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Environmental assessment of the beam trawling technique as used in Belgian fishing grounds considering the full lifespan of the vessel

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Fish is a high-protein food often included in healthy diets. Compared to other animal protein sources, fish generally have lower environmental impacts. However, Life Cycle Assessments (LCAs) quantifying the impacts of wild caught fish most often exclude data inventory on vessel construction and maintenance, commonly without sufficient rationale. This research addressed this gap by first reviewing the 16 previous LCAs on wild caught fish that did consider (some level of) construction and/or maintenance. As a case-study, an LCA was performed for the fishing activities in Belgian fishing grounds by a large beam trawler, the fleet segment responsible for 70% of Belgium's 2020 catch. The system boundaries extended from vessel construction to fish auction, incorporating construction plans, maintenance records, and expert guidance. Results showed that construction and maintenance contributed minimally to climate change, particulate matter, and fossil resource use, justifying omission in LCA studies for long-operating vessels with considerable fuel use. However, this was not true for several impact categories, including water use, toxicity-related impact, eco-toxicity freshwater, eutrophication freshwater, and resource use minerals and metals. These impacts were primarily linked to the vessel's steel, the netting, and the copper cathode. Our findings suggest that while exclusion of construction and maintenance may be justified for certain impact categories, their inclusion is recommended when assessing toxicity and resource-related impacts. When full inventory data are unavailable, representative data on key materials can offer a reasonable approximation. Our study provides suggestions for LCA practitioners to make informed decisions about system boundaries, balancing methodological rigor with practical feasibility.

KEYWORDS

Belgian fisheries, environmental impact, LCA, life cycle inventory (LCI), trawler construction, trawler maintenance

1 Introduction

Protein sources, including seafood, are part of the food production to which a quarter of the global Greenhouse Gas (GHG) emissions is attributed (Poore and Nemecek, 2018). The environmental impact of seafood products tends to be lower compared to other protein sources (Poore and Nemecek, 2018; Gephart et al., 2021; Ziegler and Hilborn, 2023). Seafood production, unlike terrestrial protein sources such as meat and dairy, is;

often perceived as more distant from consumers due to its origin in vast and less visible marine environments. This perception has historically resulted in a limited number of environmental assessments within seafood supply chains. However, seafood-related LCAs are becoming increasingly common, particularly for farmed species and studies linking environmental impacts to nutrition. Consequently, this sector is gaining growing attention in sustainability research (Hallström et al., 2019; Winther et al., 2020; Bianchi et al., 2022; Ziegler and Hilborn, 2023). According to Gephart et al. (2021), the environmental impact of seafood ranges from 5 to 20 kg CO_2 equivalent per kg of seafood ranging from farmed seaweed to flounder caught by trawling methods.

This study addresses the following research questions:

What is the environmental impact of one kilogram of fish caught by the large Belgian beam trawler, when including the full life cycle of the vessel? How does this compare to findings from the limited set of other seafood-related LCAs that do consider elements of construction and/or maintenance? Can we derive guidelines for other LCA practitioners concerning the inclusion (or not) of aspects of vessel construction and maintenance in the Life Cycle Inventory (LCI) phase?

Although modest in scale, contributing 0.02% to global and 0.47% to EU landings (Departement Landbouw & Visserij, 2021b), Belgian fisheries offer a valuable case. Approximately 26% of the world's catch is retrieved through beam trawling, with China accounting for 15% (Steadman et al., 2021). The fleet comprised 64 active vessels in 2020, which are divided into small and large segments. The small fleet comprises 12 coastal boats, 15 eurocutters, smaller trawlers operating within 12 nautical miles, and seven other vessels, including passive fishing boats and shrimp fisheries, all with engine capacities of 221 kW or less. The large fleet consists of 26 beam trawlers and four additional vessels (otter trawlers and cray fishing boats) with engine capacities exceeding 221 kW (Departement Landbouw & Visserij, 2021a). Large beam trawlers (30.58–38.93 m in length) are central to this study (Departement Landbouw & Visserij, 1981, 2021a). Beam trawling remains the dominant fishing method, accounting for 70% of 2020′s landings, particularly for targeting flatfish species that dwell on the seabed. These species are disturbed from the seabed by the trawl and caught in the passing net.

Cod, once a major catch, has declined due to overfishing and climate-driven migration. Cuttlefish, on the other hand, has emerged in recent years, due to warming seas (Departement Landbouw & Visserij, 2021a).

Belgian fishers operate in various zones of the Atlantic Ocean, notably the North Sea [ICES (International Council for the Exploration of the Sea) Areas IVb, c], the English Channel (VIId, e), and the Celtic Sea (VIIf, g), with smaller shares from the Irish Sea, the Bay of Biscay, and other regions (Lescrauwaet et al., 2010). Over the past 40 years, fishing grounds have shifted, with coastal fisheries declining and Brexit expected to further reduce the access to United Kingdom waters by 2026 (Departement Landbouw & Visserij, 2021b).

A Web of Science search conducted on 26/08/2025 using the terms "Life Cycle Assessment (LCA)" and "Fisheries OR Ship Construction OR Trawler" for the years 2021–2025 yielded, respectively, 174, 51, and 47 articles. We started our search at the year 2021 because of an existing article (Ruiz-Salmón et al., 2021) where the authors similarly searched for LCIs including construction and/or maintenance. Among the articles of the period 2021–2025, only six papers addressed vessel construction and maintenance. The other studies focused on fuel consumption, neglecting construction and/or maintenance entirely, with this methodological decision often lacking well-grounded justification. A synthesis of these six articles, together with ten older articles as listed by Ruiz-Salmón et al. (2021), is shown in Appendix, Table S1. The synthesis includes key study characteristics, covering various fishing techniques such as trawling, purse seining, and lobster fishing. Even in this set of papers, construction is frequently overlooked (Figure 1), either by excluding fishing gear or by considering only one or two materials (e.g. steel and antifouling paint), reducing the accuracy of the construction process assessment.

By incorporating the full life cycle of the Belgian fishing vessel, including construction and maintenance, our study aims to offer a comprehensive perspective on the environmental performance of Belgian beam trawlers, for which no LCA has been performed. The novelty of this work lies in the consideration of often-excluded processes in the data inventory of environmental assessments in fisheries research. This topic is thematically relevant for fisheries professionals and policymakers as it captures the full extent of the environmental impacts of wild-caught fish, and methodologically relevant for LCA practitioners regarding value-laden methodological choices.

2 Materials and methods

This study followed the LCA methodology as outlined in the International Organization for Standardization (ISO) 14040 and 14044 standards (International Organisation for Standardisation, 2006a,b). The LCA evaluated the environmental impacts associated with the full life cycle of fishing activities conducted by Belgian beam trawlers, from resource extraction and raw material processing to the landing of fish at a Spanish harbor. The ISO-framework divides the LCA into four key phases: goal and scope definition, the LCI, the life cycle impact assessment (LCIA), and the

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Abbreviations: AC, acidification; CC, climate change; CV, coefficient of variation; ECF, ecotoxicity freshwater; EF, environmental footprint; EFF, eutrophication freshwater; EFM, eutrophication marine; EFT, eutrophication terrestrial; GHG, greenhouse gas; HTC, human toxicity cancer; HTNC, human toxicity, non-cancer; IC, impact category; ICES, International Council on the Exploration of the Sea; ILVO, Flanders Research Institute for Agriculture, Fisheries, and Food; IR, ionizing radiation; ISO, International Organization for Standardization; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; LNG, liquified natural gas; LOA, length over all; LSW, lightship weight; LU, land use; OD, ozone depletion; PE, polyethylene; PM, particulate matter; POF, photochemical ozone formation; RUF, resource use, fossils; RUM, resource use, minerals and metals; SD, standard deviation; SEM, standard error of the mean; WU, water use.

