. (2016c). A comparative life cycle assessment of marine power systems. Energy Conversion and Management, 127, 477-493. https://doi.org/10.1016/j.enconman.2016.09.032

Manchinu, A., & McConnell, F. (1977). The SFI coding and classification system for ship information. In Proceedings of the REAPS Technical Symposium (Paper No. 19). National Shipbuilding Research Program. https://archive.org/details/DTIC_ADA446592

Miranda Xicotencatl, B., Kleijn, R., van Nielen, S., Donati, F., Sprecher, B., & Tukker, A. (2023). Data implementation matters: Effect of software choice and LCI database evolution on a comparative LCA study of permanent magnets. Journal of Industrial Ecology, 27(5), 1252–1265. https://doi.org/10.1111/jiec.13410

Naval Sea Systems Command. (n.d.). Expanded Ship Work Breakdown Structure (ESWBS) for all ships and ship/combat systems (S9040-AC-IDX-010). U.S. Department of the Navy. https://www.navsea.navy.mil/Portals/103/Documents/SSRAC/4E/FY26/FY26_4E_PKG_01OCT2024.pdf

Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: A scientific synthesis. PLoS ONE, 9(7), e101298. https://doi.org/10.1371/journal.pone.0101298

Olanrewaju, O. I., Enegbuma, W. I., Donn, M., & Oyefusi, O. N. (2025). Assessment of environmental product declaration and databases: Towards ensuring data quality assurance practices. Environmental Impact Assessment Review, 112, Article 107803. https://doi.org/10.1016/j.eiar.2024.107803

Papanikolaou, A. (2026). Ship design: Methodologies of preliminary design (2nd ed., pp. 757–811)). Springer. https://doi.org/10.1007/978-3-032-11960-5

Parsons, M.G. (2004). Parametric Design. In: T. Lamb (ed.) Ship Design and Construction. New ed. Jersey City, NJ: Society of Naval Architects and Marine Engineers (SNAME), Chapter 11, pp. 11-1–11-72. https://search.worldcat.org/title/759185752

Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-ion batteries and the role of key parameters – A review. Renewable and Sustainable Energy Reviews, 67, 491–506. https://doi.org/10.1016/j.rser.2016.08.039

Perčić, M., Frković, L., Pukšec, T., Ćosić, B., Li, O. L., & Vladimir, N. (2022). Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation. Energy, 251, 123895. https://doi.org/10.1016/j.energy.2022.123895

Quang, P. K., Dong, D. T., & Hai, P. T. T. (2021). Evaluating environmental impacts of an oil tanker using life cycle assessment method. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 235(3), 705–717. https://doi.org/10.1177/1475090221989195

Rahman, M. M., Pritom, M. M., Hosen, M. D., & Helal, M. M. (2026). Life cycle assessment (LCA) and cradle-to-cradle (C2C) approaches in sustainable textile wastewater treatment: Recent developments, trends, and advances. Desalination and Water Treatment, 325, 101706. https://doi.org/10.1016/j.dwt.2026.101706

Roberts, M., Allen, S., & Coley, D. (2020). Life cycle assessment in the building design process: A systematic literature review. Building and Environment, 185, 107274. https://doi.org/10.1016/j.buildenv.2020.107274

Santos, R., Costa, A. A., Silvestre, J. D., & Pyl, L. (2020). Key parameters featuring BIM–LCA integration in buildings: A practical review of the current trends. Sustainability, 12(17), 7182. https://doi.org/10.3390/su12177182

SFS. (2020a). SFS-EN ISO 14040:2006 + A1:2020. Environmental management—Life cycle assessment—Principles and framework (ISO 14040:2006). Finnish Standards Association SFS.

SFS. (2020b). SFS-EN ISO 14044:2006 + A1:2018 + A2:2020. Environmental management—Life cycle assessment—Requirements and guidelines (ISO 14044:2006). Finnish Standards Association SFS.

Tuan, D. D., & Wei, C. (2019). Cradle-to-gate life cycle assessment of ships: A case study of Panamax bulk carrier. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 233(2), 670-683. https://doi.org/10.1177/1475090218813731

Tupper, E. C. (2013). Introduction to naval architecture (5th ed.). Butterworth-Heinemann. https://doi.org/10.1016/C2011-0-07775-X

Wang, H., Oguz, E., Jeong, B., & Zhou, P. (2018). Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry. Ocean Engineering, 161, 20–28. https://doi.org/10.1016/j.oceaneng.2018.04.084

Wärtsilä. (2019). Wärtsilä 31DF Product Guide. Helsinki, Finland: Wärtsilä Corporation. Available at: https://www.wartsila.com/docs/default-source/product-files/engines/df-engine/product-guide-o-e-w31df.pdf

Watson, D. G. M., & Gilfillan, A. W. (1976). Some Ship Design Methods. Transactions of the Royal Institution of Naval Architects, 119, 279–289.Available at: https://abcdocz.com/doc/731371/some-ship-design-methods

Weidema, B. P., & Wesnæs, M. S. (1996). Data quality management for life cycle inventories—An example of using data quality indicators. Journal of Cleaner Production, 4(3–4), 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1

Weidema, B. P. (1998). Multi-user test of the data quality matrix for product life cycle inventory data. The International Journal of Life Cycle Assessment, 3(5), 259–265. https://doi.org/10.1007/BF02979832

World Steel Association. (2018). Life cycle inventory study report: 2017 data release. World Steel Association. https://worldsteel.org/media/publications/life-cycle-study-report/

Xu, C., Jia, T., Qi, J., Cai, Z., Zhang, R., Xiong, R., Chang, H., Lu, X., Li, N., Tian, J., He, K., & Xu, M. (2025). Addressing critical challenges towards a robust data system for life cycle assessment. Nature Reviews Clean Technology, 1(11), 788–800. https://doi.org/10.1038/s44359-025-00107-4

Zhang, W., Wang, J., Qin, G., Satpathi, K., Gong, F., & Yan, R. (2025). Review of the state-of-the-art of alternative marine fuels: A viable approach to zero-carbon shipping. Cleaner Logistics and Supply Chain, 16, 100232. https://doi.org/10.1016/j.clscn.2025.100232

Appendix A

NTUA RO-PAX CASE STUDY REULTS	
Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**(kg CO2e)**
Grand Total — GWP (Building + Operation + Maintenance) **(kg CO2e)**	**987 313 424**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 091 384
Operation (full cradle-to-grave row total x quantity consumed)	953 050 802
Maintenance (full cradle-to-grave row total x replacement quantity)	4 171 238
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	0
Cargo and Ballast System	20 917 030
Passenger & Crew Accommodation Systems	1 407 302
Main Machinery System	3 873 662
Ship Systems	956 896 234
Pipe Outfitting Systems	0
Electrical Outfitting Systems	2 446 540
Armament Systems	1 772 655

Figure A-1 Case study results NTUA – Ro-Pax vessel – design life 30 years

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**73 349 325**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**0**
Number of material/resource rows entered	**25**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	73 349 325
Operation (full cradle-to-grave row total x quantity consumed)	0
Maintenance (full cradle-to-grave row total x replacement quantity)	0
Module D (recycling credit, informational only, not part of Grand Total)	0
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	0
Cargo and Ballast System	0
Passenger & Crew Accommodation Systems	0
Main Machinery System	73 349 325
Ship Systems	0
Pipe Outfitting Systems	0
Electrical Outfitting Systems	0
Armament Systems	0

Figure A-2 Validation results – Kwon et al. (2025) - PCTC vessel

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**75 769 381**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**0**
Number of material/resource rows entered	**25**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	75 769 381
Operation (full cradle-to-grave row total x quantity consumed)	0
Maintenance (full cradle-to-grave row total x replacement quantity)	0
Module D (recycling credit, informational only, not part of Grand Total)	0
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	0
Cargo and Ballast System	0
Passenger & Crew Accommodation Systems	0
Main Machinery System	75 769 381
Ship Systems	0
Pipe Outfitting Systems	0
Electrical Outfitting Systems	0
Armament Systems	0

Figure A-3 Validation results – Kwon et al. (2025) – bulk carrier

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**89 113 876**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**0**
Number of material/resource rows entered	**25**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	89 113 876
Operation (full cradle-to-grave row total x quantity consumed)	0
Maintenance (full cradle-to-grave row total x replacement quantity)	0
Module D (recycling credit, informational only, not part of Grand Total)	0
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	0
Cargo and Ballast System	0
Passenger & Crew Accommodation Systems	0
Main Machinery System	89 113 876
Ship Systems	0
Pipe Outfitting Systems	0
Electrical Outfitting Systems	0
Armament Systems	0

Figure A-4 Validation results – Kwon et al. (2025) – container vessel

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**1 734 431 719**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**0**
Number of material/resource rows entered	**4**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 039 719
Operation (full cradle-to-grave row total x quantity consumed)	1 704 392 000
Maintenance (full cradle-to-grave row total x replacement quantity)	0
Module D (recycling credit, informational only, not part of Grand Total)	0
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	28 912 910
Cargo and Ballast System	0
Passenger & Crew Accommodation Systems	0
Main Machinery System	1 705 518 809
Ship Systems	0
Pipe Outfitting Systems	0
Electrical Outfitting Systems	0
Armament Systems	0