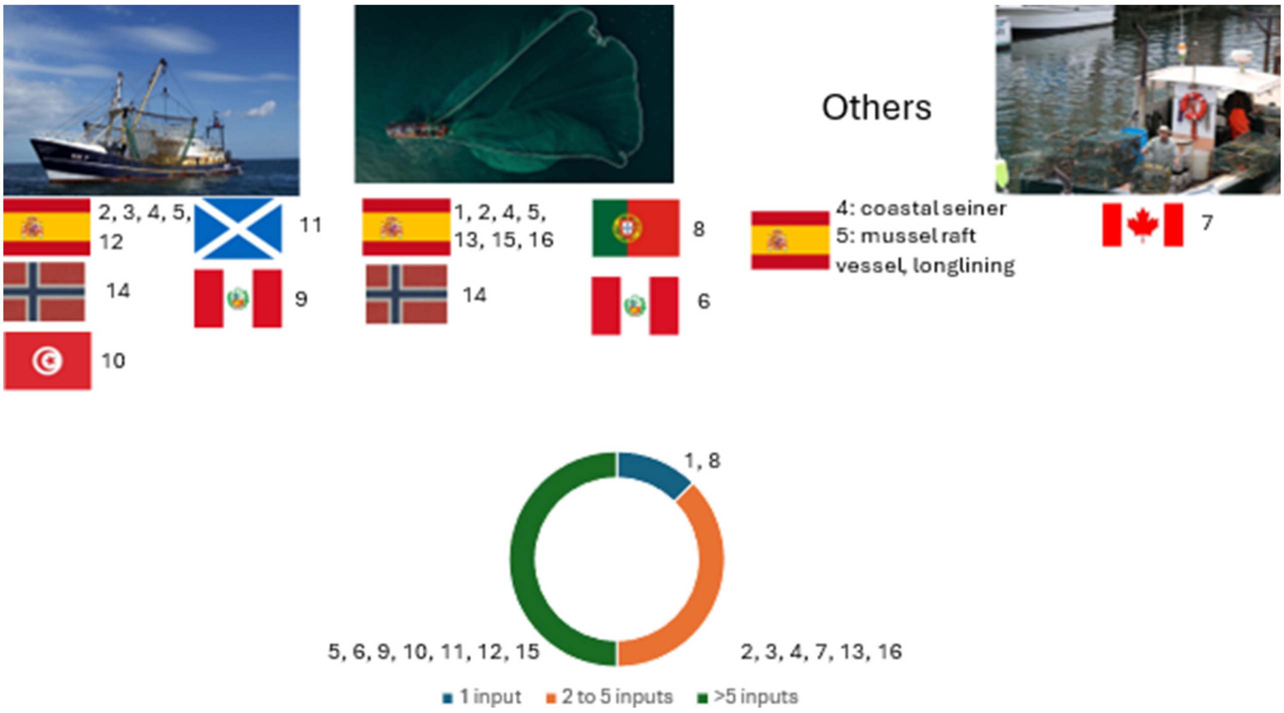

FIGURE 1
Overview of the 16 LCA wild caught fisheries studies (listed in Table S1 in the Appendix) including vessel construction and/maintenance. Top part: the main fishing technique used in each study (trawler, purse seiner, others, lobster fishing vessel) is indicated along with the country of the vessel in each study. The bottom panel categorized studies based on the number of inputs included in the construction and maintenance phase: one input, two to five inputs, or more than five inputs. More details on these 16 studies are provided in Table S1. (Photographs by mroylbca, mcsc1995, HieuNghiaMini, deMysticWay, Kaufdex, tarcisioefbarbosa0, ridvan-selli, Anna_Athan, OpenClipart-Vectors via Pixabay).

interpretation of the results. The following sections describe how the LCA phases were applied to the case study.

2.1 Goal and scope of the study

The goal of this study is to provide a comprehensive environmental assessment of the Belgian fishing activity by targeting the most representative vessel, namely a beam trawler of the large fleet segment. This accounts for 70% of Belgium's fish landings in 2020, making it a suitable proxy for the Belgian fleet. The assessment aims to incorporate infrastructural processes linked to vessel construction and maintenance, which are often omitted in fisheries LCA, and to identify key processes contributing to the environmental impact. As no previous LCAs have been conducted on Belgian fisheries, this work provides a valuable baseline for future studies.

The intended audience of the results are twofold: (1) LCA practitioners interested in the inclusion of vessel construction and maintenance in fisheries-related data inventories, and (2) stakeholders in the Belgian fisheries sector engaged in insights into the environmental impacts of their activities, as this information is currently lacking in the literature.

The intended application of the research is to document the environmental performance of wild-caught fish using the beam trawling technique in Belgium, considering the often-excluded processes of ship construction and maintenance, and to identify the environmental hotspots. For clarity, the study is descriptive and non-comparative, documenting the environmental impacts of the Belgian fisheries over the period 2007–2020.

The functional unit (FU) is defined as one kilogram of fish caught by a 38 meters beam trawler up to its delivery to the fish auction in Ostend, Belgium. The system includes all processes from vessel construction and maintenance (allocated proportionally over a 40-year lifespan) to fish captured in the Bay of Biscay, landed at Vigo (Spain), and subsequently transported by truck to the Flemish auction. This represents a cradle-to-auction scenario. The Bay of Biscay and the Vigo harbor have been selected to represent a realistic yet worst-case supply chain in terms of cruising and transport distances that remain within the range of Belgian fishing operations (Figure 2).

2.1.1 Data requirements and sources

Primary data were sourced from Belgian fleet statistics on fuel use and annual catches, as well as collaboration with a Flemish shipyard and the Flemish auction (Departement Landbouw & Visserij, 2010, 2012, 2015, 2019b, 2020b, 2021a; Departement Landbouw en Visserij, 2011, 2013). On-site visits were performed at the shipyard in April 2023 and at the fish auction in June 2023 for data collection purposes. The visited auction is a private limited liability company, operating the two auctions located in the two Flemish fishing ports of Zeebrugge and Ostend.

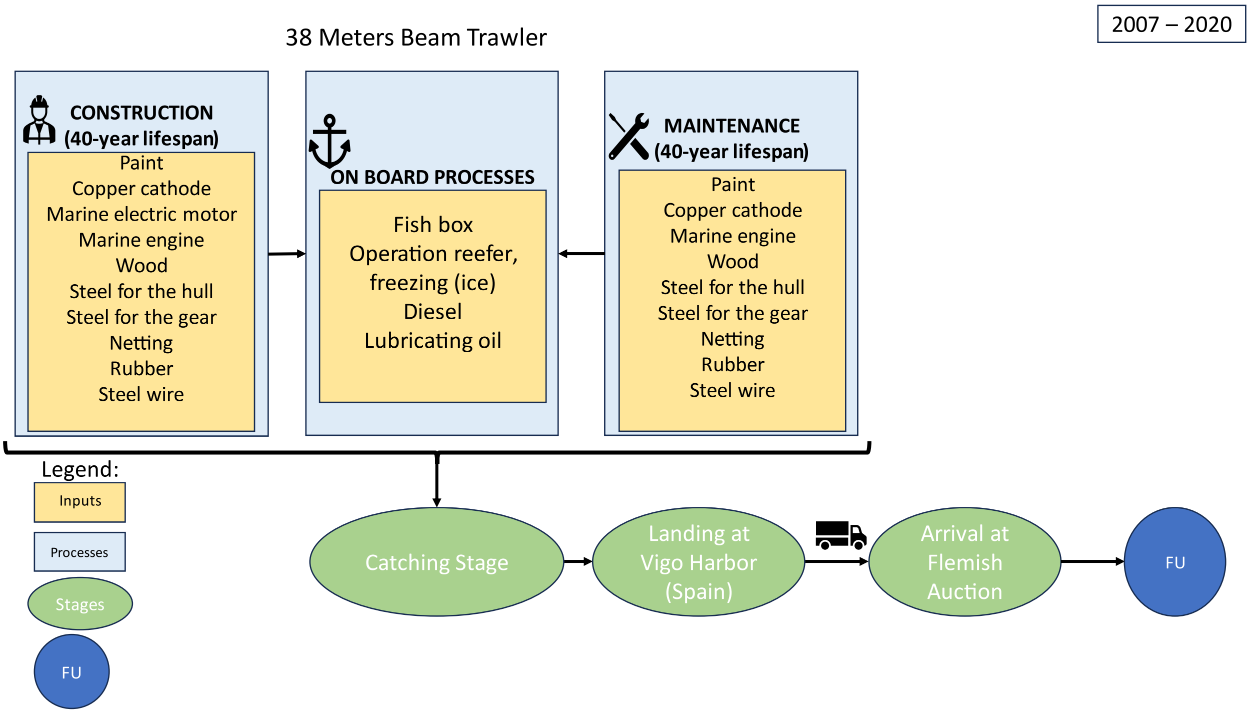

FIGURE 2
System boundaries of the cradle-to-auction assessment, illustrating the processes included in the case-study, from vessel construction and maintenance to fishing operations in the Bay of Biscay, landing at Vigo harbor, and transport to the Flemish auction.

All marine fish caught by Belgian fishing vessels (including the catch landed outside Belgium) is sold in real time online via a network that connects three auction houses: Zeebrugge, Ostend, and Nieuwpoort. Every year, approximately 14 million kg of fish is sold via the auction house to consumers throughout Europe (Vlaamse Visveiling, 2025). The research has been fully funded by an internal KU Leuven grant, and collaboration with several stakeholders (see Section 2.2) is sought for extensive information and data collection purposes. Stakeholders had no influence on the study design, data analysis, or interpretation of the results.

Primary data have been matched with the LCA ecoinvent 3.10 cut-off by classification—unit database (Wernet et al., 2016).