Figure A-5 Validation results – Quang et al. (2021) - oil tanker vessel

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**826 386 003**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 091 384
Operation (full cradle-to-grave row total x quantity consumed)	794 209 000
Maintenance (full cradle-to-grave row total x replacement quantity)	2 085 619
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	18 831 411
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	798 054 432
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-6 Sensitivity analysis results of case study vessel NTUA – Design life 25 years

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**863 684 269**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 091 384
Operation (full cradle-to-grave row total x quantity consumed)	829 421 647
Maintenance (full cradle-to-grave row total x replacement quantity)	4 171 238
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	20 917 030
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	833 267 079
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-7 Sensitivity analysis results of case study vessel NTUA – fuel type LNG

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**1 030 107 956**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 091 384
Operation (full cradle-to-grave row total x quantity consumed)	995 845 334
Maintenance (full cradle-to-grave row total x replacement quantity)	4 171 238
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	20 917 030
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	999 690 766
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-8 Sensitivity analysis results of case study vessel NTUA – fuel type HFO

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**1 082 618 504**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Tota	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 091 384
Operation (full cradle-to-grave row total x quantity consumed)	1 048 355 883
Maintenance (full cradle-to-grave row total x replacement quantity)	4 171 238
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	20 917 030
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	1 052 201 315
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-9 Sensitivity analysis results of case study vessel NTUA – fuel SFC +10%

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**892 008 344**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	30 091 384
Operation (full cradle-to-grave row total x quantity consumed)	857 745 722
Maintenance (full cradle-to-grave row total x replacement quantity)	4 171 238
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	20 917 030
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	861 591 154
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-10 Sensitivity analysis results of case study vessel NTUA – fuel SFC -10%.

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**990 928 497**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	32 872 209
Operation (full cradle-to-grave row total x quantity consumed)	953 050 802
Maintenance (full cradle-to-grave row total x replacement quantity)	5 005 485
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	24 532 103
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	956 896 234
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-11 Sensitivity analysis results of case study vessel NTUA – hull steel +20%

Results	
Auto-calculated from LCA Calculation.	
Headline KPI	**kg CO2e**
Grand Total — GWP (Building + Operation + Maintenance)	**983 698 352**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	**-1 953**
Number of material/resource rows entered	**27**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	27 310 559
Operation (full cradle-to-grave row total x quantity consumed)	953 050 802
Maintenance (full cradle-to-grave row total x replacement quantity)	3 336 990
Module D (recycling credit, informational only, not part of Grand Total)	-1 953
GWP by Main Group (full roll-up)	
Main System	**kg CO2e**
General Consumables	0
Hull Structure	17 301 958
Cargo and Ballast System	1 407 302
Passenger & Crew Accommodation Systems	3 873 662
Main Machinery System	956 896 234
Ship Systems	0
Pipe Outfitting Systems	2 446 540
Electrical Outfitting Systems	1 772 655
Armament Systems	0

Figure A-12 Sensitivity analysis results of case study vessel NTUA – hull steel -20%

ISO 14040 / 14044 Compliance Checklist

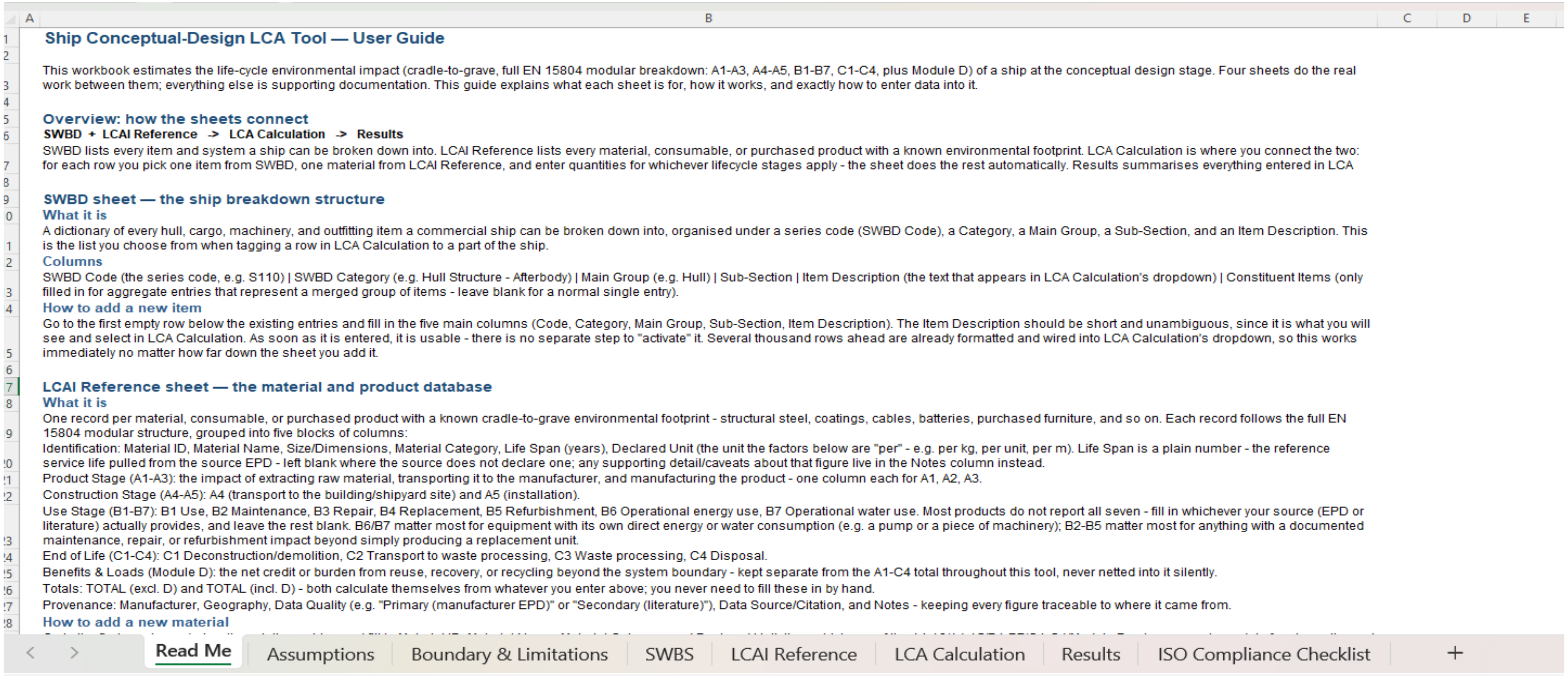
Maps each required element of ISO 14040:2006 (Principles and Framework) and ISO 14044:2006 (Requirements and Guidelines) to the specific location in this tool where it is implemented. This constitutes structural / methodological verification - confirming the tool was built to the standard's required framework

ISO Clause	Requirement	Implemented Where in This Tool	Status
ISO 14040 Clause 4.2 / ISO 14044 Clause 4.2.2	Goal definition: reason for the study, intended application, target audience	Read Me sheet (purpose statement); Assumptions sheet (project/vessel name)	Implemented
ISO 14044 Clause 4.2.3.2	Functional unit – a quantified reference to which inputs/outputs are related	Assumptions!C7 ('1 vessel, cradle-to-grave'); the associated impact indicator unit (GWP, kg CO2-eq) is recorded separately at Assumptions sheet C12	Implemented
ISO 14044 Clause 4.2.3.3	System boundary – which life cycle stages/processes are included	Assumptions sheet C10 and Boundary & Limitations sheet (cradle-to-grave A1-C4, Module D reported separately per EN 15804)	Implemented
ISO 14044 Clause 4.3.4.2	Allocation procedures (where multi-output processes require allocation)	Boundary & Limitations sheet documents where allocation is/is not applied (e.g., aggregate SWBD items)	Implemented
ISO 14044 Clause 4.2.3.6	Data quality requirements (time-related, geographical, technological coverage; precision; representativeness)	LCAI Reference sheet columns Z-AD (Manufacturer, Geography, Data Quality, Citation, Notes) for every material record	Implemented
ISO 14044 Clause 4.2.3.7	Comparative assertions (if any) – additional requirements for public comparative disclosure	Not applicable – this tool is not used to make public comparative assertions between commercial products	Implemented
ISO 14044 Clause 4.2.4	Assumptions and value choices, explicitly documented	Boundary & Limitations sheet; individual row Notes/Basis columns in LCA Calculation	Implemented
ISO 14044 Clause 4.2.5	Limitations of the study, explicitly stated	Boundary & Limitations sheet; individual row Notes / Basis columns in LCA Calculation sheet	Implemented
ISO 14044 Clause 4.3	Life Cycle Inventory (LCI): data collection and calculation procedures	LCAI Reference sheet (533 material / resource records with full EN 15804 module data A1-C4/D); SWBD sheet (ship item classification)	Implemented
ISO 14044 Clause 4.3.3.2	Data validation – checking consistency and correctness of collected data	Formula correctness verified during tool development using isolated synthetic test cases with independently hand-calculated expected values, prior to the case study data entered in LCA Calculation; recalculation confirms 0 formula errors across the tool's full formula set	Implemented
ISO 14044 Clause 4.4	Life Cycle Impact Assessment (LCIA): selection of impact categories, classification, characterization	GWP100 (IPCC) selected as the sole impact category for this tool's scope, applied via LCA Calculation sheet's per-material characterization factors	Implemented
ISO 14044 Clause 4.4.2.2	Classification – assignment of LCI results to impact categories	Each LCAI Reference sheet material record is pre-classified by EN 15804 module (A1-C4, D), which the LCA Calculation sheet reads directly	Implemented
ISO 14044 Clause 4.4.2.4	Characterization – calculation of category indicator results	LCA Calculation sheet's Building, Operation, and Maintenance formulas (columns O, Q, S), each applying a material's total impact factor (which already incorporates its End-of-life/Scrapping contribution); Module D (columns T-V) calculated and reported separately, aggregated in the Results sheet	Implemented
ISO 14044 Clause4.5	Life Cycle Interpretation: identification of significant issues	Results sheet (Grand Total, stage-by-stage breakdown, Total Module D, and Main Group rollup) identifies the Operation-stage share as the case study's dominant contributor	Implemented
ISO 14044 Clause 4.5.3.2	Completeness check	Boundary & Limitations sheet documents known gaps	Implemented
ISO 14044 Clause 4.5.3.3	Sensitivity check	Six one-at-a-time sensitivity scenarios run through the tool's own calculation engine (design life, specific fuel consumption +/-10%, fuel type, hull steel weight +/-20%).	Implemented
ISO 14044 Clause 4.5.3.4	Consistency check – are assumptions, methods and data applied consistently across the study	All LCAI Reference entries follow the same column structure/EN 15804 convention; all LCA Calculation rows use the same formula set	Implemented
ISO 14044 Clause 4.1 (general)	Iterative nature of LCA – results should be revisited as data quality improves	Boundary & Limitations sheet frames incomplete LCAI coverage as a designed, extensible feature rather than a static limitation	Implemented

Figure A-13 Iso 14040 (SFS,2020a) / 14044 (SFS, 2020b) compliance checklist

Appendix B

LCA tool architecture



Ship Conceptual-Design LCA Tool — User Guide

This workbook estimates the life-cycle environmental impact (cradle-to-grave, full EN 15804 modular breakdown: A1-A3, A4-A5, B1-B7, C1-C4, plus Module D) of a ship at the conceptual design stage. Four sheets do the real work between them; everything else is supporting documentation. This guide explains what each sheet is for, how it works, and exactly how to enter data into it.

Overview: how the sheets connect

SWBD + LCAI Reference -> LCA Calculation -> Results

SWBD lists every item and system a ship can be broken down into. LCAI Reference lists every material, consumable, or purchased product with a known environmental footprint. LCA Calculation is where you connect the two: for each row you pick one item from SWBD, one material from LCAI Reference, and enter quantities for whichever lifecycle stages apply - the sheet does the rest automatically. Results summarises everything entered in LCA

SWBD sheet — the ship breakdown structure

What it is

A dictionary of every hull, cargo, machinery, and outfitting item a commercial ship can be broken down into, organised under a series code (SWBD Code), a Category, a Main Group, a Sub-Section, and an Item Description. This is the list you choose from when tagging a row in LCA Calculation to a part of the ship.

Columns

SWBD Code (the series code, e.g. S110) | SWBD Category (e.g. Hull Structure - Afterbody) | Main Group (e.g. Hull) | Sub-Section | Item Description (the text that appears in LCA Calculation's dropdown) | Constituent Items (only filled in for aggregate entries that represent a merged group of items - leave blank for a normal single entry).

How to add a new item

Go to the first empty row below the existing entries and fill in the five main columns (Code, Category, Main Group, Sub-Section, Item Description). The Item Description should be short and unambiguous, since it is what you will see and select in LCA Calculation. As soon as it is entered, it is usable - there is no separate step to "activate" it. Several thousand rows ahead are already formatted and wired into LCA Calculation's dropdown, so this works immediately no matter how far down the sheet you add it.

LCAI Reference sheet — the material and product database

What it is

One record per material, consumable, or purchased product with a known cradle-to-grave environmental footprint - structural steel, coatings, cables, batteries, purchased furniture, and so on. Each record follows the full EN 15804 modular structure, grouped into five blocks of columns:

Identification: Material ID, Material Name, Size/Dimensions, Material Category, Life Span (years), Declared Unit (the unit the factors below are "per" - e.g. per kg, per unit, per m). Life Span is a plain number - the reference service life pulled from the source EPD - left blank where the source does not declare one; any supporting detail/caveats about that figure live in the Notes column instead.

Product Stage (A1-A3): the impact of extracting raw material, transporting it to the manufacturer, and manufacturing the product - one column each for A1, A2, A3.

Construction Stage (A4-A5): A4 (transport to the building/shipyard site) and A5 (installation).

Use Stage (B1-B7): B1 Use, B2 Maintenance, B3 Repair, B4 Replacement, B5 Refurbishment, B6 Operational energy use, B7 Operational water use. Most products do not report all seven - fill in whichever your source (EPD or literature) actually provides, and leave the rest blank. B6/B7 matter most for equipment with its own direct energy or water consumption (e.g. a pump or a piece of machinery); B2-B5 matter most for anything with a documented maintenance, repair, or refurbishment impact beyond simply producing a replacement unit.

End of Life (C1-C4): C1 Deconstruction/demolition, C2 Transport to waste processing, C3 Waste processing, C4 Disposal.

Benefits & Loads (Module D): the net credit or burden from reuse, recovery, or recycling beyond the system boundary - kept separate from the A1-C4 total throughout this tool, never netted into it silently.

Totals: TOTAL (excl. D) and TOTAL (incl. D) - both calculate themselves from whatever you enter above; you never need to fill these in by hand.

Provenance: Manufacturer, Geography, Data Quality (e.g. "Primary (manufacturer EPD)" or "Secondary (literature)"), Data Source/Citation, and Notes - keeping every figure traceable to where it came from.

How to add a new material

Read Me | Assumptions | Boundary & Limitations | SWBS | LCAI Reference | LCA Calculation | Results | ISO Compliance Checklist

Figure B-1 LCA tool architecture - Read Me sheet_1

Totals: TOTAL (excl. D) and TOTAL (incl. D) - both calculate themselves from whatever you enter above; you never need to fill these in by hand.

Provenance: Manufacturer, Geography, Data Quality (e.g. "Primary (manufacturer EPD)" or "Secondary (literature)"), Data Source/Citation, and Notes - keeping every figure traceable to where it came from.

How to add a new material

Go to the first empty row below the existing entries and fill in Material ID, Material Name, Material Category, and Declared Unit, then whichever of the A1-A3/A4-A5/B1-B7/C1-C4/Module D columns you have data for - leave the rest blank if not yet sourced. Fill in Data Quality and Data Source/Citation so the entry stays traceable, and add Notes for anything a future reader would need to know (e.g. what a combined/blended figure represents, or an assumption made). As with SWBD, several thousand rows ahead are pre-formatted and wired into LCA Calculation's dropdown, so a new material becomes selectable immediately.

Current data source

LCAI Reference is currently populated with 533 material/resource records drawn from manufacturer EPDs and equivalent primary sources - covering structural materials, welding consumables, coatings, cabling, transformers and other electrical equipment, machinery components, and similar purchased products.

A blank cell in an EN 15804 module column means that module was not declared/reported by the source; an explicit 0 means the source reported that module as zero. Every record's Data Quality and Data Source/Citation columns trace the figures back to the originating EPD, so any entry can be checked against its source.

When adding further materials of your own, follow the column reference and conventions already described above under "LCAI Reference sheet" - keep new rows with a sequential Material ID, and copy formatting from a neighbouring row.

LCA Calculation sheet — where the assessment is built

What it is

This is the sheet you actually work in. Each row represents one material or resource used somewhere on the ship, tracked across four lifecycle stages: Building (initial install), Operation (consumables used in service, e.g. fuel), Maintenance (renewals/replacements over the ship's life), and Scrapping (end-of-life).

How the factors work

Once you pick a Material/Resource, two factors are pulled in automatically:

GWP Factor: whenever a material is selected from the dropdown, the tool pulls that material's full LCAI Reference ROW TOTAL (A1 through C4, i.e. LCAI Reference column X, "TOTAL excl. Module D") - the material's complete cradle-to-grave impact per declared unit. This SAME row total is used for Building, Operation, and Maintenance alike; the only thing that differs between stages is which quantity it gets multiplied by (see below). There is no separate, narrower factor for any one stage.

This has a direct consequence for how LCAI Reference should be populated: every material record should reflect its OWN complete, appropriate life-span impact. Solid or replaceable items (steel, aluminium, furniture, etc.) should have A1-A3 (or A1-A5) populated for production, AND C1-C4 populated where a genuine physical disposal/end-of-life step exists for that material. Consumables that are used up or combusted in operation (fuel, lubricating oil, filters, etc.) should have their full production-plus-use burden entered in B6, since for these items use and disposal are the same event - there is nothing left afterward to dispose of separately, so C1-C4 should normally stay blank for these. Leaving a material's C1-C4 blank when real end-of-life data actually exists for it will understate every stage that calls that material, since the row total will be incomplete.