2.1.2 Allocation and assumptions

For the vessel construction and maintenance, physical allocation is applied in alignment with ISO standards (International Organisation for Standardisation, 2006a,b). Particularly, construction and maintenance impacts are attributed to the total mass of seafood caught by the large beam trawlers. To do so, annual landings from large beam trawlers have been first derived from the annual reports and then evenly distributed across all active vessels for that year, as vessel-specific catch data are currently unavailable. This approach evenly allocates environmental impacts to the wild-caught fish, without distinction on the basis of fish species. A review by Ruiz-Salmón et al. (2021), indicates that mass allocation was the primary allocation method in fish and seafood LCAs (Vázquez-Rowe et al., 2010b, 2011b; Driscoll et al., 2015; Avadí et al., 2018). This methodological choice reflects the same rationale adopted in the cited work. Economic allocation has also been considered in their review; however, it relies on market prices of the species under study, which is not applicable in this case study due to lack of species-specific data.

2.1.3 Value choices and optional elements

An attributional LCA has been performed as a retrospective analysis, appropriate for establishing an environmental baseline. Following Schaubroeck et al. (2021), the attributional approach provides information on what portion of the global environmental burdens can be associated with a product (and its life cycle). This choice reflects a rule-based (deontological) ethical perspective, which concords with our aim, which is to address the research questions (see Section 1) using the standard additivity principle in the LCIA phase (Schaubroeck, 2023). The objective is to quantify the share of global environmental impacts attributable to the life cycle of the Belgian catch, a topic that has not yet been examined in Belgium.

Future research may explore a consequential LCA perspective to assess how decision-driven changes influence environmental impacts (Schaubroeck, 2023).This approach aligns with ideological viewpoint criteria by (i) covering realistic consequential effects over time from a theoretical perspective and (ii) supporting ethical considerations related to responsibility in accounting and decision-making, elements partially addressed by attributional LCA. By incorporating the decision effects on environmental impacts, a consequential LCA situates product systems within a realistic and decision-relevant context.

2.1.4 Interpretation

Results were interpreted at the fleet level, focusing on hotspot identification rather than species-specific impacts. A contribution analysis is used to determine the most contributing processes to environmental impacts. The Environmental Footprint (EF) 3.1 method was selected as it aligns with the latest European Commission Product and Organization Environmental Footprint guidelines (European Commission, 2022). All impact categories (ICs) assessed will be presented in the Results section.

2.1.5 Data quality assessment using the pedigree matrix

Data quality is assessed using the Pedigree matrix approach, which evaluates data on five criteria (i) reliability, (ii) completeness, (iii) temporal difference, (iv) geographical difference, and (v) technological difference (Weidema and Suhr Wesnaes, 1996). Each dimension has been scored on a scale from 1 (high quality) to 5 (low quality).

For foreground processes, such as the fuel consumption, trawler construction, and maintenance, data quality scores have been assigned based on the characteristics of the primary data collected. For background processes, such as steel production, and electricity generation, data quality scores have been retrieved directly from the ecoinvent database.

The uncertainty analysis ensures consistent treatments of uncertainty across both foreground and background systems. When comparing our approach to the studies listed in the Supplementary Table S1, only four out of 16 papers conducted an uncertainty analysis (Driscoll et al., 2015; Avadí et al., 2018; Cortés et al., 2022; Fernández-Ríos et al., 2022), pointing to the only partial adoption of uncertainty analysis in seafood LCAs. The methodological decision to acknowledge and quantify sources of uncertainty further aligns with the recommendations of Schaubroeck (2023).

In terms of data representativeness, the data cover the following aspects:

- Temporal: Data reflect recent fleet operations (2007–2020).
- Geographical: Belgian North Sea fisheries and operations in the Bay of Biscay.
- Technological: Large beam trawlers using conventional gears and refrigeration systems.

2.2 Life cycle inventory (LCI)

The LCI phase involves compiling all material and energy flows required to deliver the FU in accordance with the ISO standards (International Organisation for Standardisation, 2006a,b). As detailed in Section 2.1.1, primary data through fisheries stakeholders have been collected and matched with background LCA databases. This section details the data inventory and underlying assumptions.

This study focuses on the large beam trawler segment due to its dominant share of landings. Technical details for vessel construction have been obtained for one representative beam trawler (namely, the Z47 “De Marie Louise”) through stakeholder collaboration. Due to confidentiality constraints, construction plans cannot be disclosed, but relevant details are included in the inventory.

2.2.1 Trawler construction and trawler maintenance

To assess the environmental impact of vessel construction and maintenance, the lightship weight (LSW) of the beam trawler is used as an essential baseline for calculating material inputs. The LSW of the 38.31 meters beam trawler Z47 (“De Marie Louise”) equals 564,555 kg, based on confidential construction plans provided by GARDEC (personal communication, 20/04/2023, GARDEC).

The construction process is modeled starting from the ecoinvent dataset “Trawler, steel {RoW}|trawler construction, steel|Cut-off, U” (Avadí et al., 2018), with modifications. For example, solvent is added to the alkyd paint process, which originally consisted solely of resin, and wood inputs were included to reflect the vessel’s actual construction. Primary data are used where available; the remaining inputs are supplemented with Flemish reports or derived by scaling ecoinvent values according to the vessel’s LSW (Table 1). Further details on the calculations are provided in the next paragraphs.

Each year, the vessel receives applications of alkyd and antifouling paint, resulting in 39 applications over its 40-year lifespan (personal communication on 20/04/2023, GARDEC) Wood and rubber were added manually to the chosen trawler maintenance process (Trawler maintenance, steel {RoW}|trawler maintenance, steel|Cut-off, U). The inputs associated with vessel construction and maintenance were distributed evenly across the vessel’s 40-year lifespan and then allocated proportionally to the annual landing weights of a single vessel. This approach allows for estimating the environmental contribution of construction and maintenance per kilogram of fish caught.

The original process specified copper wire, but Belgian fisheries use steel wire for its superior strength (personal communication on 12/03/2024, ILVO). The vessel’s engine, an ABC motor 8DZC, was assumed to undergo one replacement over its lifespan as a conservative scenario although it could last the entire period with proper maintenance (personal communication on 20/04/2023, GARDEC).

The remaining inputs are calculated based on the LSW, as they have not been provided during the shipyard or auction visit. Data on steel, rubber, polyethylene (PE) netting and gear weights are sourced from literature. Depestele et al. (2011) report a gear weight of 6,700 kg where 75% of the gear weight is attributed to the beam and shoes and the remaining portion divided among the chains, netting, and rubber accounting for roughly 15%, 9% and 1% of the gear weight, respectively (personal communication on 12/03/2024,

TABLE 1 Processes and material inputs related to the construction of the vessel and fishing gear of the beam trawler De Marie Louise, including end-of-life treatment of steel, based on its detailed construction plan and maintenance information, as obtained from stakeholders in the sector. The inputs are further used in the necessary calculations (columns 2 and 3). For transparency, the selected LCI process in ecoinvent is listed in the fourth column.