Scrapping is NOT a separate calculated stage. Disposal impact (C1-C4) is already embedded in the row total used by Building and Maintenance, so a separate Scrapping-C calculation would double-count it - this was corrected from an earlier version of the tool that did calculate Scrapping separately. Module D (the recycling credit) is the one exception: it is calculated on the CUMULATIVE quantity of a material ever installed on the ship (the base quantity plus every replacement made during the ship's life, since each replaced unit is eventually recycled too), and is reported as a separate, standalone informational figure on the Results sheet. Module D is never subtracted from the Grand Total - it shows the recycling benefit available, not a net-impact adjustment.

Step by step

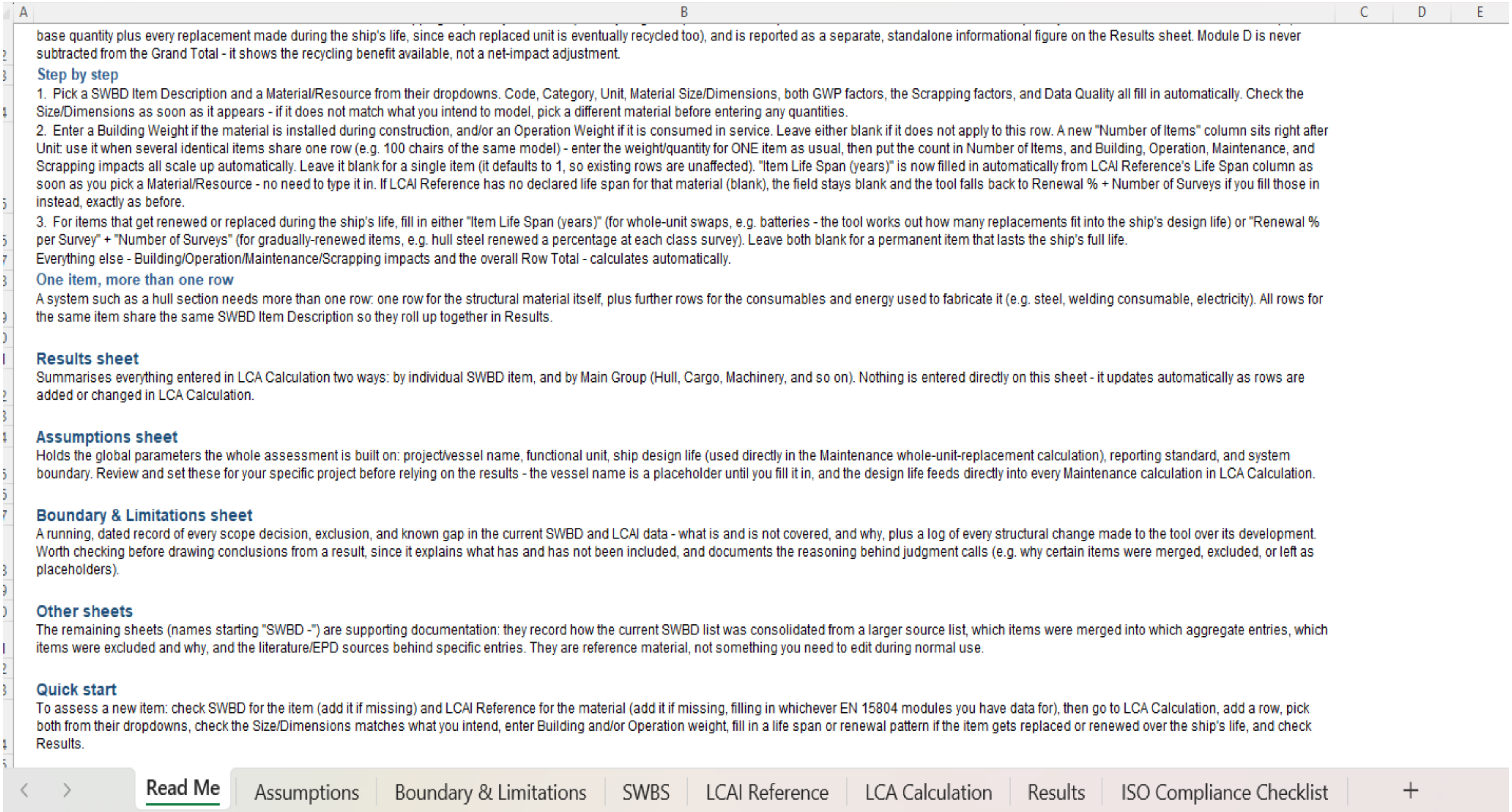
1. Pick a SWBD Item Description and a Material/Resource from their dropdowns. Code, Category, Unit, Material Size/Dimensions, both GWP factors, the Scrapping factors, and Data Quality all fill in automatically. Check the Size/Dimensions as soon as it appears - if it does not match what you intend to model, pick a different material before entering any quantities.

2. Enter a Building Weight if the material is installed during construction, and/or an Operation Weight if it is consumed in service. Leave either blank if it does not apply to this row. A new "Number of Items" column sits right after Unit: use it when several identical items share one row (e.g. 100 chairs of the same model) - enter the weight/quantity for ONE item as usual, then put the count in Number of Items, and Building, Operation, Maintenance, and Scrapping impacts all scale up automatically. Leave it blank for a single item (it defaults to 1, so existing rows are unaffected). "Item Life Span (years)" is now filled in automatically from LCAI Reference's Life Span column as soon as you pick a Material/Resource - no need to type it in. If LCAI Reference has no declared life span for that material (blank), the field stays blank and the tool falls back to Renewal % + Number of Surveys if you fill those in instead, exactly as before.

3. For items that get renewed or replaced during the ship's life, fill in either "Item Life Span (years)" (for whole-unit swaps, e.g. batteries - the tool works out how many replacements fit into the ship's design life) or "Renewal %

Read Me | Assumptions | Boundary & Limitations | SWBS | LCAI Reference | LCA Calculation | Results | ISO Compliance Checklist

Figure B-2 LCA tool architecture - Read Me sheet_2



base quantity plus every replacement made during the ship's life, since each replaced unit is eventually recycled too), and is reported as a separate, standalone informational figure on the Results sheet. Module D is never subtracted from the Grand Total - it shows the recycling benefit available, not a net-impact adjustment.

Step by step

1. Pick a SWBD Item Description and a Material/Resource from their dropdowns. Code, Category, Unit, Material Size/Dimensions, both GWP factors, the Scrapping factors, and Data Quality all fill in automatically. Check the Size/Dimensions as soon as it appears - if it does not match what you intend to model, pick a different material before entering any quantities.
2. Enter a Building Weight if the material is installed during construction, and/or an Operation Weight if it is consumed in service. Leave either blank if it does not apply to this row. A new "Number of Items" column sits right after Unit: use it when several identical items share one row (e.g. 100 chairs of the same model) - enter the weight/quantity for ONE item as usual, then put the count in Number of Items, and Building, Operation, Maintenance, and Scrapping impacts all scale up automatically. Leave it blank for a single item (it defaults to 1, so existing rows are unaffected). "Item Life Span (years)" is now filled in automatically from LCAI Reference's Life Span column as soon as you pick a Material/Resource - no need to type it in. If LCAI Reference has no declared life span for that material (blank), the field stays blank and the tool falls back to Renewal % + Number of Surveys if you fill those in instead, exactly as before.
3. For items that get renewed or replaced during the ship's life, fill in either "Item Life Span (years)" (for whole-unit swaps, e.g. batteries - the tool works out how many replacements fit into the ship's design life) or "Renewal % per Survey" + "Number of Surveys" (for gradually-renewed items, e.g. hull steel renewed a percentage at each class survey). Leave both blank for a permanent item that lasts the ship's full life.

Everything else - Building/Operation/Maintenance/Scrapping impacts and the overall Row Total - calculates automatically.

One item, more than one row

A system such as a hull section needs more than one row: one row for the structural material itself, plus further rows for the consumables and energy used to fabricate it (e.g. steel, welding consumable, electricity). All rows for the same item share the same SWBD Item Description so they roll up together in Results.

Results sheet

Summarises everything entered in LCA Calculation two ways: by individual SWBD item, and by Main Group (Hull, Cargo, Machinery, and so on). Nothing is entered directly on this sheet - it updates automatically as rows are added or changed in LCA Calculation.

Assumptions sheet

Holds the global parameters the whole assessment is built on: project/vessel name, functional unit, ship design life (used directly in the Maintenance whole-unit-replacement calculation), reporting standard, and system boundary. Review and set these for your specific project before relying on the results - the vessel name is a placeholder until you fill it in, and the design life feeds directly into every Maintenance calculation in LCA Calculation.

Boundary & Limitations sheet

A running, dated record of every scope decision, exclusion, and known gap in the current SWBD and LCAI data - what is and is not covered, and why, plus a log of every structural change made to the tool over its development. Worth checking before drawing conclusions from a result, since it explains what has and has not been included, and documents the reasoning behind judgment calls (e.g. why certain items were merged, excluded, or left as placeholders).

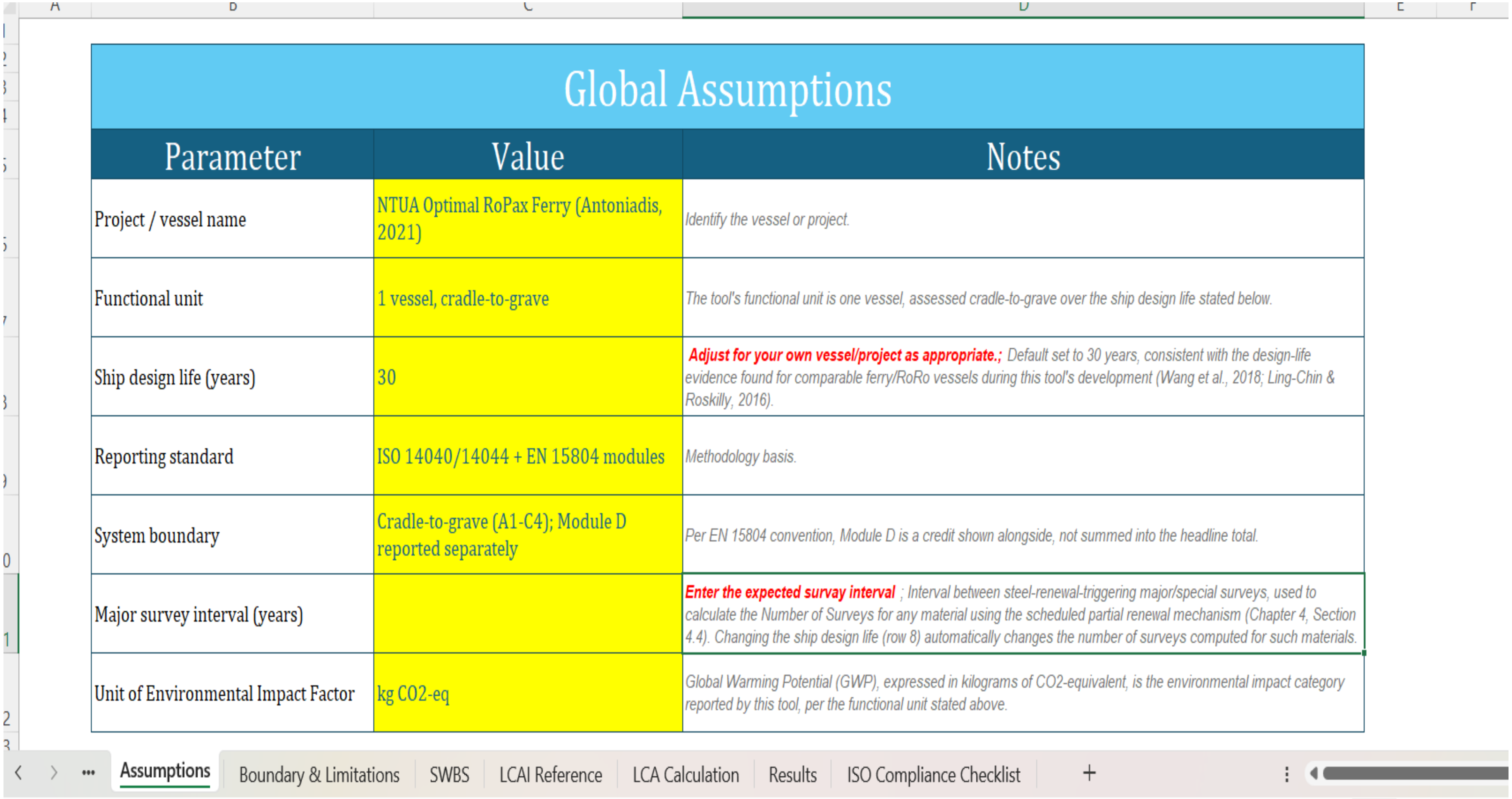
Other sheets

The remaining sheets (names starting "SWBD -") are supporting documentation: they record how the current SWBD list was consolidated from a larger source list, which items were merged into which aggregate entries, which items were excluded and why, and the literature/EPD sources behind specific entries. They are reference material, not something you need to edit during normal use.

Quick start

To assess a new item: check SWBD for the item (add it if missing) and LCAI Reference for the material (add it if missing, filling in whichever EN 15804 modules you have data for), then go to LCA Calculation, add a row, pick both from their dropdowns, check the Size/Dimensions matches what you intend, enter Building and/or Operation weight, fill in a life span or renewal pattern if the item gets replaced or renewed over the ship's life, and check Results.

Figure B-3 LCA tool architecture - Read Me sheet_3



Global Assumptions		
Parameter	**Value**	**Notes**
Project / vessel name	NTUA Optimal RoPax Ferry (Antoniadis, 2021)	*Identify the vessel or project.*
Functional unit	1 vessel, cradle-to-grave	*The tool's functional unit is one vessel, assessed cradle-to-grave over the ship design life stated below.*
Ship design life (years)	30	***Adjust for your own vessel/project as appropriate.;*** *Default set to 30 years, consistent with the design-life evidence found for comparable ferry/RoRo vessels during this tool's development (Wang et al., 2018; Ling-Chin & Roskilly, 2016).*
Reporting standard	ISO 14040/14044 + EN 15804 modules	*Methodology basis.*
System boundary	Cradle-to-grave (A1-C4); Module D reported separately	*Per EN 15804 convention, Module D is a credit shown alongside, not summed into the headline total.*
Major survey interval (years)		***Enter the expected survay interval*** *; Interval between steel-renewal-triggering major/special surveys, used to calculate the Number of Surveys for any material using the scheduled partial renewal mechanism (Chapter 4, Section 4.4). Changing the ship design life (row 8) automatically changes the number of surveys computed for such materials.*
Unit of Environmental Impact Factor	kg CO2-eq	*Global Warming Potential (GWP), expressed in kilograms of CO2-equivalent, is the environmental impact category reported by this tool, per the functional unit stated above.*

Figure B-4 LCA tool architecture - Assumptions sheet

SWBS — Ship Work Breakdown Structure

Rebuilt on the ESWBS major-group structure (General Consumables, then ESWBS 100-800). Four columns: SWBD Code, Main System, Sub System, Description. See Boundary & Limitations for scope notes on this structure.

SWBD Code	Main System	Sub System	Description
10	General Consumables	Design Consumables	Drafting Paper, Printing Consumables- Aggregate
20	General Consumables	Production Consumables	Flame Cutting Equipment & Consumables & (Propane, Lpg, Oxygen, Etc...) - Aggregate
20	General Consumables	Production Consumables	Welding Consumables (Electrodes, Fluxes, Shielding Gases, Etc...)-
20	General Consumables	Production Consumables	Provisional Staging
20	General Consumables	Production Consumables	Jigs & Fixtures
20	General Consumables	Production Consumables	Internal Transport Of Hull Sections / Materials & Personals
20	General Consumables	Production Consumables	Consumption Articles Miscellaneous-
21	General Consumables	Production Consumables	Fuel & Lub Oil
30	General Consumables	Supply Chain Consumables	External Transport
30	General Consumables	Supply Chain Consumables	Crane Operation For Material Transport
40	General Consumables	General Consumables	Electricity
40	General Consumables	General Consumables	Water
40	General Consumables	General Consumables	Yard Compressed Air Consumption
40	General Consumables	General Consumables	Material Protection Equipment & Consumables
100	Hull Structure	Hull Testing & Plate Preparation	Tank Testing / Leak Testing -Aggregate
100	Hull Structure	Hull Testing & Plate Preparation	NDT Inspection Of Hull Structure (X-Ray, Ultrasonic) - Aggregate
100	Hull Structure	Hull Testing & Plate Preparation	BACKWELD PREPARATION & Finishing(CHISELLING, GRINDING, BURNING) - AGGREGATE
100	Hull Structure	Hull Testing & Plate Preparation	Composite Material Fitting & Joining - Aggregate
100	Hull Structure	Hull Testing & Plate Preparation	Loft & Mould Work (Templates) - Aggregate
100	Hull Structure	Hull Testing & Plate Preparation	Plate Forming (Bending, Flanging, Rolling) - Aggregate
100	Hull Structure	Hull Testing & Plate Preparation	Surface Preparation (Blasting, Cleaning, Shop Priming) - Aggregate
100	Hull Structure	Hull Testing & Plate Preparation	Tightness Testing Of Hull Tanks & Bulkheads (Pressure/Spray Test) - Aggregate
110	Hull Structure	Fore Hull	Forebody Structure (Plating, Framing, Bulkheads, Stem) - Aggregate
120	Hull Structure	Mid Hull	Parallel Mid Body, Machinery Compartments & Cargo Tank Structure (Plating, Framing, Bulkheads, Double Bottom) - Aggregate
130	Hull Structure	Aft Hull	Afterbody Structure (Plating, Framing, Bulkheads, Stern Frame) - Aggregate
140	Hull Structure	Special Cargo Tanks	Cargo Area Structure - Chemical Cargo Tank Containment (Stainless Steel / Special Alloy) - Aggregate
140	Hull Structure	Special Cargo Tanks	Cargo Area Structure - Gas Cargo Tank Containment (Lng/Lpg: 9% Ni Steel, Stainless Steel, Aluminium, Or Invar) - Aggregate
140	Hull Structure	Special Cargo Tanks	Loose Cargo Tanks & Its Support Structure
140	Hull Structure	Special Cargo Tanks	Misalaniuos Loose Tanks & Support Structure