Material	Value	Explanation of the used values	Life cycle inventory process and source
Alkyd paint	188.l * 1.3 kg/L = 244 kg	As the input is considering 100% of resin, solvent was added to the existing process to achieve the 60% of solution state. The density is retrieved from JOTUN (2024a)	Alkyd paint, white, without solvent, in 60% solution state {RoW}| market for alkyd paint, white, without solvent, in 60% solution state + solvent_SM|Cut-off, U. This is based on an expert value estimate The solvent process added was Solvent for paint {GLO}| market for solvent for paint|Cut-off, U
Antifouling paint	160.l * 1.3 kg/L = 208 kg	(JOTUN, 2024b)	Alkyd paint, white, without solvent, in 60% solution state {RoW}| market for alkyd paint, white, without solvent, in 60% solution state + solvent_SM | Cut-off, U, with 600 g of alkyd paint and 400 g of solvent to obtain one kilogram of 60% solution state paint. This is based on an expert value estimate
Copper cathode for the electric circuit of the ship	$\frac{0.009\ \text{kg}}{1\ \text{kg LSW}} \times 564{,}555\ \text{kg LSW} = 5.36 \times 10^3\ \text{kg}$	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg) to derive the amount needed for this research	Copper, cathode {GLO}| market for copper, cathode | Cut-off, U
Copper wire	$\frac{0.009\ \text{kg}}{1\ \text{kg LSW}} \times 564{,}555\ \text{kg LSW} = 5.36 \times 10^3\ \text{kg}$	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg) to derive the amount needed for this research	Wire drawing, copper {RoW}|wire drawing, copper|Cut-off, U
Marine electric motor for the ship	$\frac{6.2\times10^{-6}\ \text{pieces}}{1\ \text{kg LSW}} \times 564{,}555\ \text{kg} = 3.47\ \text{pieces}$	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg) to get the amount needed for this research. Knowing that 1 piece = 1,000 kg	Marine electric motor {GLO}| market for marine electric motor|Cut-off, U
Marine engine for the ship	Weight recalculated based on an ABC motor 8DZC: 13.905 pieces	This motor is typically used in Belgian beam trawlers and weighs 13,905 kg, expressed in pieces of 1,000 kg (Anglo Belgian Corporation, 2024)	Marine engine {GLO}| market for marine engine | Cut-off, U (personal communication, GARDEC, 20/04/2023)
Metal working for the ship	$\frac{0.009\ \text{kg}}{1\ \text{kg LSW}} \times 564{,}555\ \text{kg} = 4.86 \times 10^3\ \text{kg}$	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg) to derive the amount needed for this research	Metal working, average for steel product manufacturing {GLO}|market for metal working, average for steel product manufacturing | Cut-off, U
Wood for the ship	20,000 kg	The amount of wood for this type of vessel is estimated to 20,000 kg by the Flemish shipyard	Purse seiner, wood {GLO}| market for purse seiner, wood | Cut-off, U (personal communication, GARDEC, 20/04/2023). This is based on an expert value estimate
Reinforcing steel for the ship	$\frac{0.009\ \text{kg}}{1\ \text{kg LSW}} \times 564{,}555\ \text{kg LSW} = 4.86 \times 10^3\text{kg}$	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg) to derive the amount needed for this research	Reinforcing steel {GLO}|market for reinforcing steel|Cut-off, U
Steel for the ship	$5.64 \times 10^5 - 244 - 208 - 5.36 \times 10^3 - 5.36 \times 10^3 - 3.47 \times 10^3 - 13.905 \times 10^3 - 1.21 \times 10^3 - 4.86 \times 10^3 - 20 \times 10^3 - 1.21 \times 10^4 - 134 - 3.626 \times 10^3 = 4.94 \times 10^5\ \text{kg}$	This is calculated based on the LSW and construction plans of the Z47 minus the weight of the inputs related to the ship and the inputs related to gear	Steel, low-alloyed, hot rolled {GLO}| market for steel, low-alloyed, hot rolled|Cut-off, U through personal communication (construction plans)
PE for the net	$\frac{6{,}700\ \text{kg}\times0.09\times2}{0.976} = 1.24 \times 10^3\ \text{kg}$	Based on Depestele et al. (2016) with a gear weight of 6,700 kg with 2 gears per vessel	Polyethylene, low density, granulate {GLO}|market for polyethylene, low density, granulate|Cut-off, U. It was assumed to equal 9% of the gear weight [confirmed through personal communication, ILVO (Flanders Research Institute for Agriculture, Fisheries, and Food), 12/03/2024]. The manufacturing process is added manually with the following extrusion process: extrusion, plastic film {GLO}| extrusion, plastic film| Cut-off, U, which has a yield of 0.976 kg
Steel for the gear	$6{,}700\ \text{kg} \times 0.9 \times 2 = 1.21 \times 10^4\ \text{kg}$	Based on Depestele et al. (2016) with 2 gears per vessel	Steel, low-alloyed {GLO}|market for steel, low-alloyed|Cut-off, U. It was assumed to equal 90% of the gear weight (confirmed through personal communication, ILVO,12/03/2024)
Steel wire for the gear	3,626 kg	Regarding the steel wire, a length of 1,000 m is accounted for across the two winches, each with a diameter of 32 mm, resulting in a weight of 3,626 kg (confirmed through personal communication, ILVO, 12/03/2024)	Wire drawing, steel {GLO}|market for wire drawing, steel|Cut-off, U. Steel is added manually as an input as it is not taken into account in the process: Steel, low-alloyed, hot rolled {GLO}| market for steel, low-alloyed, hot rolled| Cut-off, U

(Continued)

TABLE 1 (Continued)

Material	Value	Explanation of the used values	Life cycle inventory process and source
Rubber for the gear	6,700 kg × 0.01 ×2 = 134 kg	Based on Depestele et al. (2016) with 2 gears per vessel	Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U. It was assumed to equal 1% of the gear weight (confirmed through personal communication, ILVO, 12/03/2024)
Used trawler steel also known as the end of life of the trawler	$\frac{1\text{ kg}}{1\text{ kg LSW}} * 564,555\text{ kg LSW}$ $=5.64 \times 10^5$ kg	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg) to derive the amount needed for this research	Output: used trawler, steel {GLO}| market for used trawler, steel|Cut-off, U

ILVO). Regarding the steel wire, a length of 1,000 m is accounted for across the two winches, each with a diameter of 32 mm, resulting in a weight of 3,626 kg (personal communication on 12/03/2024, ILVO; Tyson's Rigger Ltd, 2024).

In the maintenance phase, input values from the construction phase have been adjusted using replacement rates (Table 2). The steel replacement rate, as indicated by Dong and Cai (2020) is 14.9% over a 20-year period. According to the European Union (2020), netting is typically replaced up to five times annually, totaling 200 replacements over 40 years. Wood is assumed to be replaced twice, based on a 15-year lifespan for wooden docks (Alumi-Span Docks, 2018). Rubber replacement is set at a rate of 10% according to Liu et al. (2020). The remaining input values have been calculated relative to the LSW. For the engine, a single replacement was assumed over the vessel's operational life, following the principle of Avadí et al. (2018) (Table 2).

2.2.2 Estimates for the vessel's fuel consumption

A typical journey begins when the trawler leaves its home harbor and cruises to fish grounds to catch flatfish. The catch is retrieved every three hours, resulting in eight hauls per day. In 2020, this yielded an average of 1,795 kg of fish per seaday per fishing vessel across 26 large beam trawlers, totaling 6,850 sea days. In comparison, the average was 975 kg of fish per sea day per large beam trawler, based on 37,899 days over 208 vessels in 1980. The amount of active vessels decreased to 66 vessels in 2020, without specifications for the large beam trawlers in the report of 1980. Total annual landings declined from 40,129 tonnes in 1980 to 18,306 tonnes in 2020 (Departement Landbouw & Visserij, 1981, 2023).

The fishing gear includes tickler chains, attached to the shoes, and the ground rope activates fish living on and in the sea bottom. During each haul, the net is heaved, and the catch is deposited into large containers on board. The containers are flushed with seawater and the catch is then transported via a conveyor belt to sort the marketable catches from unwanted ones (Uhlmann et al., 2021). For example, Belgian fishers only keep rays that are at least 50 cm in length and weigh at least one kilogram. Smaller rays are discarded due to their limited economic value and high survival rate (Schram and Molenaar, 2018). However, other fish species subject to the Landing Obligation are managed by quota limits or minimum sizes.

When the fishing stage ends, the vessel heads to the nearest harbor and is typically not cruising back to the home harbor. Some of the catch may remain in the country where it lands, while the remainder is transported by truck to the Belgian fish auction (personal communication on 14/06/2023, Vlaamse Visveiling).

Exact fuel consumption figures for Belgian large beam trawlers are available from 2007 to 2020, sourced from yearly reports (Departement Landbouw & Visserij, 2016, 2017, 2018, 2019a, 2020a). Research by Basurko et al. (2022) indicate that most fuel consumption is due to vessel cruising, followed by fishing operations, vessel inactivity at sea and harbor stays. Fuel consumption per day for large trawlers was divided by the total supply per seaday of those trawlers, yielding fuel consumption per kilogram of fish brought to the auction without making a distinction between the fish species (Tables S2, S3; Thrane, 2004; Dabat et al., 2023).

2.2.3 Other processes during handling on board and the arrival at the auction

Marketable fish is gutted and placed on ice in boxes stored in cool rooms on board. The fish box typically weighs 3.5 kg and can hold between five to 15 kg of fish along with 25–35 kg of ice. The fish box composition was assumed to be PE, based on auction personnel input, considering a lifespan of eight years (FAO, 1981b). According to FAO (1981a) guidelines, a 3:1 ice-to-fish ratio is required to chill freshly caught fish. During transport, a 1:2 ice-to-fish ratio is recommended to ensure proper mixing, with an additional 30% of ice needed to compensate for possible heat losses. These proportions allow the fish to remain fresh for three to four days, which, when adjusted to the five-day fishing trip of the study, corresponds to 6.5 kg of ice used per kilogram of fish (FAO, 1981a; Table 3). To simulate onboard ice production, a freezing operation reefer process was used as a proxy similar to other LCA studies of seafood products (e.g. Avadí et al., 2018).

2.3 Life cycle impact assessment

The software SimaPro 9.6.0.1 was used with EF3.1 V1.00/EF3.1 as the impact assessment method. The EF3.1 method assesses impacts across 16 ICs [Acidification (AC), Climate Change (CC), Ecotoxicity freshwater (ECF), Particulate matter (PM), Freshwater Eutrophication (EFF), Marine Eutrophication (EFM), Terrestrial Eutrophication (EFT), Human Toxicity Cancer (HTC), Human Toxicity Non Cancer (HTNC), Ionizing Radiation (IR), Land Use

TABLE 2 Processes and material inputs related to the maintenance of the vessel and fishing gear of the beam trawler De Marie Louise, assessed over its full 40-year operational lifespan.

Material	Input value	Explanation	Life cycle inventory process
Alkyd paint for the ship	$188\,\mathrm{l} \times 39 \times 1.3\frac{\mathrm{kg}}{\mathrm{l}} = 9.53 \times 10^3\mathrm{kg}$	The amount is multiplied by 39, resulting in 39 applications in the vessel's 40-year lifespan (JOTUN, 2024a)	Alkyd paint, white, without solvent, in 60% solution state {RoW}| market for alkyd paint, white, without solvent, in 60% solution state + solvent_SM | Cut-off, U
Antifouling paint	$160\,\mathrm{l} \times 39 \times 1.3\frac{\mathrm{kg}}{\mathrm{l}} = 8.11 \times 10^3\mathrm{kg}$	The amount is multiplied by 39, resulting in 39 applications in the vessel's 40-year lifespan (JOTUN, 2024b).	Alkyd paint, white, without solvent, in 60% solution state {RoW}| market for alkyd paint, white, without solvent, in 60% solution state + solvent_SM | Cut-off, U
Copper cathode for the electric circuit of the ship	5.36×10^3 kg × 1.5 = 8.04×10^3 kg	The construction value is multiplied by 1.5 replacement rate as specified in the ecoinvent process	Copper, cathode {GLO}|market for copper, cathode|Cut-off, U
Copper scrap, sorted, pressed {GLO}| copper scrap, sorted, pressed, Recycled Content cut-off | Cut-off, U	-5.36×10^3 kg × 1.5 = -8.04×10^3 kg	The value corresponds to that of the copper cathode, although it appears with a negative sign	Copper scrap, sorted, pressed {GLO}|copper scrap, sorted, pressed, Recycled content cut-off|Cut-off, U
Copper wire	5.36×10^3 kg × 1.5 = 8.04×10^3 kg	The construction value is multiplied by 1.5 replacement rate as specified in the ecoinvent process.	Wire drawing, copper {RoW}| wire drawing, copper | Cut-off, U
Iron scrap, unsorted {GLO}| iron scrap, unsorted, Recycled Content cut-off | Cut-off, U	$-\frac{0.50\ \mathrm{kg}}{1\,\mathrm{kg\ LSW}} \times 564,555\ \mathrm{kg\ LSW} = -2.81 \times 10^5\ \mathrm{kg}$	The ecoinvent value is multiplied by the LSW of the Z47 (564,555 kg)	Iron scrap, unsorted {GLO}|iron scrap, unsorted, Recycled Content cut-off|Cut-off, U
Marine engine for the ship	13.905 pieces	A one-time replacement is assumed	Marine engine {GLO}|market for marine engine|Cut-off, U
Steel for the ship	4.94×10^5 kg × 0.12 × 20 = 1.19×10^6 kg	The steel hull sheets have a 12% replacement rate every two years as specified in the ecoinvent process	Steel, low-alloyed, hot rolled {GLO}|market for steel, low-alloyed, hot rolled|Cut-off, U
Wood for the ship	20,000 kg × 2 = 4.0×10^4	Wooden docks are assumed to have a lifespan of 15 years, meaning a two times replacement over a 40-year period (Alumi-Span Docks, 2018)	Purse seiner, wood {GLO}|market for purse seiner, wood | Cut-off, U
PE	1.24×10^3 kg × 199 = 2.47×10^5 kg	It is assumed that over a 40-year period, the netting is replaced 199 times	Polyethylene, low density, granulate {GLO}| market for polyethylene, low density, granulate | Cut-off, U
Steel net for the gear	1.21×10^4 kg × 0.149 × 2 = 3.59×10^3 kg	Steel is considered to have a replacement rate of 14.9% for a period of 20 years, so this is multiplied by 2 as we cover a 40-year period (Dong and Cai, 2020)	Steel, low-alloyed {GLO}| market for steel, low-alloyed | Cut-off, U
Rubber for the gear	134 kg × 0.1 = 13.4 kg	Rubber has a replacement rate of 10% (Liu et al., 2020).	Synthetic rubber {GLO}| market for synthetic rubber | Cut-off, U
Steel wire for the gear	3,626 kg × 2 × 0.149 = 1.08×10^3 kg	Steel is considered to have a replacement rate of 14.9% for a period of 20 years, so this is multiplied by 2 as we cover a 40-year period (Dong and Cai, 2020)	Wire drawing, steel {GLO}|market for wire drawing, steel | Cut-off, U

(LU), Ozone Depletion (OD), Photochemical Ozone Formation (POF), Resource Use Fossils (RUF), Resource Use Minerals and Metals (RUM), Water Use (WU)]. The EF3.1 has been selected as it represents the most recent version aligned with the European Commission's Product and Organization Environmental Footprint guidelines (European Commission, 2022).

To assess uncertainty, a Monte Carlo simulation with 10,000 iterations was conducted using SimaPro 9.6.0.1, assuming lognormal distributions. The simulation incorporated a Pedigree matrix (Weidema and Suhr Wesnaes, 1996) which attributed uncertainty scores to each process based on five indicators: reliability of the source, completeness, temporal differences, geographical differences, and further technological differences. Results are reported with key descriptive statistics to detail the uncertainty associated with the assessment.

3 Results

This section presents the environmental impact results for one kilogram of fish caught by a large beam trawler and delivered to the Flemish auction. The analysis covers fish landed over a 14-year period and each year includes a proportional (namely 1/40th) share of vessel construction and maintenance impacts based on

TABLE 3 Processes and amounts for handling on board and transport back to Belgium.

Material	Input value	Explanation	Life cycle inventory process with source and used database
Fish box	$\frac{\left(\frac{3.5\ \text{kg}}{8\ \text{years lifespan}}\right)}{365\ \text{days}} *$ 7 days = 0.008 kg	The fish box has a lifespan of eight years (FAO, 1981a). With the trip back to Belgium, a maximal use of seven days was considered. The weight of the fish box was 3.5 kg based on the input of a personnel member of the Flemish Auction	Polyethylene, high density, granulate {GLO}|market for polyethylene, high density, granulate|Cut-off, U (personal communication—Vlaamse Visveiling, 14/06/2023)
Ice-making	6.5 kg * day	According to FAO (1981a), a ratio of 3:1 of ice: fish is needed (3 kg) for the cooling on board. A 1:2 ice:fish ratio was considered for the mixing during the trip (0.5 kg). Finally, 30% of the total amount was added to account for possible heat losses (1.05 kg), resulting in 4.55 kg of ice for 3.5 days, and 6.5 kg of ice for 5 days	Operation, reefer, freezing {GLO}|market for operation, reefer, freezing|Cut-off, U
Transport	1.948 tkm	Calculated using the distance by road between the harbor of Vigo (Spain) and the harbor of Ostend (Belgium)	Transport, freight, lorry with reefer, cooling {GLO}|market for transport, freight, lorry with reefer, cooling|Cut-off, U
Diesel (example for the year 2020)	2.0 l × 10.74 kWh/l = 21.5 kWh	(Forest Research, 2025)	Diesel, burned in fishing vessel {GLO}| diesel, burned in fishing vessel|Cut-off, U
Lubricating oil (for the year 2020)	0.025 l × 0.88 $\frac{\text{kg}}{\text{l}}$ = 0.022 kg	(Oil Analysis Services, 2025)	Lubricating oil {RER}| lubricating oil production|Cut-off, U

a 40-year vessel lifespan. The catch is unloaded in Vigo (Spain) and then transported by truck to the Flemish auction in Belgium, representing a cradle-to-auction system boundary.

3.1 Absolute values and uncertainty analysis

Absolute values of the different impact indicators considered for the year 2020 are given as mean and median in Table 4. The uncertainty analysis for the year 2020 is presented in Table 4 as well.

The uncertainty results for 2020 include the mean, median, standard deviation (SD), the coefficient of variation (CV), 2.5th percentile, 97.5th percentile, and the standard error of the mean (SEM), providing a complete statistical overview of uncertainty. Uncertainty results for the remaining years are available in the supplementary material (Tables S4–S16). Overall, the SEM values are relatively small in comparison with the mean values, and hence, indicate that the mean was quite reliably estimated.

3.2 Interpretation of the impact categories

The year 2020 is discussed in detail for which the characterized values of the ICs are available in Table 5. These values are deterministic outputs from the LCIA phase, obtained by applying characterization factors to the inventory flows. They represent a single best estimate based on the input data and the selected impact assessment method. The contribution analysis (Figure 3) shows the processes that contribute the most to each IC.