Assumptions | Boundary & Limitations | SWBS | LCAI Reference | LCA Calculation | Results | ISO Compliance Checklist

Figure B-5 LCA tool architecture - SWBD sheet

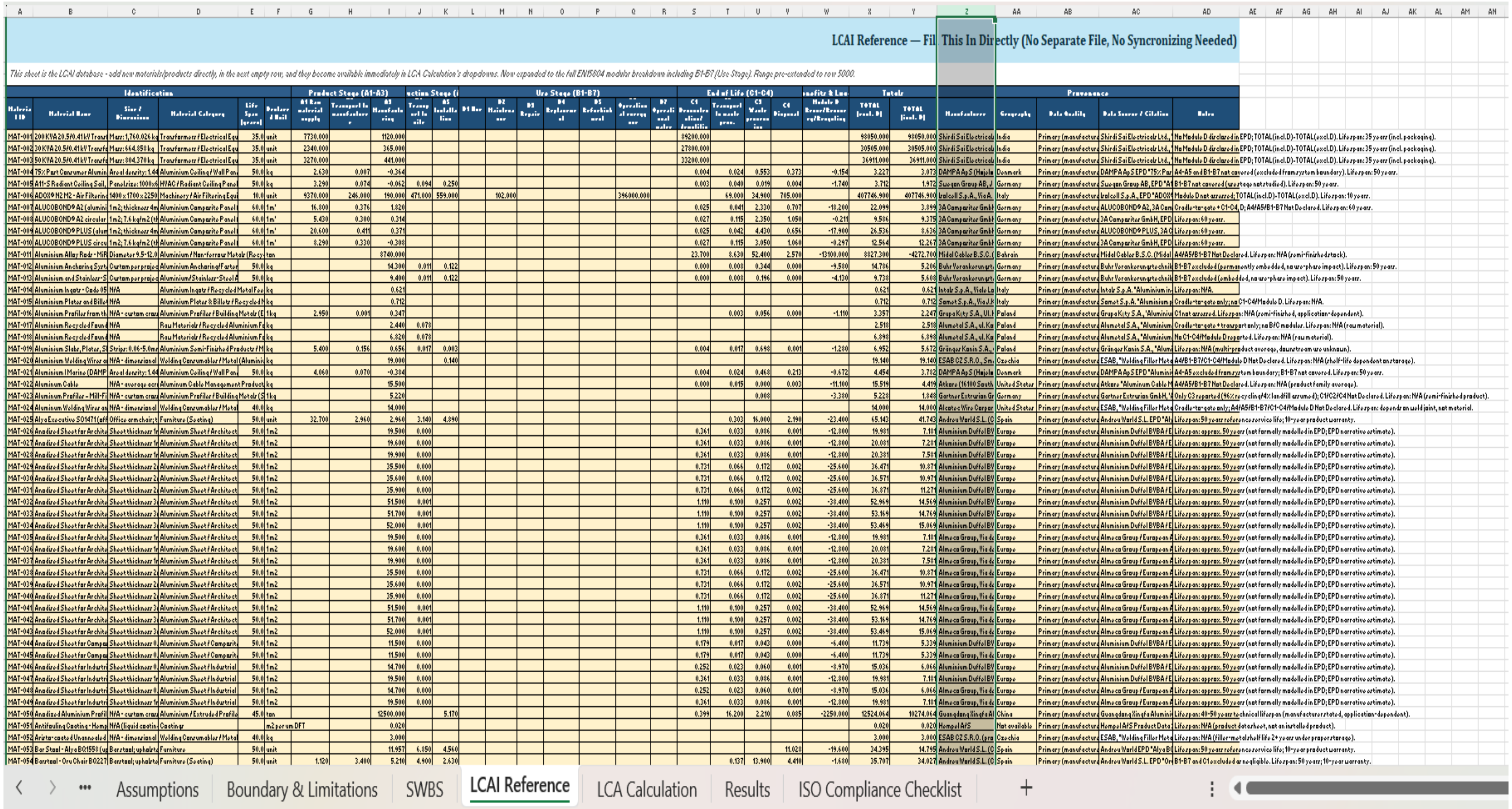
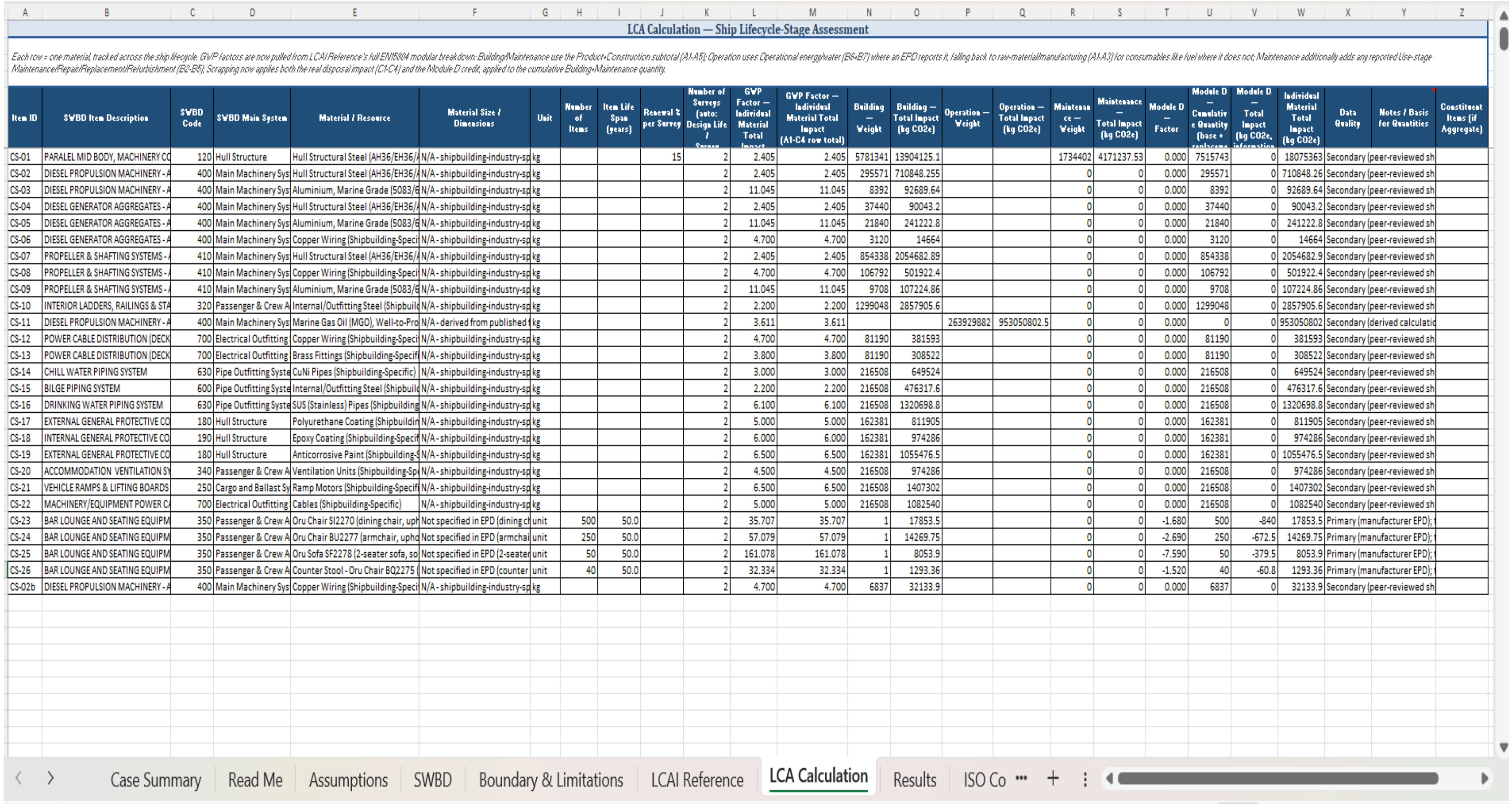


Figure B-6 LCA tool architecture - LCAI Reference sheet



LCA Calculation — Ship Lifecycle-Stage Assessment

Each row = one material, tracked across the ship lifecycle. GWP factors are now pulled from LCAI Reference's full EN15804 modular breakdown: Building/Maintenance use the Product+Construction subtotal (A1-A5); Operation uses Operational energy/water (B6+B7) where an EPD reports it, falling back to raw-material/manufacturing (A1-A3) for consumables like fuel where it does not; Maintenance additionally adds any reported Use-stage Maintenance/Repair/Replacement/Refurbishment (B2-B5); Scrapping now applies both the real disposal impact (C1-C4) and the Module D credit, applied to the cumulative Building+Maintenance quantity.