Figure 3 (center) shows that fuel consumption is the main contributor to several ICs, with an impact ranging from 11% (RUM) to 98% (AC, EFT, and EFM). This indicates that efforts to reduce fuel consumption offer the greatest potential for improving environmental performance.

Maintenance (Figure 3, right) is found to contribute substantially to ICs. These include ECF (36%), EFF (37%), HTC (46%), HTNC (21%), IR (22%), RUM (45%), and WU (32%). Vessel construction contributed to ECF (15%), EFF (17%), HTC (19%), HTNC (12%), RUM (29%), and WU (10%) (Figure 3, left). Combined, construction and maintenance may account for up to 74% of the impacts (RUM).

A closer look at the construction phase (Figure 3, left) reveals that steel is the main contributor (12–92%), while copper cathode significantly affects AC, EFF, HTNC, and RUM, where it has a moderate to high contribution (28–66%). For the vessel maintenance (Figure 3, right), the environmental burden is more evenly distributed among key materials: copper cathode, netting, and steel for the vessel. Netting contributes significantly due to its frequent replacement, a consequence of the destructive nature of beam trawling, which accelerates wear and tear on gear components. The production of copper cathodes is particularly resource-intensive, making them a consistent contributor to multiple ICs.

Considering most ICs, the main source of variation arises from changes in fuel consumption per FU. The associated yearly SDs in fuel use are shown in Figure 4, as diesel remains one of the dominant contributors in 15 out of the 16 ICs. For the uncertainty analysis, we will focus on four ICs that are particularly relevant to marine fisheries (Table S1): AC, RUM, PM, and EFM. AC and PM are the ICs where fuel use is the dominant contributor, while RUM is driven mainly by construction and maintenance. EFM is included because it is directly linked to the marine environment under study. Between 2007 and 2020, a slight downward trend in overall environmental impacts is observed, although recent years seem to indicate an upward trend (Figure 5).

TABLE 4 Absolute values and uncertainty results for the different impact indicators for the year 2020, based on a Monte Carlo simulation with 10,000 iterations; the results are given for the study's FU.

Impact category 2020	Unit	Mean	Median	SD	CV	2.50%	97.5%	SEM
AC	mol H+ eq	0.235532289	0.2313812	0.04233824	17.97556	0.1659265	0.3294637	0.000423
CC	kg CO_2 eq	8.008375556	7.8469921	1.55896666	19.4667	5.4647113	11.561486	0.01559
ECF	CTUe	1.68E+01	1.66E+01	1.04E+02	617.2981	−1.93E+02	2.28E+02	1.04E+00
EFF	kg P eq	2.70E−04	2.44E−04	1.14E−04	42.06866	1.34E−04	5.57E−04	1.14E−06
EFM	kg N eq	5.76E−02	5.47E−02	1.85E−02	32.06087	2.98E−02	1.01E−01	1.85E−04
EFT	Mol N eq	0.630120616	0.5982077	0.20222406	32.09291	0.3260366	1.1061294	0.002022
HTC	CTUh	3.39E−08	3.40E−08	3.66E−08	107.942	−4.03E−08	1.08E−07	3.66E−10
HTNC	CTUh	8.97E−08	3.36E−08	7.75E−06	8646.267	−1.57E−05	1.56E−05	7.75E−08
IR	kBq U-235 eq	4.40E−02	3.16E−02	4.15E−02	94.17336	1.53E−02	1.51E−01	4.15E−04
LU	Pt	1.11E+01	1.07E+01	2.92E+00	26.34259	6.48E+00	1.79E+01	2.92E−02
OD	kg CFC11 eq	1.26E−07	1.21E−07	3.33E−08	26.45801	7.44E−08	2.03E−07	3.33E−10
PM	disease inc.	1.83025E−06	1.75E−06	4.312E−07	23.55969	1.237E−06	2.895E−06	4.31E−09
POF	kg NMVOC eq	0.173789862	0.1665146	0.04781473	27.51296	0.1011554	0.2862584	0.000478
RUF	MJ	106.5898128	102.78078	27.4033035	25.70912	63.908812	170.01389	0.274033
RUM	kg Sb eq	1.07E−05	1.06E−05	9.80E−07	9.151802	9.06E−06	1.29E−05	9.80E−09
WU	m3 depriv	0.42411233	2.9415175	28.327413	6679.224	−63.61226	49.695536	0.283274

4 Discussion

4.1 Alignment with previous research and relevance of trawler construction and maintenance

In 2020, the carbon footprint per kilogram of fish caught by a large Belgian beam trawler and landed in a Spanish harbour is 8.01 kg CO_2 eq/kg of fish. The carbon footprint of various wild caught fish species ranges from 5 to 20 kg CO_2 equivalents per kilogram of fish, herring representing the lower bound and sole ranking among the highest (Gephart et al., 2021). This reported range considers different fishing methods such as gill nets, bottom trawls, mid trawls, and traps. Consequently, the results of this study lie within the carbon footprint figures that were assessed for various seafood species.

The analysis also reveals that vessel construction and maintenance contribute minimally for most impact indicators, typically around 1% for AC, CC, PM, EFT, POF, and RUF. This finding aligns with standard LCA practice, where infrastructure is often excluded due to its (assumed) relatively minor influence. Hence, the results of this study support the validity of that approach for most ICs in fisheries. However, in WU, EFF, HTC/HTNC, ECF, IR, and RUM, vessel construction and maintenance showed a more notable influence (12–74%). These impacts are linked to the use of materials such as steel, copper, and the netting, which are energy-intensive to produce. Additionally, the extraction and refining processes are associated with the emission of toxic substances. This pattern is consistent with findings from the 16 previous LCA studies on purse seiners and trawlers that do consider construction and/or maintenance (Figure 1 and Table S1).

For instance, Hospido and Tyedmers (2005) confirm that fuel consumption is the dominant contributor to CC, OD, AC, and POF. Our results show that construction and maintenance significantly affect HTC, HTNC, and EFF. Similarly, Avadí et al. (2018) identify the steel of the hull as a key contributor to EFF, ECF, and WU, which aligns with our findings. Abdou et al. (2018), in their study on Tunisian trawlers, also report substantial contributions to ECF and the toxicity-related ICs. The selection of ICs varies across studies. For example, Ceballos-Santos et al. (2023) do not explain their choice of ICs, whereas Abdou et al. (2018) refer to using the most commonly applied ones (AC, CC, OD, HTC/HTNC, POF, LU). In contrast, Avadí et al. (2018) prioritize ICs that contribute most to the single environmental score, derived after normalization and weighting, but also consider those with lesser contributions. Overall, there is no clear consensus on the selection of ICs across the analyses.

Further confirmation comes from Ceballos-Santos et al. (2023), who found that maintenance was the top contributor to EFF in Spanish purse seiners, while construction was the main contributor to WU. The latter result mirrors our findings, where construction ranks third after diesel and maintenance in WU.

Other studies, including Vázquez-Rowe et al. (2010b, 2011a) and Driscoll et al. (2015) compared their findings with those of Hospido and Tyedmers (2005), while González-García et al. (2015) built upon the findings of Vázquez-Rowe et al. (2010a), collectively covering all known LCAs in fisheries where construction and/or maintenance were considered. Since this study develops an LCI in collaboration with industry stakeholders and bases its interpretation on the actual inventory outcomes rather than previous assumptions, it provides an updated perspective on the environmental profile of the vessel. This approach focuses on

TABLE 5 Environmental impact expressed as absolute values across all ICs for the year 2020, split according to the materials and phases considered in the system boundaries.

Impact category	Unit	Total	Fish box	Lubricating oil	Operation, reefer (ice-making)	Transport, refrigerated	Trawler maintenance	Trawler construction	Diesel
AC	mol H+ eq	0.23574517	9.15E−05	0.000151177	0.000432124	0.001401168	0.001175426	0.000511805	0.23198202
CC—total	kg CO_2 eq	8.01E+00	2.60E−02	3.61E−02	0.038217322	0.2789183	0.2294563	0.076772062	7.3287798
CC—biogenic	kg CO_2 eq	1.23E−03	1.20E−05	3.05E−05	5.72E−05	6.33E−05	0.000402353	0.000242379	0.000422669
CC—fossil	kg CO_2 eq	8.01E+00	2.60E−02	3.60E−02	0.038147407	0.27826868	0.22812685	0.076460273	7.327937
CC—land use and LU change	kg CO_2 eq	2.05E−03	1.37E−05	2.43E−05	1.27E−05	5.86E−04	9.27E−04	6.94E−05	0.000420066
ECF—part 1	CTUe	1.21E+01	5.94E−02	8.14E−02	0.071036813	1.173213	5.1884346	2.1416561	3.4295131
ECF—part 2	CTUe	4.23E+00	1.22E−01	8.54E−02	0.047698346	0.29833102	0.65689758	0.2701348	2.7510468
ECF—inorganics	CTUe	8.3645079	0.15599689	0.11654879	0.074368496	0.63552223	2.2138999	0.91867122	4.2495003
ECF—organics-p.1	CTUe	7.4416728	0.021171423	0.039376365	0.036497543	0.79239973	3.5919909	1.4815499	1.478687
ECF—organics-p.2	CTUe	5.70E−01	4.21E−03	1.10E−02	0.007869121	0.043622073	0.039441424	0.011569827	0.45237258
EFF	kg P eq	0.00027	5.19E−06	7.67E−06	2.80E−06	2.14E−05	1.01E−04	4.49E−05	8.68E−05
EFM	kg N eq	0.057792	1.86E−05	2.53E−05	1.90E−04	5.51E−04	2.19E−04	7.98E−05	0.056707954
EFT	mol N eq	6.32E−01	1.95E−04	2.63E−04	0.002076	0.005965	0.002246	0.000851	0.62065657
HTC	CTUh	3.38E−08	8.47E−11	1.67E−10	1.61E−10	1.46E−09	1.56E−08	6.57E−09	9.74E−09
HTC—inorganics	CTUh	4.48E−10	2.42E−12	4.57E−12	2.87E−12	1.98E−11	1.23E−10	5.96E−11	2.36E−10
HTC—organics	CTUh	3.33E−08	8.23E−11	1.63E−10	1.58E−10	1.44E−09	1.54E−08	6.51E−09	9.51E−09
HTNC	CTUh	2.91E−08	1.95E−10	3.87E−10	1.72E−10	2.78E−09	6.20E−09	3.50E−09	1.58E−08
HTNC—inorganics	CTUh	2.65E−08	1.77E−10	3.05E−10	1.60E−10	2.32E−09	5.89E−09	3.33E−09	1.43E−08
HTNC—organics	CTUh	2.60E−09	1.80E−11	8.19E−11	1.22E−11	4.61E−10	3.11E−10	1.74E−10	1.54E−09
IR	kBq U-235 eq	0.044071	0.00105	0.003291	0.000366	0.003511	0.009744	0.002961	0.023147897
LU	Pt	11.07413	0.073863	0.134616	0.045052	3.122791	1.213692	0.449385	6.0347349
OD	kg CFC11 eq	1.25E−07	7.77E−10	1.99E−09	1.14E−09	4.70E−09	2.34E−09	4.42E−10	1.14E−07
PM	disease inc.	1.83E−06	9.79E−10	1.43E−09	1.00E−09	2.75E−08	1.83E−08	7.15E−09	1.77E−06
POF	kg NMVOC eq	0.174166	0.000122	0.000698	0.000583	0.001999	0.000892	0.00029	0.16958296
RUF	MJ	105.8344	0.67944	1.41169	0.472979	3.972429	3.095225	0.815757	95.386878
RUM	kg Sb eq	1.07E−05	1.85E−07	3.14E−07	2.13E−07	8.59E−07	4.81E−06	3.15E−06	1.18E−06
WU	m3 depriv.	0.261408	0.007405	0.008572	0.001719	0.018949	0.084593	0.025285	0.1148856

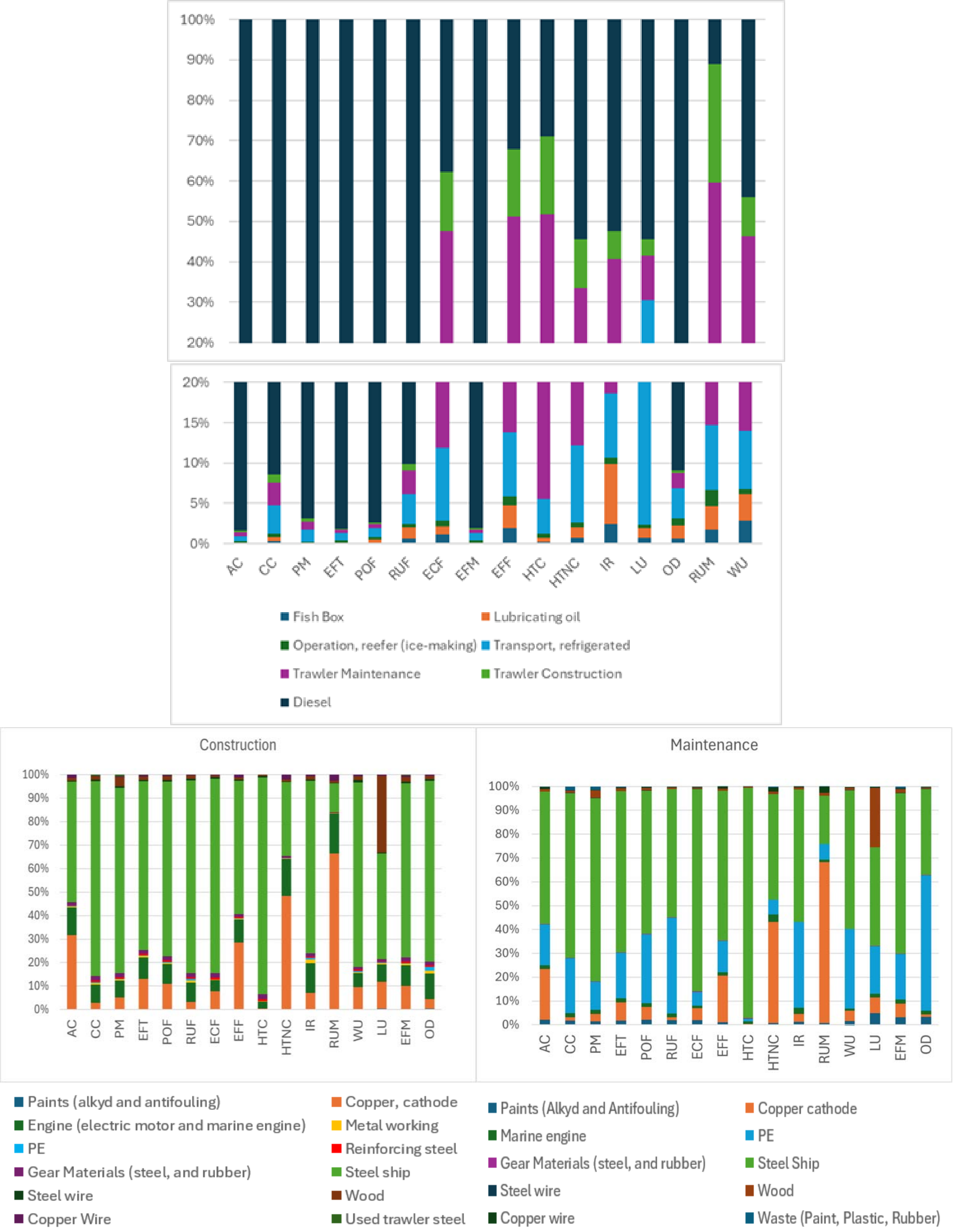

FIGURE 3
Center: contribution analysis of the environmental impacts of one kilogram of wild caught fish with a large beam trawler in the Belgian fishing grounds near Vigo (Spain), for the year 2020, including trawler construction (light green) and maintenance (purple); and with detailed view on construction inventory elements **(bottom left)** and maintenance (bottom right). The legend has to be read from the left to the right starting from the complete first line to the complete last line and indicates the processes from bottom to top in each bar.

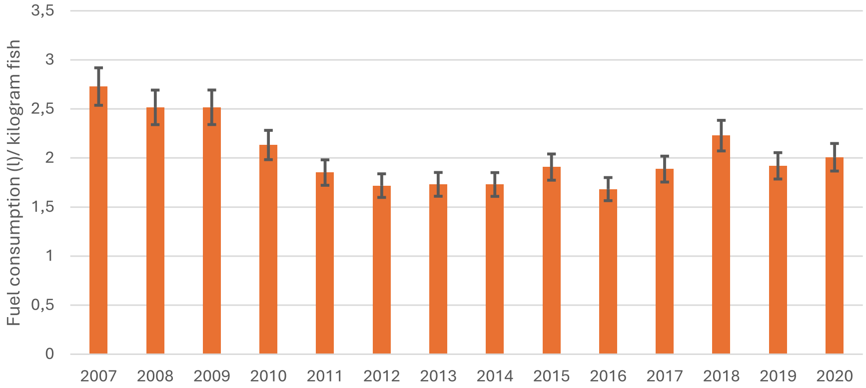

FIGURE 4
Fuel consumption values and associated SD per FU based on the fuel consumption figures from 2007 to 2020.