Item ID	SWBD Item Description	SWBD Code	SWBD Main System	Material / Resource	Material Size / Dimensions	Unit	Number of Items	Item Life Span (years)	Renewal % per Survey	Number of Surveys (auto: Design Life / Survey	GWP Factor — Individual Material Total Impact	GWP Factor — Individual Material Total Impact (A1-C4 row total)
CS-01	PARALEL MID BODY, MACHINERY CO	120	Hull Structure	Hull Structural Steel (AH36/EH36/	N/A - shipbuilding-industry-sp	kg			15	2	2.405	2.405
CS-02	DIESEL PROPULSION MACHINERY - A	400	Main Machinery Sys	Hull Structural Steel (AH36/EH36/	N/A - shipbuilding-industry-sp	kg				2	2.405	2.405
CS-03	DIESEL PROPULSION MACHINERY - A	400	Main Machinery Sys	Aluminium, Marine Grade (5083/6	N/A - shipbuilding-industry-sp	kg				2	11.045	11.045
CS-04	DIESEL GENERATOR AGGREGATES - A	400	Main Machinery Sys	Hull Structural Steel (AH36/EH36/	N/A - shipbuilding-industry-sp	kg				2	2.405	2.405
CS-05	DIESEL GENERATOR AGGREGATES - A	400	Main Machinery Sys	Aluminium, Marine Grade (5083/6	N/A - shipbuilding-industry-sp	kg				2	11.045	11.045
CS-06	DIESEL GENERATOR AGGREGATES - A	400	Main Machinery Sys	Copper Wiring (Shipbuilding-Speci	N/A - shipbuilding-industry-sp	kg				2	4.700	4.700
CS-07	PROPELLER & SHAFTING SYSTEMS - A	410	Main Machinery Sys	Hull Structural Steel (AH36/EH36/	N/A - shipbuilding-industry-sp	kg				2	2.405	2.405
CS-08	PROPELLER & SHAFTING SYSTEMS - A	410	Main Machinery Sys	Copper Wiring (Shipbuilding-Speci	N/A - shipbuilding-industry-sp	kg				2	4.700	4.700
CS-09	PROPELLER & SHAFTING SYSTEMS - A	410	Main Machinery Sys	Aluminium, Marine Grade (5083/6	N/A - shipbuilding-industry-sp	kg				2	11.045	11.045
CS-10	INTERIOR LADDERS, RAILINGS & STA	320	Passenger & Crew A	Internal/Outfitting Steel (Shipbuild	N/A - shipbuilding-industry-sp	kg				2	2.200	2.200
CS-11	DIESEL PROPULSION MACHINERY - A	400	Main Machinery Sys	Marine Gas Oil (MGO), Well-to-Pro	N/A - derived from published f	kg				2	3.611	3.611
CS-12	POWER CABLE DISTRIBUTION (DECK	700	Electrical Outfitting	Copper Wiring (Shipbuilding-Speci	N/A - shipbuilding-industry-sp	kg				2	4.700	4.700
CS-13	POWER CABLE DISTRIBUTION (DECK	700	Electrical Outfitting	Brass Fittings (Shipbuilding-Specifi	N/A - shipbuilding-industry-sp	kg				2	3.800	3.800
CS-14	CHILL WATER PIPING SYSTEM	630	Pipe Outfitting Syste	CuNi Pipes (Shipbuilding-Specific)	N/A - shipbuilding-industry-sp	kg				2	3.000	3.000
CS-15	BILGE PIPING SYSTEM	600	Pipe Outfitting Syste	Internal/Outfitting Steel (Shipbuild	N/A - shipbuilding-industry-sp	kg				2	2.200	2.200
CS-16	DRINKING WATER PIPING SYSTEM	630	Pipe Outfitting Syste	SUS (Stainless) Pipes (Shipbuilding	N/A - shipbuilding-industry-sp	kg				2	6.100	6.100
CS-17	EXTERNAL GENERAL PROTECTIVE CO	180	Hull Structure	Polyurethane Coating (Shipbuildin	N/A - shipbuilding-industry-sp	kg				2	5.000	5.000
CS-18	INTERNAL GENERAL PROTECTIVE CO	190	Hull Structure	Epoxy Coating (Shipbuilding-Specif	N/A - shipbuilding-industry-sp	kg				2	6.000	6.000
CS-19	EXTERNAL GENERAL PROTECTIVE CO	180	Hull Structure	Anticorrosive Paint (Shipbuilding-S	N/A - shipbuilding-industry-sp	kg				2	6.500	6.500
CS-20	ACCOMMODATION VENTILATION SY	340	Passenger & Crew A	Ventilation Units (Shipbuilding-Sp	N/A - shipbuilding-industry-sp	kg				2	4.500	4.500
CS-21	VEHICLE RAMPS & LIFTING BOARDS	250	Cargo and Ballast Sy	Ramp Motors (Shipbuilding-Specifi	N/A - shipbuilding-industry-sp	kg				2	6.500	6.500
CS-22	MACHINERY/EQUIPMENT POWER CA	700	Electrical Outfitting	Cables (Shipbuilding-Specific)	N/A - shipbuilding-industry-sp	kg				2	5.000	5.000
CS-23	BAR LOUNGE AND SEATING EQUIPM	350	Passenger & Crew A	Oru Chair SI2270 (dining chair, uph	Not specified in EPD (dining ch	unit	500	50.0		2	35.707	35.707
CS-24	BAR LOUNGE AND SEATING EQUIPM	350	Passenger & Crew A	Oru Chair BU2277 (armchair, upho	Not specified in EPD (armchai	unit	250	50.0		2	57.079	57.079
CS-25	BAR LOUNGE AND SEATING EQUIPM	350	Passenger & Crew A	Oru Sofa SF2278 (2-seater sofa, so	Not specified in EPD (2-seater	unit	50	50.0		2	161.078	161.078
CS-26	BAR LOUNGE AND SEATING EQUIPM	350	Passenger & Crew A	Counter Stool - Oru Chair BQ2275 (	Not specified in EPD (counter	unit	40	50.0		2	32.334	32.334
CS-02b	DIESEL PROPULSION MACHINERY - A	400	Main Machinery Sys	Copper Wiring (Shipbuilding-Speci	N/A - shipbuilding-industry-sp	kg				2	4.700	4.700

Item ID	Building — Weight	Building — Total Impact (kg CO2e)	Operation — Weight	Operation — Total Impact (kg CO2e)	Maintenance — Weight	Maintenance — Total Impact (kg CO2e)	Module D — Factor	Module D — Cumulative Quantity (base + replaceme	Module D — Total Impact (kg CO2e, information	Individual Material Total Impact (kg CO2e)	Data Quality	Notes / Basis for Quantities	Constituent Items (if Aggregate)
CS-01	5781341	13904125.1			1734402	4171237.53	0.000	7515743	0	18075363	Secondary (peer-reviewed sh		
CS-02	295571	710848.255			0	0	0.000	295571	0	710848.26	Secondary (peer-reviewed sh		
CS-03	8392	92689.64			0	0	0.000	8392	0	92689.64	Secondary (peer-reviewed sh		
CS-04	37440	90043.2			0	0	0.000	37440	0	90043.2	Secondary (peer-reviewed sh		
CS-05	21840	241222.8			0	0	0.000	21840	0	241222.8	Secondary (peer-reviewed sh		
CS-06	3120	14664			0	0	0.000	3120	0	14664	Secondary (peer-reviewed sh		
CS-07	854338	2054682.89			0	0	0.000	854338	0	2054682.9	Secondary (peer-reviewed sh		
CS-08	106792	501922.4			0	0	0.000	106792	0	501922.4	Secondary (peer-reviewed sh		
CS-09	9708	107224.86			0	0	0.000	9708	0	107224.86	Secondary (peer-reviewed sh		
CS-10	1299048	2857905.6			0	0	0.000	1299048	0	2857905.6	Secondary (peer-reviewed sh		
CS-11			263929882	953050802.5	0	0	0.000	0	0	953050802	Secondary (derived calculatio		
CS-12	81190	381593			0	0	0.000	81190	0	381593	Secondary (peer-reviewed sh		
CS-13	81190	308522			0	0	0.000	81190	0	308522	Secondary (peer-reviewed sh		
CS-14	216508	649524			0	0	0.000	216508	0	649524	Secondary (peer-reviewed sh		
CS-15	216508	476317.6			0	0	0.000	216508	0	476317.6	Secondary (peer-reviewed sh		
CS-16	216508	1320698.8			0	0	0.000	216508	0	1320698.8	Secondary (peer-reviewed sh		
CS-17	162381	811905			0	0	0.000	162381	0	811905	Secondary (peer-reviewed sh		
CS-18	162381	974286			0	0	0.000	162381	0	974286	Secondary (peer-reviewed sh		
CS-19	162381	1055476.5			0	0	0.000	162381	0	1055476.5	Secondary (peer-reviewed sh		
CS-20	216508	974286			0	0	0.000	216508	0	974286	Secondary (peer-reviewed sh		
CS-21	216508	1407302			0	0	0.000	216508	0	1407302	Secondary (peer-reviewed sh		
CS-22	216508	1082540			0	0	0.000	216508	0	1082540	Secondary (peer-reviewed sh		
CS-23	1	17853.5			0	0	-1.680	500	-840	17853.5	Primary (manufacturer EPD); t		
CS-24	1	14269.75			0	0	-2.690	250	-672.5	14269.75	Primary (manufacturer EPD); t		
CS-25	1	8053.9			0	0	-7.590	50	-379.5	8053.9	Primary (manufacturer EPD); t		
CS-26	1	1293.36			0	0	-1.520	40	-60.8	1293.36	Primary (manufacturer EPD); t		
CS-02b	6837	32133.9			0	0	0.000	6837	0	32133.9	Secondary (peer-reviewed sh		