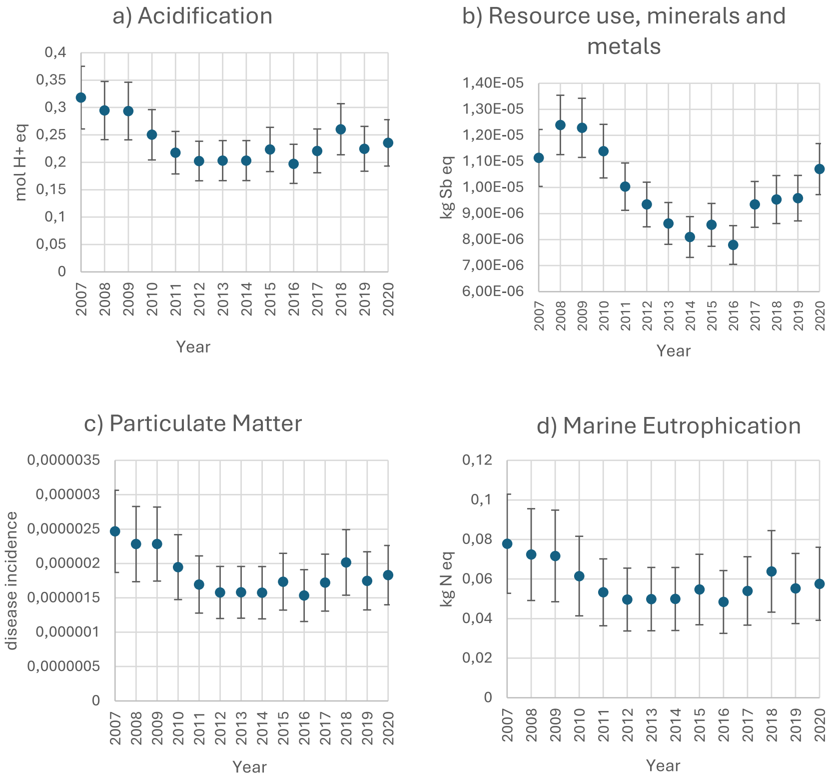

FIGURE 5
Mean values of acidification **(a)**, resource use, minerals and metals **(b)**, particulate matter **(c)**, and marine eutrophication **(d)** impact categories considering 14 years with the SDs derived from the Monte Carlo analysis with 10,000 iterations.

Belgium, a country that has not previously been the subject of fisheries-related LCAs.

4.2 Importance of fuel consumption

Previous research has identified beam trawling as the fishing method with the highest carbon footprint (Koričan et al., 2022; Quemper et al., 2024). Beyond the method itself, several factors such as fisheries management practices and crew expertise also significantly influence diesel consumption (Vázquez-Rowe and Tyedmers, 2013). Given that beam trawling is expected to remain in use, it is essential to explore more sustainable alternatives, both in terms of fuel efficiency and reduced seabed impact.

Impact mitigation strategies exist in fuel use. Fuel could be replaced with more environmentally friendly alternatives, such as biodiesel and Liquified Natural Gas (LNG). Recently, the CORDIS project demonstrated that optimizing the use of ice-making machines on small to medium-sized vessels by reusing waste heat generated during vessel maneuvering can save diesel and produce ice based on recycled heat, thereby reducing the environmental impact (European Commission, 2024). Simultaneously, other technological innovations, such as the Sumwing and the use of biofuels (HfK Engineering BV, 2010; Caslake, 2021; Koričan et al., 2022; Matthys et al., 2024), also show potential to achieve fuel savings and warrant further investigation.

Such alternatives can pave the way towards improving the sustainability of the fisheries sector.

4.3 The Belgian beam trawler and its relevance for other fisheries activities

Due to the long lifespan of beam trawlers, construction and maintenance are either omitted or only partially considered in existing LCA studies (Ruiz-Salmón et al., 2021). Our findings support this practice, as the environmental impact of these phases is relatively minor compared to other operational emissions. While construction materials vary by region, Belgian and French trawlers use more steel, whereas Sicilian and Tunisian vessels incorporate more wood, its environmental impact is largely driven by steel, copper cathodes, and netting. Hence, these components should be prioritized when aiming to reduce the environmental footprint over a vessel's lifetime. This interpretation only holds when the fuel efficiency is maintained as not replacing steel might decrease this efficiency because of increased drag caused by organisms, rust or corrosion, meaning proper maintenance is of real importance. This could be an interesting trade-off to be considered for future research.

Worldwide, most vessels have a LOA (Length Over All) below 24 m, yet they account for a third of the world's engine power (FAO, 2024). Over time, vessel length and engine power have increased. According to Steadman et al. (2021), 26% of the world's catch is retrieved through beam trawling, with China accounting for 15% of this catch. Studying large trawlers, like the one considered in this study (Z47) offers insights into the upper segment of the global fleet, particularly relevant to Europe and North America as LOAs and engine capacity increase over time. Given these insights, the Belgian beam trawler can serve as a representative model for similar vessels worldwide.

Our results support the broader applicability of omitting construction and maintenance phases in LCA studies for large trawlers. Beam trawling also shares operational characteristics with other trawling methods, such as otter, shrimp, and prawn trawling, all of which involve seabed contact and high fuel consumption. Therefore, the omission of construction and maintenance in LCA studies may be justified for these methods as well.

Conversely, coastal fisheries differ significantly. These vessels operate in shallower waters and employ different techniques such as hook-and-line, net fishing, or passive gear, which involve minimal movement and lower fuel use. For these fisheries, the environmental impact of vessel construction and maintenance may be more significant and warrants further investigation.

4.4 Limitations

This study sheds light on the influence of vessel construction and maintenance on the environmental impacts of wild-caught fish sourced from large beam trawlers in Belgian fishing grounds. Nonetheless, it is bound to several methodological limitations. First, when primary data on input processes were unavailable, we relied on ecoinvent values and adapted them using the LSW of the considered vessel type to approximate a Belgian perspective. Using a best-estimate approach helps address data gaps, albeit at the potential cost of geographical representativeness. Nonetheless, the consistency of the outcomes with seafood LCAs (see Section 4.1) supports the conclusions of this study.

Second, similar to most studies listed in Table S1, this analysis adopts a cradle-to-gate perspective, meaning that subsequent supply chains up to fish consumption are not included. Extending the system boundaries to the consumer will likely lower the contribution of vessel construction and maintenance, given that impacts will be distributed to downstream processes to a certain extent. However, we do not expect significant changes in the overall results, as a previous seafood LCA that applied a cradle-to-consumer approach concludes that impacts are primarily attributed to the fishing stage rather than subsequent processing stages (van Putten et al., 2016). Additionally, it would be valuable to consider a nutritional FU as an alternative to conventional mass-based FU, offering a different perspective on the influence of construction and maintenance on the impact assessment results.

Finally, while this study captures environmental impacts, its environmental impact coverage is limited to the chosen impact assessment method. Importantly, it does not include biodiversity-related indicators. Currently, none of the impact assessment methods fully capture the multi-dimensional issues related to biodiversity, including biodiversity pressures, ecosystems, taxonomic groups, and essential biodiversity variable classes (Damiani et al., 2023). In this study, biodiversity-related impacts are particularly relevant for beam trawling, which disturbs the seabed and affects benthic biodiversity, an aspect that would be valuable to address in future research. The work of Woods and Verones (2019) on capturing ecosystem degradation from human-induced seabed disturbance constitutes a promising approach for future seafood LCA studies.

5 Conclusions

This study concludes that, due to long operational lifespan and dominant fuel consumption of Belgian beam trawlers, the environmental contributions of vessel construction and maintenance are minimal and can be reasonably omitted from LCAs when focusing on these impact indicators: AC, CC, PM, POF, EFT, RUF, EFM, IR, and LU. However, for a more comprehensive evaluation of the environmental footprint of fisheries, it remains advisable to include as many relevant factors as feasible within the constraints of the study timeline, considering that the data inventory phase is often the most resource-intensive component of an LCA. Nevertheless, construction and maintenance do appear to be contributing to different ICs: EFF, HTC, HTNC, RUM, and WU.

When full inclusion of construction and maintenance data is not feasible, collecting representative data of key materials, such as steel, copper cathode, and netting, can offer a reasonable approximation of their environmental impact. As this study demonstrates, these materials are among the primary contributors from construction and maintenance, representing up to 74% of contribution to various impact indicators.

The findings suggest that the exclusion of construction and maintenance may be justifiable not only for Belgian beam trawling but potentially for other trawling-based methods as well. Nonetheless, further research is needed to assess the relevance of these processes in other types of fisheries, where vessel design, gear configuration, and operational patterns may differ significantly.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SM: Writing – original draft, Formal analysis, Writing – review & editing, Data curation, Conceptualization. JD: Supervision, Writing – original draft, Writing – review & editing. AG: Conceptualization, Writing – review & editing, Funding acquisition, Resources, Supervision, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2025.1734805/full#supplementary-material

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