Case Summary | Read Me | Assumptions | SWBD | Boundary & Limitations | LCAI Reference | LCA Calculation | Results | ISO Co

Figure B-7 LCA tool architecture - LCA Calculation sheet

A | B | C

Boundary & Limitations — Conceptual Design Stage LCA

Purpose

This sheet documents the scope, exclusions, and known gaps of the LCA Tool, so results are interpreted correctly.

1. Ship Work Breakdown Structure (SWBD) scope

The main classification logic follows the main functions of the ship systems. The original source material was used only as a starting term list; the classification logic follows Its own group

Resolution: the main systems are divided into sub-groups based on their functionality, and each sub-group is further decomposed and aggregated based on category and functionality, considering the conceptual design stage requirments.

Ship zones are considered but not clearly defined. The user can define their own dimensions to specify them (FWD/AFT/MIDSHIP). Materials are allocated by system/discipline, not by physical

Classification method: based on functionality or intended purpose.

Coverage: only material-relevant systems and components are covered.

2. LCAI material library scope

Structure: cradle-to-grave environmental total impact of the relevant product/material, based on the EN 15804 standard. Recycling credit is included.

Material categories: no special material category definition; all relevant materials related to shipbuilding are covered.

Environmental impact: the total Global Warming Potential impact of the product (Kg CO2-e /

Provenance: Manufacturer, Geography, Data Quality (e.g. "Primary (manufacturer EPD)" or "Secondary (literature)"), Data Source/Citation, and Notes

3. LCA Calculation mechanics

Calculate only the Global Warming Potential (Kg CO2-equivelent)

Quantities are entered manually per row;

The Material/Resource dropdown shows the full LCAI material list regardless of the selected SWBD term.

Building-stage material impact: the total environmental impact factor is multiplied by the weight at the building stage.

Operational-stage material impact: the total environmental impact factor of the material or product is multiplied by the weight of material used during the operational stage.

Maintenance-stage material impact: the total environmental impact factor of the material or product is multiplied by the weight, or the number of units, replaced during the ship's life span.

1) For hull material, steel is replaced at every major survey of the ship. This is calculated as the percentage of total hull weight that would be replaced, multiplied by the number of major surveys during the ship's life span.

2) For components that are replaced as a full unit, the number of units replaced during the ship's life span is calculated based on the product's life span.

Scrapping-stage material impact: the material's scrapping/end-of-life environmental impact is already included when it is considered during the other three stages, since the environmental impact value of the material - as entered in the LCAI Reference sheet - already includes it. A separate Scrapping-stage impact is therefore not included in the LCA Calculation sheet; including one separately would duplicate this impact and result in double counting.

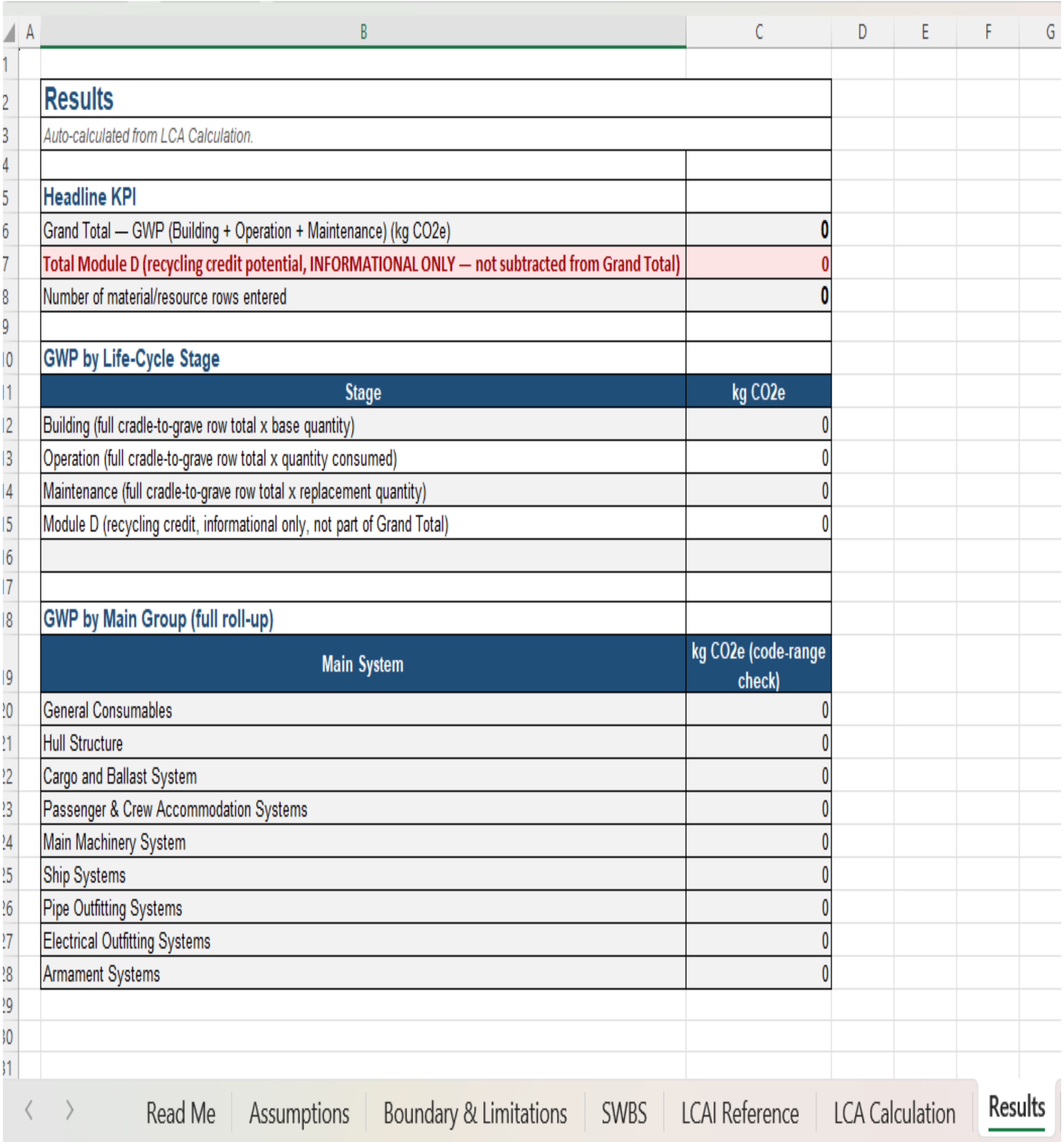
Recycling credit: the total weight of material used during the Building, Operation, and Maintenance stages is summed and multiplied by the Module D value, to calculate the recycling credit for the total material used by the ship during its life span.

4. Life-cycle scope

Cradle-to-grave (A1-C4) per EN 15804 modules; Module D reported separately as a credit, not summed into the headline total, per the Assumptions sheet.

> ... Assumptions | **Boundary & Limitations**

Figure B-8 LCA tool architecture – Boundary & Limitation sheet



Results	
Auto-calculated from LCA Calculation.	
Headline KPI	
Grand Total — GWP (Building + Operation + Maintenance) (kg CO2e)	**0**
Total Module D (recycling credit potential, INFORMATIONAL ONLY — not subtracted from Grand Total)	0
Number of material/resource rows entered	**0**
GWP by Life-Cycle Stage	
Stage	**kg CO2e**
Building (full cradle-to-grave row total x base quantity)	0
Operation (full cradle-to-grave row total x quantity consumed)	0
Maintenance (full cradle-to-grave row total x replacement quantity)	0
Module D (recycling credit, informational only, not part of Grand Total)	0
GWP by Main Group (full roll-up)	
Main System	**kg CO2e (code-range check)**
General Consumables	0
Hull Structure	0
Cargo and Ballast System	0
Passenger & Crew Accommodation Systems	0
Main Machinery System	0
Ship Systems	0
Pipe Outfitting Systems	0
Electrical Outfitting Systems	0
Armament Systems	0

Figure B-9 LCA tool architecture - Results sheet

DEPARTMENT OF MECHANICS AND
MARITIME SCIENCES
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY