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Keeping the World Afloat

A Prospective LCA of Modular Floating Structure Substructures

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Preface

As I come to the end of this thesis I also come to the end of a chapter of my life. An end of formal education and, for me, an end of juvenility. This journey has been long and often obscure but has nonetheless brought me to a place where I am quite satisfied with my progress at a wholistic level. The list of names I am thankful of for this progress is innumerable and better placed elsewhere. However, the people who have edged me to the finish line of this academic milestone do deserve their thanks. To this end I extend my deepest gratitude to my supervisors Dr. Tomer Fishman, Dr. Gil Wang, and Dr. Benjamin Sprecher. To Tomer and Gil I want to say a special thanks for the time and patience you have afforded me all along. Every step of the way giving me advice, recommendations, and reality checks with smiles on your faces. To Tomer, your approach as supervisor was much appreciated, the perfect blend of softness and firmness to keep me on track while always remaining congenial. To Gil I want to also say thanks for taking the time out your own busy personal schedule and for the invaluable lesson of the role of passion in conducting and completing work. To Benjamin I want to say thank you for your honesty and for being another friendly face I can associate with this journey. Finally, I would like to give thanks to the universe and god for guiding me to this point.

Mo Bei Du
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Abstract

40% of the global population live in coastal cities. This figure is predicted to increase as inland populations migrate to coastal areas. This is due to land availability steadily decreasing due to several factors such as drought and increasing requisite cropland stemming from growing populations and the growth of the biofuels market. Simultaneously, sea level rise (SLR) means that further strain will be put on land availability in coastal areas. It is important to have solutions prepared for this event. One such potential solution is the use of Modular Floating Structures (MFS) as dynamic platforms for floating urbanisations. An MFS consists of a floating substructure on top of which a superstructure (buildings) can be built. While MFS technology is not currently used anywhere in the world the technical feasibility and use case potential of MFS has been demonstrated in previous research. However the environmental impacts of MFS technology had previously not been investigated. A prospective life cycle assessment (LCA) of potential MFS substructure designs was devised in order to quantify and compare the potential environmental impacts and to find potential for optimisation of the environmental performance of the substructures.

A case study of Taranto, Italy, a city which has the potential for using MFS technology was taken for this research. In the baseline case it was assumed that the substructures would have to travel 1898 km across the sea throughout their lifetime. All cradle-to-grave life cycle inputs were included, excepting cut-offs. Only two main materials were considered suitable for use in substructure construction: steel and reinforced-concrete. However four designs were deployed. Virgin steel (VS), recycled steel (RS), 35 MPa Portland concrete (35 PC) and 50 MPa Portland concrete (50 PC). The concrete designs did not have equivalent buoyancy to the steel designs given the default geometric dimensions so these dimensions were altered considering several factors (bending moment, stress, second moments of area, draft).

A holistic approach was taken and all impact categories were considered, however particular attention was given to the impact categories of climate change and marine ecotoxicity. For all designs the raw materials used and the transport across the ocean held the greatest share of the impacts. In the concrete designs a surprising finding was that the stainless steel rebars used in their design held a larger share of the impacts across the board. The *50 PC design* performed by far the best overall however due to issues with working with concrete of higher strengths it is unclear if the 50 MPa Portland concrete can be easily applied to MFS substructure construction in the present day. In terms of present-day usability and environmental performance the two forerunning designs were the *RS design* and the *35 PC design*. Trade-offs were found between design choices. The *RS design* had significantly lower CO_2-Eq emissions with 7,292 t compared to the 35 MPa concrete design, which had 9,770 t CO_2-Eq. However, the 35 MPa design had much lower marine ecotoxicity with 984 t DCB-Eq, than the *RS design* 4,256 t DCB-Eq. This higher marine ecotoxicity for the *RS design* was largely (63%) due to the local environmental impact of sacrificial zinc anodes corroding into the sea. These are used as cathodic protection for the steel. Altering the cathodic protection is a possibility for reducing the marine ecotoxicity impacts of the steel designs.

Normalisation and even weighting were applied to compare the overall impacts of the designs. When total oceanic transport distance of the substructures is 482 km, in terms of overall environmental impacts the *35 PC design* outperforms the *RS design* by 22%. At 1898 km this decreases to 3%. At longer distances the *RS design* performs better due to its lighter mass and subsequent lower impacts from oceanic transport. At 2467 km the *RS design* outperforms the *35 PC design* by 2%.

In the context of the EU, the legislation surrounding deconstruction of end of life (EoL) ships and offshore installations is a key factor to consider. For offshore instalments which are to be recycled, the deconstruction can only take place in a limited number of shipbreaking yards. This directly affects the distance which the substructures must travel across the sea. And this is a main influencing factor which can lead to MFS substructure optimisation, in terms of environmental impacts.

Finally, environmental impacts are not the only considerations important to design choice. Other factors should be considered, namely the material availability in a given region and the disparity in recyclability between steel and concrete. Further research can develop these findings and investigate other highlighted potential concrete reinforcement material options such as epoxy coated steel and plastic fibre reinforcements. Furthermore, this research can be used as a building block for comparing the environmental impacts of MFS technology to coastal urban expansion alternatives such as land reclamation.

Key words: sea level rise (SLR), life cycle assessment (LCA), climate change, marine ecotoxicity, oceanic transport distance

Contents

List of figures

List of tables

Nomenclature

CO_2	Carbon dioxide
DCB	Dichlorobenzene
EoL	End of Life
EC	European Commission
EF	Environmental footprint
EU	European Union
FU	Functional unit
ISO	International Organisation for Standardisation
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MFS	Modular Floating Structure
NMVOC	Non-methane volatile organic compound
OECD	Organisation for Economic Co-operation and Development
OSPAR	(The Convention for the) Protection of the Marine Environment of the North-East Atlantic
PC	Portland concrete
PEFCR	Product Environmental Footprint Category Rules
RQ	Research question
RS	Recycled steel
SLR	Sea level rise
VLFS	Very large floating structure
VOC	Volatile organic compound
VS	Virgin steel

1 Introduction

1.1 Problem statement

40% of the current global population live in coastal cities (Swapna et al., 2020; Wang et al., 2020). As migration towards coastal areas continues to increase (McMichael et al., 2020) it causes strain on housing availability within these regions. It is estimated that by 2050 50% of the global population will live within 100km of the coast (Roeffen et al., 2013). The migration from inland areas to coastal areas is driven by increased land scarcity. The growing need for cropland due to population increases and the expansion of the biofuel industry (Roeffen et al., 2013) coupled with land degradation and the expansion of drylands driven by climate change, especially in the global south, are major factors (Hermanns & Lemans, 2021). The increase in coastal populations leads to urban expansion in these areas. At the same time, global sea-level rise (SLR) is predicted to significantly disrupt coastal areas (Church et al., 2013). It is estimated that up to 1.4 billion people are at risk of displacement due to SLR (Hauer et al., 2020; McMichael et al., 2020). Even if high carbon emission reductions are achieved SLR is underway and will impact coastal cities (Hauer et al., 2020).

1.2 Proposed Solutions

To address the need for suitable living spaces urban densification and expansion into floodplains have been suggested (Roeffen et al., 2013). Floating urban developments are another proposed solution to help alleviate the strain on land availability (Wang et al., 2019). Currently this technology is conceptual and no example of a floating urbanisation exists. However smaller scale developments exist in protected/harboured areas e.g. a floating housing community exists in Amsterdam, the Netherlands (Yang et al., 2022). Additionally, alternative technologies urban expansion into the sea exist. These include land reclamation and very large floating structures (VLFS) (Wang et al., 2019).

Land reclamation

Land reclamation involves creating new land where a body of water lies. This can be done by pumping out the water or by using a filler material (Wang et al., 2019). This latter method causes disruption of the local natural habitat and is not economically viable beyond seabed depths of twenty metres (Wang et al., 2006). It is also not technically viable if the seabed is too soft (Bo et al., 2012). Additionally the filler material used (sediment consisting of sand, gravel, clay and bedrock) is becoming increasingly scarce (Wang et al., 2019).

Very large floating structures

Very large floating structures (VLFS) are man-made structures which can theoretically be used as artificial surfaces to fulfil urban functions (Wang et al., 2006). The use of VLFS entails some significant issues, namely: transportation of the VLFS, and complexity of manufacturing (Wang et al., 2019). The layout of VLFS is dictated by its functional use and operational environment therefore VLFS do not have the flexibility to alter use throughout the course of their lifetime (Wang et al., 2019).

Modular Floating Structures

Wang et al. (2019; 2020; 2023) have done extensive research developing the concept of modular floating structures (MFS). MFS are to be potentially used as a sustainable alternative to current coastal urban expansion practices. An MFS consists of several smaller modules. Each module has a substructure (barge) forming the base of the MFS and superstructures (buildings) atop. The modular design of MFS allows for dynamic spatial expansion and rearrangement and MFS can, theoretically, act as a platform for any urban function.

1.3 Knowledge gap and Relevance

As mentioned, floating urbanisations are touted as a sustainable, climate-adaptive solution to the societal need for urban expansion while considering the diminishing availability of land. There is an abundance of literature concerning floating urbanisations (e.g. Bhat, 2020; Umar, 2020; Yang et al., 2022) but the majority tends to be quite general and investigates floating urbanisations at a conceptual rather than practical level. However more specific research has shown the technical feasibility (Wang et al., 2019; Wang et al., 2020; Wang et al., 2023) and the technical potential (Bikker, 2023) of MFS technology. Prior to this research a knowledge gap existed regarding the quantifications of the environmental impacts of floating urbanisations. Only research concerning vaguely comparable large-scale structures such as ships or concrete based buildings (Kameyama et al., 2007; Florin-Nicolae et al., 2014; Goldstein & Rasmussen, 2018) had been done. Due to the broad scope of accounting for the environmental impacts of an entire (floating) city the current research focussed on MFS technology, specifically MFS substructures. The sustainability of the design using various suitable construction materials needed to be assessed. This is important because the MFS urbanisations would, in theory, have the same superstructure designs while the substructures can differ. The substructure systems are quite simple themselves but it is nonetheless important to investigate their environmental impacts and see how these can be reduced. MFS has a technical potential to accommodate 1.6 billion people (Bikker, 2023). If MFS technology is used for even a fraction of its potential reducing the environmental impact of the MFS design by even a marginal amount, on the individual substructure level, could lead to the avoidance of significant environmental pressures when upscaled. The relevance of this lies in the fact that earth is under unsustainable pressure from human induced activities (namely extraction of resources and emissions to air, soil, and water) and this may lead to catastrophic consequences (Rockström et al., 2009; Richardson et al., 2023).

Additionally, it is important to highlight potential alterations *early* in the design process so that changes can be implemented without major disruptions thus avoiding the misuse of resources such as time, capital, and/or materials (Cucurachi et al., 2018). The quantification of the environmental impacts of the substructures is furthermore important because it provides a starting point for comparing the environmental performance of MFS technology to other urban expansion alternatives. The value of this is so that it can be ascertained early on whether or not MFS technology is, environmentally, a preferable solution to the urban expansion alternatives.

Finally, Industrial Ecology aims to study the interactions between economy, society and the natural environment and offer solutions to advancing all three simultaneously (Graedel, 1996). This thesis aims to lower potential pressures on the natural environment while contributing towards an economic solution for a looming societal problem. Therefore, it is relevant to the field of Industrial Ecology.

1.4 Research questions

The main research objective of the current study was to investigate the environmental impacts of MFS substructures from a holistic standpoint accounting for a complete range of environmental impacts. This study also aimed see how the design of MFS substructures could be altered, based on material use and geometric properties, and how this would affect environmental performance. To achieve this the following research question (RQ) has been formulated:

How can the design of MFS substructures be improved in terms of environmental performance?

A further three sub research questions (SRQ) were devised to answer this RQ:

SRQ1: What materials are suitable for the construction of MFS substructures and how does this affect substructure design?

SRQ2: What are the environmental outcomes of the various MFS substructure designs?

SRQ3: Where can environmental impacts be reduced in the life cycle of MFS substructures? (Hotspot analysis)

1.5 Report structure

The next section presents a review of the relevant state of the art scientific literature. Subsequently, in section 3, the research approach devised to answer the research question (and sub-research questions) proposed above is discussed in depth. The main research tool used is life cycle assessment (LCA). Thus from section 5 onwards the report is structured in line with an LCA study as stipulated by ISO 14044:2006. The results of the LCA are presented in section 7, by which stage SRQ 1-3 are answered. Sensitivity analyses is provided in section 9. And an interpretation of these results is presented in section 10. Limitations and conclusions of the research can be found in sections 11 and 12, respectively.

2 Literature Review

2.1 Floating urbanisations

MFS

2.1.1.1 Design & feasibility

Previous research has demonstrated the proof of technology of MFS (Wang et al., 2019; Wang et al., 2020; Wang et al., 2023). An MFS consists of two main parts: the substructure (the barge/floating platform); and the superstructure (the buildings atop the barge). The substructure can be seen as the platform/foundation of the built environment (see below for definition of built environment).- An MFS urbanisation consists of several modules. The proposed module design, Module9000, consists of three parts: the continuous structure; side structure; and watertight bulkheads. Wang et al. (2019) determined geometric dimensions for Module9000, these can be seen in *table 1*. These dimensions were chosen in the range of conventional ships and barges so that the design can be executed using existing technologies and shipyards (Wang et al., 2019). Module 9000 can be seen in *Figure 1.*

Main particulars.

Length	L	100.0	[m]	Metacentric radius	BMT	14.70	[m]
Beam	B	30.0	[m]	Center of buoyancy	KB	2.55	[m]
Depth	D	8.1	[m]	Center of gravity	KG	16.74	[m]
Design Draft	T	5.1	[m]	Metacentric height	GMT	0.56	[m]
Displacement	Δ	15,688	[ton]	Block coefficient	Cb	1.00	[-]

Table 1. Main particulars of Module9000 (source: Wang et al., 2019).

Wang et al. (2019) concluded that an individual Module 9000 cannot deliver occupant comfort or ‘fundamental seakeeping qualities required for offshore dwelling’. Therefore a twin hull design was proposed to tackle the issue of occupant comfort. This consists of two Module 9000s (mono-hull) being conjoined rigidly in a catamaran-like configuration with a distance of 15 m between hulls.

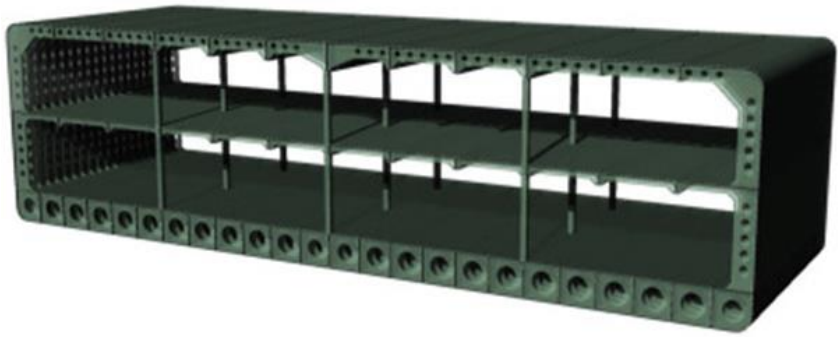


Figure 1. Module9000 typical structure 3-D representation (continuous and side structure) (source: Wang et al., 2019).

2.1.1.2 Effect on local environment

Throughout the literature there are some concerns of how floating structures could affect the local marine habitat. However de Lima et al. (2015) found evidence that underwater life can continue in the presence of floating structures and not be negatively affected by them. De Lima et al even found that floating houses offer a new substrate for vegetation and organisms to attach to while also providing shelter for fish.

2.1.1.3 Regulatory concerns

Specific regulation and policy may be needed to address MFS. However, there is a large body of existing regulation surrounding offshore installations in EU seas. The OSPAR convention (1992) provides regulation specifically for the north east Atlantic while the Barcelona convention (1976, amended 1995) provides regulation specifically for the Mediterranean. Additionally there are several EU mandates relevant to offshore installations. The classification of MFS and the effect of this in end of life (EoL) is a concern for the research at hand. MFS being classified as a ship dictates the possible locations for EoL processing within an EU context. Under current EU waste shipment law, shipments of hazardous waste and waste destined for disposal are prohibited to non-OECD countries outside the EU (Regulation 1013/2006, EUR-Lex). Furthermore, ship recycling is limited to selected yards EU (Regulation 1257/2013, EUR-Lex). This regulation is relevant to offshore installations when they are to be recycled. However these EoL regulations are circumvented in traditional ship ownership by registering ship ownership under non-EU nations (Wan et al., 2021).

2.2 Suitable materials for substructure construction

The only materials which were found to be both technically and economically feasible were (a) steel and (b) reinforced concrete.

2.2.1.1 Steel

Steel is a staple of modern day maritime engineering. It is used for various applications: ships; off-shore wind turbines; oil rig frames, and other off-shore structures (Roelofs, 2020; Garcia-Teruel, et al., 2022). Steel based ships need to be supplemented by anti-corrosion protection and this is achieved using protective coatings and cathodic protection (see Appendix B). Sacrificial zinc anodes are commonly used for cathodic protection used in modern day shipbuilding (Rees et al., 2020). The American Bureau of Shipping (ABS) provides standardisation for steel used in shipbuilding. For ordinary-strength structural steel a minimum specified yield strength of 34 ksi (235 MPa) is required (Svenskt Stål AB, 2024). Yield strength is the maximum stress the material can be put under before it is bent permanently out of place, unable to return to its original shape.

2.2.1.2 Concrete

Concrete is commonly used in marine and aquatic environments, e.g. for docks, piers, LNG terminals (Pratiwi et al., 2021). Caissons are another marine structure most commonly made with concrete, steel, or steel-reinforced concrete (Tanimoto & Takahashi, 1994). The Progresso Pier in Mexico is an example of a long-lasting stainless steel reinforced concrete structure. This pier was constructed in the 1940's and has been in service for over 70 years with no major maintenance or repair required (Rabi et al., 2022). It should be noted that concrete used in marine construction should have a compressive strength ≥5000 psi (34.5 MPa) and Portland cement-based-concrete is most commonly used in the marine environment (Thomas, 2016).

Unlike steel, concrete cannot bend, instead, beyond certain stress it simply breaks. See *figure 2* below for an illustration of the response of steel and concrete to stress.

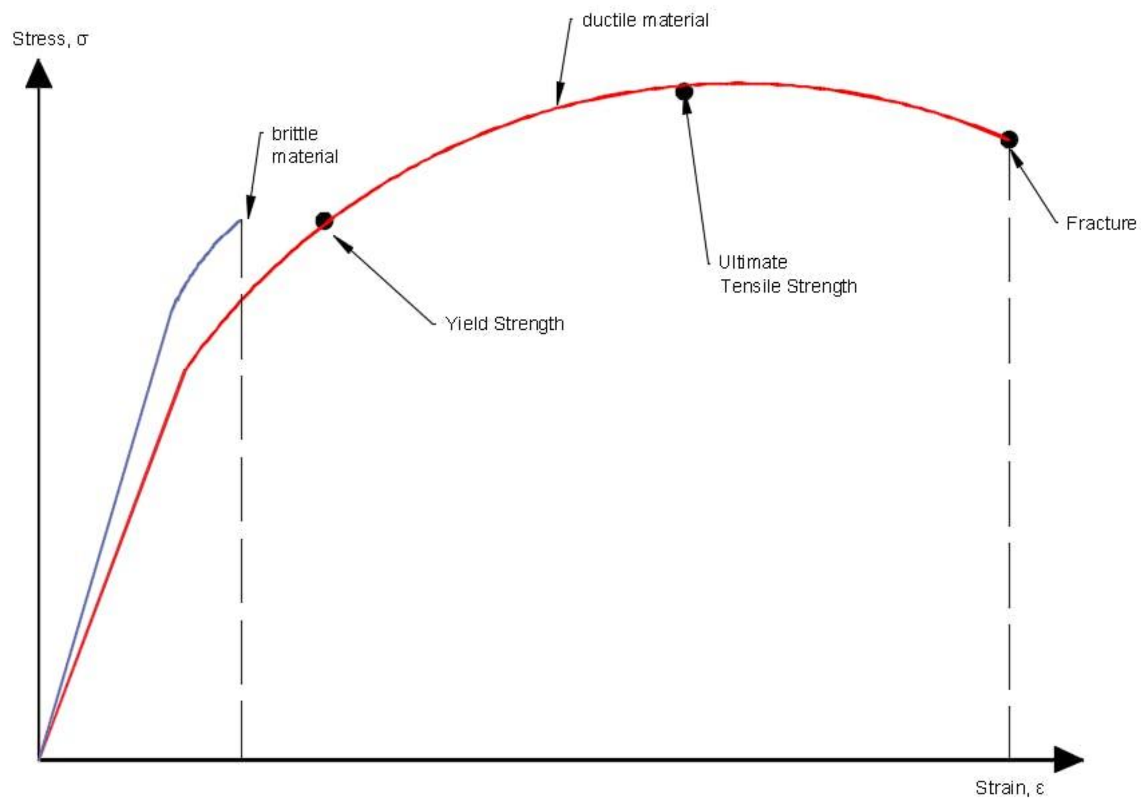


Figure 2. Graphic representation of brittle and ductile material. The blue line is representative of brittle materials which cannot bend and only break beyond a certain amount of strain, e.g. concrete. the red is representative of ductile materials which will be (source: www.CivilsGuide.com, 2024).

The marine environment is highly aggressive towards concrete and its reinforcement due to the salinity of the water (Pratiwi, 2021; Brueckner et al., 2022). The saltwater causes deterioration due to chemical attack. This comes in three forms: sulphate-attack, carbonation, and chloride-induced corrosion of reinforcement (Pratiwi, 2021; Brueckner et al., 2022). Concrete's chemical resistance is determined by its chemical composition and porosity (Pratiwi, 2021). Concrete is also susceptible to weathering due to physical and mechanical factors, freeze-thaw cycles and erosion/abrasion, respectively and structural overloading of the concrete also contributes to failure (Pratiwi, 2021). The longevity of a concrete structure in a marine environment depends upon several factors such as geometry, material composition, and curing of the concrete (Pratiwi et al., 2021). The most common cause of degradation (70-90%) in marine concrete applications is corrosion of reinforcement steel (Angst, 2018). In harsh environments (e.g., severe marine environments), steel corrosion can commence within a few years (>2 years, <5 years) of exposure even in apparently high-quality concrete with substantial cover to the rebars (Tierney & Safuiddin, 2022). However sufficient cover depth and stainless steel rebars can protect against this corrosion (Mistry et al., 2016; Rabi et al., 2022).

According to Polder et al. (2012) protection at the inception of the concrete is the best method of ensuring longevity because corrosion-induced repairs, of reinforced concrete structures in marine environments, have low success rates and do not last long even when initially successful.

2.3 LCA

LCA is an iterative modelling approach. According to the International Organisation for Standardisation (ISO 14044:2006) LCA is the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle". It can be used to estimate the environmental burden of product systems/product service systems at all stages throughout their life cycles (EC-JRC, 2010) and it is a key tool used in the field of Industrial Ecology. LCA is, for the most part, quantitative in character, but when this is not possible qualitative aspects can, and should, be accounted for (Guinée, 2002). LCA aims to be scientific however technical assumptions are unavoidable. This can best be remedied by transparency of assumption choices (Guinée, 2002).

2.3.1 LCA of buildings and the built environment

Definitions of the built environment are not wholly consistent throughout the literature. Goldstein & Rasmussen (2018) define the built environment as a collection of autonomous buildings and the underlying infrastructure and human activity between these buildings; Lotteau et al. (2015) define it as all man-made structures, infrastructure and transportation systems (in a defined area).

LCA for individual buildings differ slightly in methodology from that of LCA for built environment. For instance building LCA tends to focus on the entire cradle-to-grave life cycle of the building while built environment LCA take a snapshot of the material, energy and waste inputs and outputs, of the system studied, over a short period, often a calendar year (Goldstein & Rasmussen, 2018). In the case of LCA of individual buildings it should be noted that practitioners often don’t estimate actual lifespan but instead apply default values (Goldstein & Rasmussen, 2018; Ji et al., 2021). These estimations vary from 40-150 years (Ji et al., 2021) with 50-80 years being habitually used even though the physical structure of an average building has the potential to last longer (Goldstein & Rasmussen, 2018). LCA of other long lasting structures include, but are not limited to: roads (Birgisdottir et al., 2006), railway bridges (Du & Karoumi, 2013), and insulation materials used in buildings (Llantoy et al., 2020).

In LCA of older buildings the operational phase has typically contributed greatly to life cycle impacts but with modern energy efficient designs the greatest portion of life cycle impacts of buildings tend to be found in the embodied impacts (the impacts associated with the procuring, transporting and processing of the raw materials (Goldstein & Rasmussen, 2018)).

2.3.2 LCA of ships

Steel production accounts for the majority of environmental impacts associated with shipbuilding, 75%, followed by shipbuilding itself, 12%, and other materials, 9%. Regarding the ships overall environmental impacts the operational phase (25 year lifecycle) carries the brunt (98.3%)(Kameyama et al., 2007). Fuel usage and ship maintenance are the main contributors to the operational phase environmental impacts of ships (Kameyama et al., 2007). Ship maintenance includes: sandblasting (to remove old paint coats)(Dong & Cai, 2020), repainting (to ensure adequate protection from corrosion)(Wang et al., 2018), replacement of sacrificial anodes (to ensure cathodic protection and prevent corrosion)(Sagüés & Powers, 1998), and steel replacement, 14.91%, (Dong & Cai, 2020). Ship maintenance is performed frequently due to the wear and tear from constant movement and rough sea conditions. A general survey and maintenance is mandatory every 5 years (International Marine Organisation, 2014) however throughout the literature there are various recommendations for optimal frequency of maintenance which are specific to the type of maintenance required e.g. replacement of steel, repainting etc. (Tribou & Swain, 2017; Wang et. al., 2018).

A further source of relevant environmental impacts, especially ecotoxicity and eutrophication, arising from ship operation come from the emissions of substances into the air and the marine environment. This is mainly due to paint coats (in particular antifouling) and sacrificial anodes. Antifouling coats are highly toxic and are regularly applied to ensure that ships do not have marine organisms attached to hulls which greatly increases friction with water and therefore increases fuel consumption (Sagüés & Powers, 1998; Kameyama et al., 2007; Cucinotta et al., 2021). Antifouling and other paint coats also have significant volatile organic compound (VOC) emissions (Cucinotta et al., 2021).

3 Research approach

The primary research approach to answer the research questions proposed in section 1.4 was LCA. The methodology is described in depth in section 3.1. To conduct this LCA extensive desk research was conducted to. This was streamlined using the search engines such as Google Scholar (Google) and Web of Science (Clarivate). The artificial intelligence (AI) tool ChatGPT (OpenAI) was also used to streamline the desk research by providing specific academic sources. Step-by-step the sub research questions were answered by:

SRQ1

Literature review and the expertise of Dr Gil Wang was used to identify suitable construction materials for MFS superstructures. Materials were considered technically suitable if they have proven longevity in marine environments and pertain the physical properties needed to support the superstructures. Materials also had to be economically viable. Material properties had a direct impact on the substructure designs and calculations (see Appendix A) were performed to test these designs and estimate material requirements.

SRQ2

This SRQ was answered during the LCIA phase of the LCA from the results garnered from the LCA model which was built using desk research and the expertise of Dr Gil Wang for input of the life cycle processes which are necessary in the MFS substructure's life cycle.

SRQ3

Contribution analysis highlighted hotspots (activities which contribute heavily to environmental impacts) in a product system's life cycle. This provided insight into where the impacts are focussed. Thus it highlighted where changes in the design can have the greatest chance of reducing impacts. Sensitivity was also used here to estimate the potential for reduction of environmental impacts.

3.1 LCA

The objective of the current project was to investigate the future potential environmental impacts of MFS substructures, a technology which has a low-mid technology readiness level (TRL). In accordance with the definitions provided by Guinee (2002) this study is a detailed LCA. The product systems and their integrant flows are explored, analysed and reported in depth. LCA was suitable as it allows for the quantification of the environmental burdens of a product system throughout its lifecycle (see section 2.2). Prospective LCA in particular was suitable because the product-system being studied, MFS, does not currently exist.

LCA results are the product of assumptions. Where there is no data available assumptions can be made in order to complete the model. These assumptions should justified to the best of the researcher's ability. The data inputs, based on literature or assumptions, were modelled using background processes from the Ecoinvent (v.3.9.1) database. In LCA the background refers to the activities and processes which are not specific to the system under study and are not modelled by the researcher. The foreground refers to activities and processes which are directly related to product system understudy, i.e. what is modelled by the researcher.

In the life cycle interpretation phase a consistency check was performed to determine whether the assumptions, methods, models and data were consistent with the study's goal and scope. The findings of LCA results and sensitivity analyses are irrelevant if the model and its assumptions are inconsistent with the goal and scope of the study (Guinée, 2002). Furthermore a completeness check was performed to ensure that all necessary data and information required by the interpretation phase are accessible and complete.

3.1.1 LCA framework

The LCA framework and methodology has been standardised by ISO with the most recent update coming in ISO 14044:2006. The interactions between methodological steps can be seen in *Figure 3.* The framework consists of four iterative stages:

1. goal and scope definition
2. life cycle inventory (LCI)
3. life cycle impact assessment (LCIA)
4. interpretation (EC-JRC, 2010)

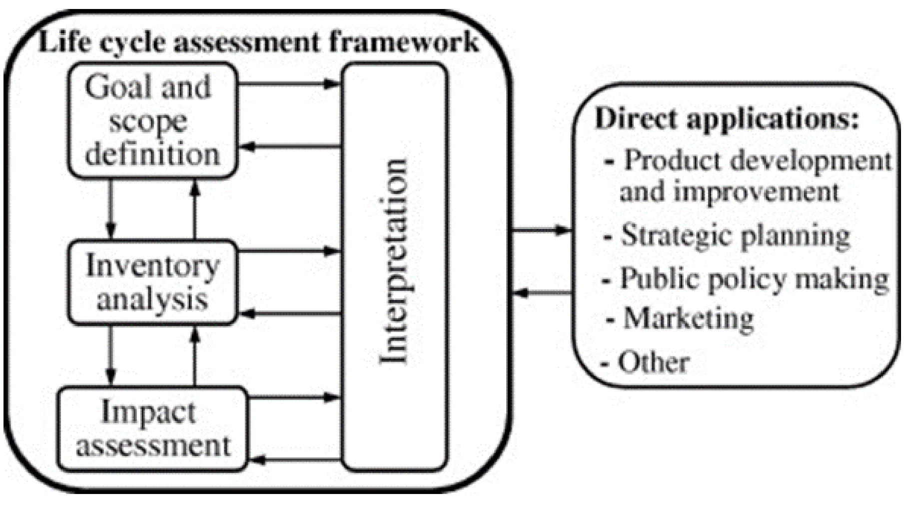


Figure 3. LCA framework and applications (source: Roy et al., 2009).

4 Goal and Scope definition

4.1 Goal

The goal of this LCA was to answer the research questions and open up research regarding the quantification of the environmental impacts of floating urbanisations. The target audience for this research is actors in the fields of urban planning and marine construction. These include policy makers, public officials, residents' representatives, engineering firms, contractors, surveyors, environmental organisations, government agencies, and research institutions.

This LCA was also conducted as a component of a thesis project for the joint-degree MSc of Industrial Ecology at Leiden University and TU Delft. The study was *not* commissioned by an external entity and was carried out for academic purposes. Expert discussion and insight were provided by the thesis supervisors Dr. Gil Wang, Dr. Tomer Fishman, and Dr Benjamin Sprecher. This insight supported decisions made regarding the models.

These assumptions were necessary for several components due to the lack of available data and the prospective nature of the product systems under study. Accordingly, it is important to note that the results of this study provide academic insight, however absolute claims of environmental performance should be avoided.

4.2 Scope

Four product systems were investigated in this study. All systems were MFS twin-hull Module9000's however different construction materials were used for each system. The LCA covers all life cycle stages of the product system from cradle-to-grave. Note that some processes were not included due to a lack of data (see section 5.1.2). The LCA performed can be described as detailed, prospective, attributional LCAs. The scope of these typologies is defined in Appendix E.

4.2.1 Geographical scope

The study aimed to offer recommendations for improving MFS substructure in a general context however due to the nature of LCA a case study needed to be taken so that input elements (transport distances, raw material & energy production geography) of the model could be determined. The elected case study was of Taranto, Italy. This geographical scope was chosen because Taranto is a suitable location for the use of MFS, with 709 km^2 of suitable waters, and can potentially benefit from MFS implementation (Bikker, 2023). The urban area is projected to have an average annual exponential rate of growth of the population of: 0.24% (2025-2030); 0.26% (2030-2035) (United Nations Department of Economic and Social Affairs, 2018).

4.2.2 Temporal scope

The temporal scope will be 2025-2125. This study aims to represent contemporary production and implementation of MFS. The 100 year period is an estimation of the lifetime of an MFS module. This estimation was informed by a 50 year minimum lifetime of the MFS (personal communication with Dr. Wang, December 7, 2023) and the researcher's personal judgement based on the longevity of other long term infrastructures, see the following paragraphs.

Other marine infrastructure e.g. ships and offshore wind turbines have shorter lifespans of ~25-30 years (Kameyama et al., nd ; Elginoz & Bass, 2017). In the case of ships, the constant motion leads to rapid wear and tear. While in the case of offshore wind turbines, EoL is dictated by the wearing of the permanent magnets as opposed to the (often) steel substructure and tower (Garcia-Teruel et al., 2022). Reinforced concrete structures such as piers can last up to 100 years with proper design (Mistry et al., 2016).

The systems under study are intended as a (largely) stationary and (often) protected marine infrastructure which behaves as urban 'built environment' infrastructure. Therefore, to perform this role the substructure must have a lifetime proportional to the longevity of other built environment infrastructure e.g. buildings and roads which have lifetimes of 40-150 years (Goldstein & Rasmussen, 2018; Ji et al., 2021) and 120 years (Birgisdottir et al., 2006). It is assumed that a MFS lifetime of 100 years is feasible. Routine maintenance is required in the case of the steel designs (see Appendix B).

4.2.3 Technology scope

While there are no operational MFS substructures in existence, the substructures are designed so that existing technologies and facilities can be used to produce and transport the substructures (Wang et al., 2019). Therefore present day technology is assumed to be used in all life cycle steps.

4.2.4 Environmental scope

Rather than focus on specific impact categories this LCA aimed for a holistic overview of the environmental impacts stemming from the product systems. Therefore a broad range of impact categories was considered (see section 6.1 for further details)

4.3 Function, functional unit, alternatives, reference flows

It is necessary to define the (1) **function**, (2) **functional unit** (**FU**), and (3) **reference flows** of the systems analysed:

(1) Refers to the actual purpose fulfilled by the system being analysed; (2) refers to the quantified expression of the function which enables different product systems to be treated as functionally the same; and (3) refers to the amount of product parts that are required to meet the FU (Guinée, 2002).

- **Function:** to provide a floating platform, in the marine environment, which can be used as a foundation for any urban activity

- **FU:** full life cycle of a floating platform, total area coverage of 7500 m^2, suitable for any urban activity over 100 years

- Four alternative designs were devised
    - Virgin steel (VS) based substructure
    - Recycled steel (RS) based substructure
    - Reinforced 35 MPa Portland concrete (35 PC) substructure
    - Reinforced 35 MPa Portland concrete (50 PC) substructure

- **Reference flows:**
    - A floating platform in the marine environment made from **steel** which can be used as the foundation of any urban activity over a 100 year period
    - A floating platform in the marine environment made from **recycled steel** which can be used as the foundation of any urban activity over a 100 year period
    - A floating platform in the marine environment made from **35 MPa Portland concrete** which can be used as the foundation of any urban activity over a 100 year period
    - A floating platform in the marine environment made from **50 MPa Portland concrete** which can be used as the foundation of any urban activity over a 100 year period

For the reference flows each design type implies idiosyncratic dimensions and mass of materials. This will be described in the next section.

5 Inventory analysis

In this section the system boundaries, the cut-offs applied to the product systems, and the coinciding flowcharts are introduced. This is succeeded by a description of the baseline cases for the studied product systems. This section concludes with a discussion of the data quality and the occurrence of multi-functional processes within the systems. The entire inventory can be seen in Appendix C.

5.1 System boundaries

5.1.1 Economy-environment system boundary

As indicated above the LCA will follow the cradle-to-grave life cycle of an MFS substructure. This life cycle can be separated into distinct foreground stages (EN-15978, 2011) as shown in *figure 4* below. In the background process the economy-environment boundary is, for the most part, crossed by elementary flows found within the stages A1-A4 and C1-C4. This is due to: the numerous raw materials needed to be produced and processed in the construction of the substructures; the direct emissions from the oceanic transport of the substructures; and the emissions associated with the EoL treatments of the substructures.

In the foreground processes elementary flows were concentrated in the use phase (stages B1-B2) of the steel design substructures. Here there are four instances of elementary flows. Solids, inorganic emissions to the ocean (this represents waste paint and corroded iron); particulate matter (from the sandblasting of the paint during maintenance, see Appendix B); VOC emissions to air (which are released from the paint when it is applied to the substructure) ;and zinc emissions to the ocean (from the corrosion of the sacrificial zinc anodes). Particulate matter emissions were also modelled in stage C1 (again from sandblasting). With the exception of these, economic flows were used to model all the other processes.

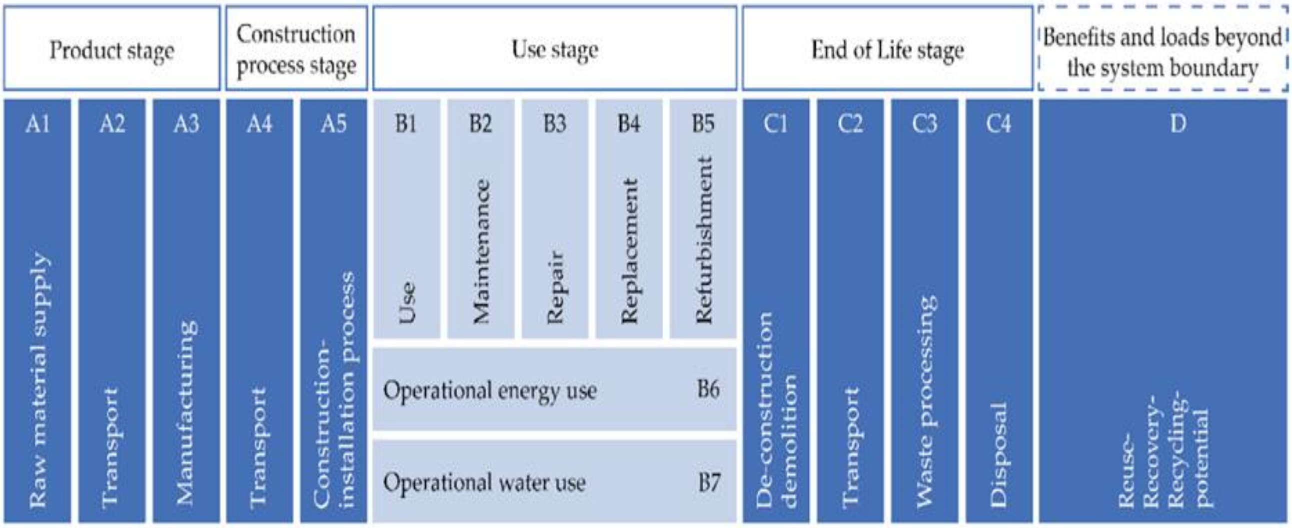


Figure 4. Life cycle stages according to EN-15978 (2011).

5.1.2 Cut-offs

The product systems under study are ex-ante and therefore no actual data was available. However the systems could be modelled using proxies. Regardless, cut-offs had to be made. In LCA cut-offs are flows which exist in the real-world product system however when modelled are excluded. In the foreground of the present study cut-offs were made for:

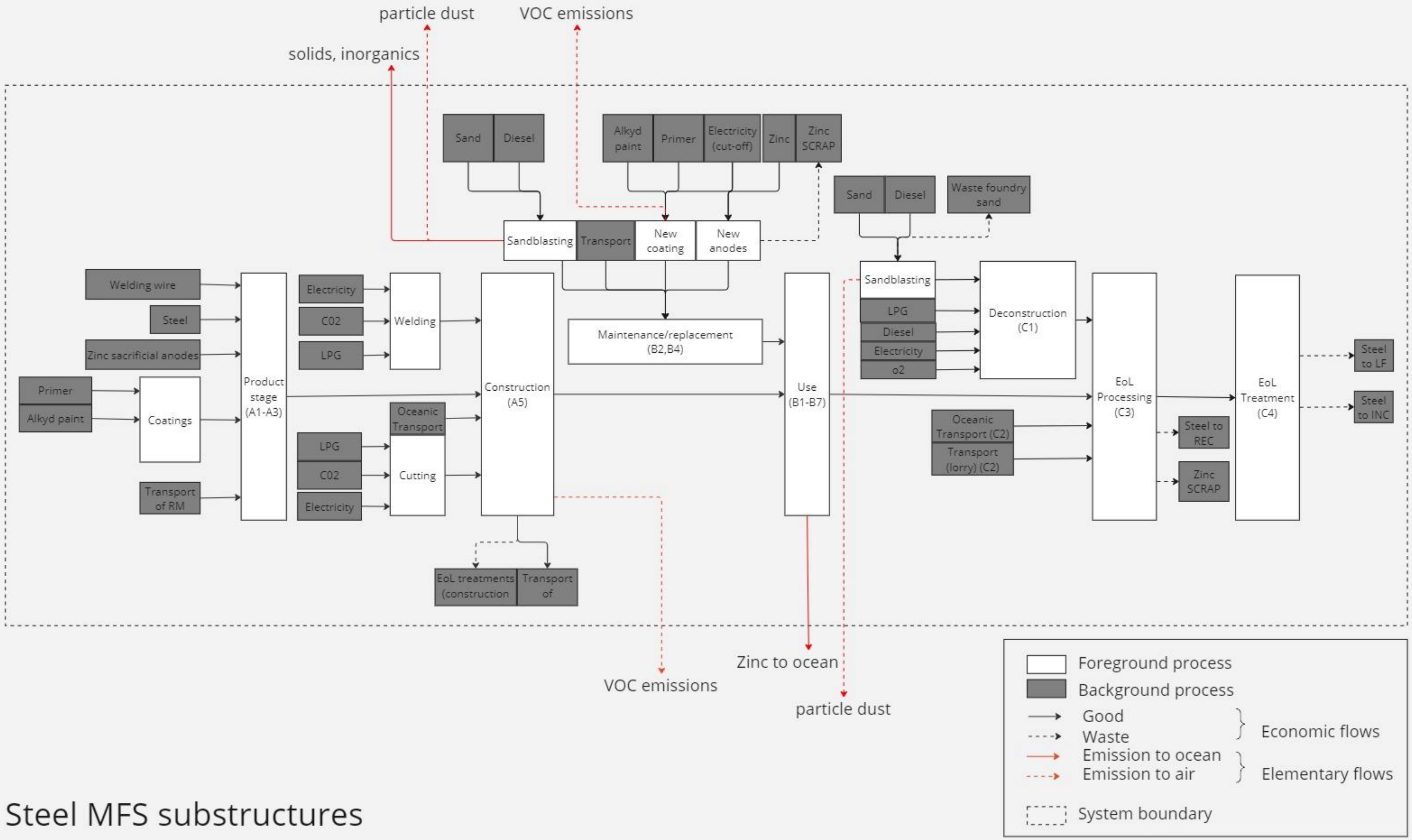
- Energy (diesel) required for concrete pumping
- Electricity used in paint application
- Electricity used in zinc anode attachment/welding

The energy processes cut-off were all associated with the application of materials and not the production of said materials. Therefore they were predicted to have much lower energy requirements than the energy intensive production processes which *were* included in the models. In the final results the energy used had a small share of the impacts, implying that the cut-offs would not significantly affect the results. Therefore the cut-offs were deemed as acceptable.

A cut-off was also applied for capital goods. This is a common practice in LCA as stipulated by the Product Environmental Footprint Category Rules Guidance (PEFCR)(European Commission, 2018). A final cut-off was applied to Module D (see figure 4 above for an illustration of what is included in Module D). This implies that the benefits of recycling/reusing steel and concrete are allocated to separate systems outside of the boundaries of the product systems which were studied.

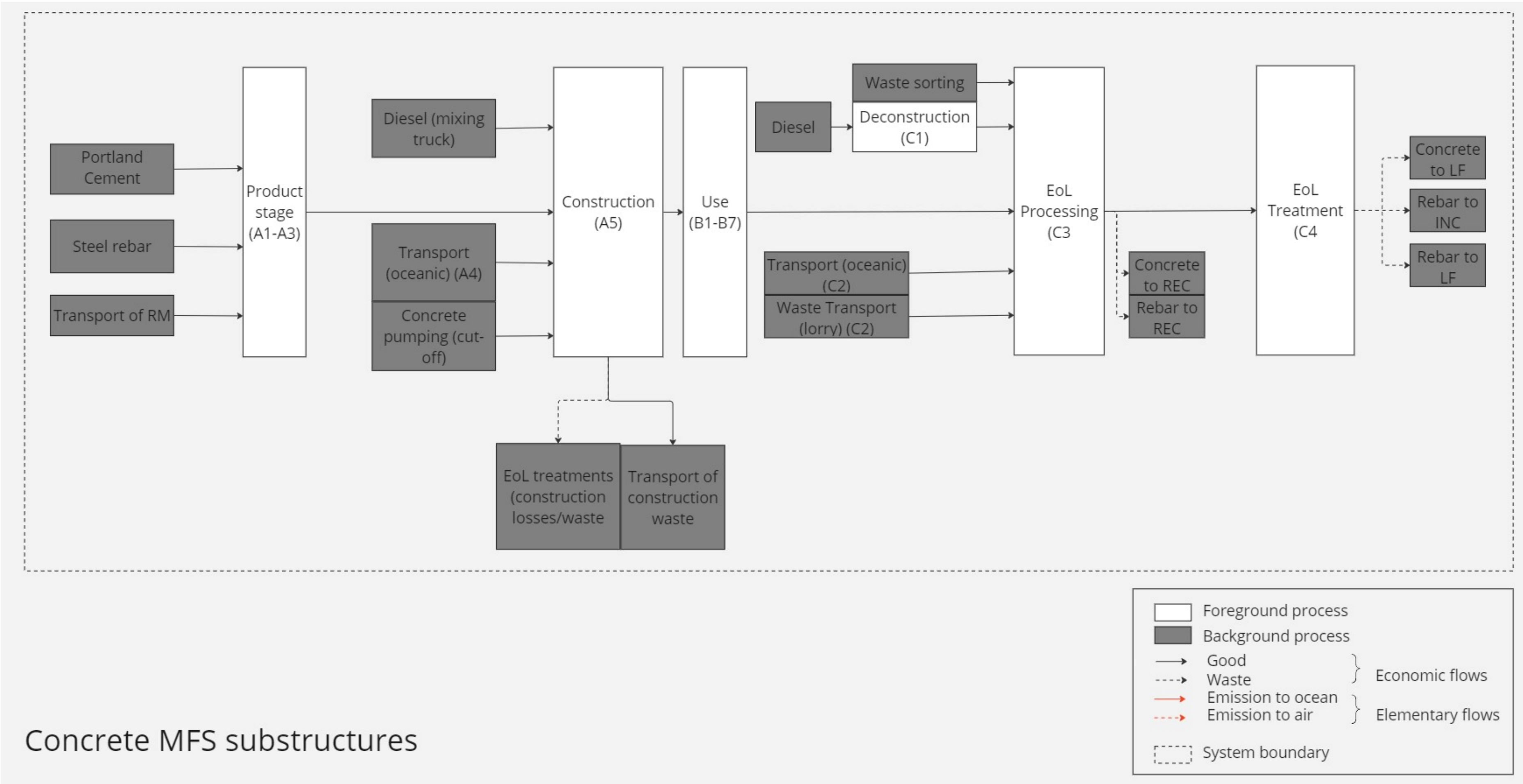
5.1.3 Flowcharts

Figure 5. Flowchart of steel design substructures.



Steel MFS substructures

Figure 6. Flowchart of concrete design substructures



5.2 Data collection and data relating to unit processes

In this subsection the data used in this study is discussed. As mentioned before, this research not only applied theory and methods from the field of Industrial Ecology, it also required the application of engineering concepts. For the alternative construction materials used in the MFS substructure designs it was paramount that they can all theoretically perform satisfactorily in supporting the superstructure. To do this they had to retain an acceptable height above the water when loaded with superstructures and have an equivalent calculated 'total' bending moment. The methodology used for calculating the bulk material requirements is described in Appendix A. The baseline scenario for the substructure designs is also illuminated in the subsequent sections. The modelling decisions specific to each design type can be found in Appendix B. Appendix C contains a list of all the data inputs and their respective Ecoinvent dataset. All calculations are also available in Appendix C.

5.2.1 Data collection

All of the data used in this study came from secondary sources with the majority of the data coming from state-of-the-art academic literature (see the references list). To find port-to-port distances, indicative of the sea distances travelled by the substructures, the website www.searoutes.com was used. Information on the VOC content of paint coatings was obtained from product information sheets of coatings. The coatings in question have equivalent function and main material content to those required by substructure designs modelled. Other sources such as European Commission (EC) reports, OECD peer reviews, etc were also used.

5.2.2 Baseline scenario

Construction

For construction, the energy inputs and raw materials (and their losses) were considered. The transport of the raw materials was also considered. It was assumed that construction of the substructures would take place in the nearest shipyards which are certain to have facilities for (new) shipbuilding- several shipyards have the facilities for ship maintenance and conversion, but not necessarily for (new) shipbuilding. The nearest suitable shipyard found was the CANTIERI NAVALI RODRIGUEZ shipyard located at Messina, Italy (OECD, 2024). Messina to Taranto has a port-to-port distance of 481 km. This distance does not represent the exact positioning of the substructure relative to Taranto, as shown by Bikker (2023). However because this distance is only +/- 1km it is negligible compared to the overall results.

Operation

It was also assumed that the substructure designs would not require structural maintenance. Due to their stationary nature the rate of wear of the substructures is assumed to be very low (G. Wang, personal communication, February 15, 2024). Furthermore the structural maintenance of the MFS would require transport to a port where the MFS can be ‘dry docked’. This would lead to an unfeasible scenario where the MFS inhabitants’ housing would be taken away for several weeks while the substructure is repaired. So protection at inception is intended in the design.

End of Life

As mentioned in section 2.1.1.3 regulations may lead to restrictions on where the structure can be broken in its EoL. In the baseline scenario it is assumed that the MFS must be broken in EU selected shipbreaking facilities. The nearest one to Taranto being San Giorgio de Porto S.p.A. (Genoa). Taranto to Genoa has a port-to-port distance of 1417 km. For the EoL processing of the steel and concrete, after the substructures are broken down in the shipyard, local facilities were assumed to process the materials. Those with closest proximity to the Genoa port were selected. Where specific facilities were not locatable a default distance of 50 km (Gervasio & Dimova, 2018) was taken for the transport distances travelled in the EoL stage (C2). See *table 2* for a list of these locations.

Facility name	**Waste-type processed**	**Distance (from previous stage) (km)**
Ferrotrade (Genoa)	Steel	11.3
Default (Gervasio & Dimova, 2018)	Concrete & steel	50
Scarpino (dicarica di Scarpino)	Landfill site	9.7

Table 2. List of transport distances in substructure EoL

5.2.3 Data quality

As mentioned in section 5.1.2, due to the ex-ante nature of the product systems under study, actual data does not exist. This meant numerous assumptions had to be made in order to model the systems e.g. lifetime of MFS, EoL fate of substructures. The assumptions made are discussed in detail in Appendix B. Furthermore the Ecoinvent database used for background modelling did not contain processes for every activity required in the systems. Where this was the case proxy processes with similar functions had to be used as an estimation of the impacts of the real world activity.

Notably, a proxy was used for the modelling of the oceanic transport of the substructures from: their place of construction; to their place of operation; to their place of deconstruction. It was hypothesised that this should be done using tugboats (Wang et al., 2019) however due to limited options in Ecoinvent the oceanic transport option with the most similar deadweight tonnage (DWT) to a tugboat, 'GLO: transport, freight, sea, ferry' was used. Further proxies were used for the paint coats applied to the steel design substructures. Epoxy and polyester resin based 'RER: coating powder' protective coat was used for the primer. For the topcoat the proxy 'RER: alkyd paint, white, without solvent, in 60% solution state' was used. A final proxy, 'solids, inorganic to ocean' was used to represent waste paint sandblasted directly into the sea.

A further issue was the geography of datasets used. The current research is a case study of Taranto, Italy and therefore datasets specific to Italy were the ideal choice. However this was only possible for the electricity input modelled. For all other inputs aggregated datasets had to be used. Where available, datasets representative of the geographies 'European region (RER)' or 'Europe without Switzerland' were used, however in several instances datasets representative for the 'Global (GLO)' and 'Rest of World (RoW)' scale had to be employed. The implications of the data quality are further discussed in section 10.1. See Appendix C for a full list of the data sets used and their representative geographies.

5.2.4 Multi-functionality and allocation

The modelled product systems are simple in the sense that they did not contain multifunctional processes. Therefore allocation was not required.

6 Impact Assessment

6.1 Impact categories

The impact categories and coinciding characterisation factors used for the main analysis of this research were obtained from the latest version of the Environmental Footprint method, EF 3.1. This method is recommended by the European Commission (2021). As discussed in section 4.2.4 this LCA aimed to investigate the holistic environmental impacts of the substructure designs. Accordingly all impact categories were analysed they are shown below in *table 3*. The LCIA are relative expressions of midpoint indicators and are not predictive of category endpoints. The LCIA also does not predict the exceeding of thresholds, safety margins or risks.

The impact category '*ecotoxicity: marine'*, from the ReCiPe 2016 v1.03, midpoint hierarchist (H) impact assessment method was also added to the analysis. This impact category was included in order to account for the effect of the MFS substructures on the marine environment. The EF 3.1 method lacks an impact category for this. The midpoint (H) characterisation factors from the ReCiPe method were chosen because this research as a whole assesses environmental impacts at the midpoint level and the time horizon of 100 years was chosen as it is the most applicable to the current research. 'The hierarchist (H) perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms' - Rijksinstituut voor Volksgezondheid en Milieu (2017).

Impact Category	**Parameter**	**Unit**
	Core environmental impact indicators	
Climate change – total	Global warming potential, GWP-total	kg CO_2 eq.
Climate change – fossil	Global warming potential fossil fuels, GWP-fossil	kg CO_2 eq.
Climate change – biogenic	Global warming potential biogenic, GWP-biogenic	kg CO_2 eq.
Climate change - land use and land use change	Global warming potential land use and land use change3, GWP-luluc	kg CO_2 eq.

Ozone depletion	Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 eq
Acidification	Acidification potential, Accumulated Exceedance, AP	Mol H^+ eq
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment, EP-freshwater	kg PO_4 eq.
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching marine end compartment, EP-marine	kg N eq.
Eutrophication terrestrial	Eutrophication potential, accumulated exceedance, EP - terrestrial	Mol N eq
Photochemical ozone formation	Formation potential of tropospheric ozone, POCP	kg MNVOC eq.
Depletion of abiotic resources – minerals and metals	Abiotic depletion potential for non-fossil resources (ADP-minerals&metals)	kg Sb equiv.
Depletion of abiotic resources – fossil fuels	Abiotic depletion potential for fossil resources (ADP-fossil fuels)	MJ, net caloric value
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived

Additional environmental impact indicators

Particulate matter emissions	Potential incidence of disease due to PM emissions, PM	Disease incidence

Ionizing radiation, human health	Potential human exposure efficiency relative to U235, IRP	kBq U235 eq
Eco-toxicity (freshwater)	Potential comparative toxic unit for ecosystems, ETP-fw	CTUe
Human toxicity, cancer effects	Potential Comparative toxic unit for humans, HTP-c	CTUh
Human toxicity, non-cancer effects	Potential Comparative toxic unit for humans, HTP-nc	CTUh
Land use related impacts/Soil quality	Potential soil quality index, SQP	Pt. (unitless)
Eco-toxicity (marine)	Ecotoxicity potential	DCB eq

Table 3. Summary of impact categories analysed and their respective parameters and units.

The LCA software 'Activity Browser' (v.2.9.7) was used to perform the LCA calculations (Steubing et al., 2020). This software allows for the modelling of foreground unit processes by connecting them to background data.

6.2 Economic and environmental flows not followed to the system boundary

It should be repeated that some economic and environmental flows were not included in the system boundaries. This occurred in the flows which were cut-off which was explained in section 5.1.2. Therefore the results presented in the following sections do not fully represent all impacts of the product systems in reality.

6.3 Baseline scenario

In this section the characterisation results and contribution analysis refer to the baseline scenario. The findings provided grounds to develop various alternative scenarios. These scenarios will be discussed in depth in section 8. The raw LCIA results can be found in Appendix C.

6.3.1 Characterisation results

A full list of the characterisation results from the baseline scenario can be seen in *table 4* below. The *VS design* had higher impacts than all substructure designs in several impact categories including climate change (total). In terms of marine ecotoxicity the steel designs had far greater impacts than the concrete designs with the *RS design* having 3% greater marine ecotoxicity impacts than the *VS design*. The *RS design* had the lowest impacts for acidification and photochemical oxidant formation impacts. It also had the second lowest climate change impact of all alternatives with less than half the CO_2-Eq emissions of the *VS design* and 34% less than the *35 PC design*. Only the *50 PC design* had a lower climate change impact (by 12%). The *RS design* also had by far the lowest abiotic depletion: minerals impact of all alternatives, less than half the impact seen in the *35 PC design*.

Impact category	Unit	VS design	RS design	50 PC design	35 PC design
acidification	(mol H +-Eq)	9.72E+04	6.60E+04	8.62E+04	1.20E+05
climate change	(t CO_2-Eq)	1.51E+04	7.29E+03	7.09E+03	9.77E+03
climate change: biogenic	(kg CO_2-Eq)	1.51E+04	1.78E+04	6.37E+03	8.79E+03
climate change: fossil	(kg CO_2-Eq)	1.50E+07	7.25E+06	7.08E+06	9.75E+06
climate change: land use and land use change	(kg CO_2-Eq)	2.29E+04	2.08E+04	6.27E+03	7.84E+03
ecotoxicity: freshwater	(CTUe)	7.65E+07	6.06E+07	3.46E+07	4.80E+07
abiotic depletion (ADP): fossil fuels	(TJ, net calorific value)	1.77E+02	1.11E+02	7.74E+01	1.07E+02
eutrophiction (freshwater)	(t P-Eq)	6.32E+00	2.98E+00	1.35E+00	1.87E+00
eutrophication: marine	(kg N-Eq)	2.45E+04	1.62E+04	2.18E+04	3.04E+04
eutrophication: terrestrial	(thousand mol N-Eq)	2.53E+02	1.74E+02	2.39E+02	3.32E+02
human toxicity: carcinogenic	(CTUh)	8.49E-02	1.69E-01	6.86E-02	9.63E-02
human toxicity: non carcinogenic	(CTUh)	1.82E-01	1.23E-01	9.21E-02	1.28E-01
ionising radiation: human health	(kBq U2335-Eq)	7.65E+05	1.38E+06	2.65E+05	3.69E+05
land use	(Pt)	4.41E+07	2.75E+07	3.07E+07	4.28E+07

abiotic depletion: minerals	(kg Sb-Eq)	7.10E+01	5.15E+01	8.28E+01	1.16E+02
ozone depletion	(kg CFC-11-Eq)	3.03E-01	1.33E-01	8.28E-02	1.15E-01
particulate matter formation	(disease incidence)	1.23E+00	6.53E-01	5.07E-01	7.06E-01
photochemical oxidant formation	(t NMVOC-Eq)	9.97E+01	5.58E+01	6.79E+01	9.45E+01
water use	(m3 world-eq. deprived)	6.64E+06	5.05E+06	1.23E+06	1.70E+06
marine ecotoxicity	(t DCB-eq)	4.13E+03	4.26E+03	7.04E+02	9.84E+02

Table 4. Characterisation results (baseline scenario for all impact categories).

6.3.2 Normalisation

In LCA normalisation allows for all impact categories to be 'normalised' to a comparable scale so that the magnitude of the indicator results can be better understood in relation to the reference information. This also means that different environmental impacts can be compared with each other directly. For the current research the EF 3.1 normalisation factors (Andresai Bassi et al., 2023) were used. The normalisation factors used refer to the environmental impacts incurred by an average global citizen in the reference year 2010.

The EF 3.1 normalisation method provides a specific normalisation factor for each EF 3.1 impact category bar: climate change: fossil; climate change: biogenic; and climate change: land use and land use change. However in the EF methodology the sum of these impact categories comprise climate change: total. It is also prudent to mention that the EF method does not provide a normalisation factor for marine ecotoxicity. The single impact category with the highest normalised score in each respective substructure design was human toxicity: carcinogenic. An in depth analysis of this is provided in Appendix D.

In LCA weighting can be applied to normalised scores based on the importance assigned to each impact category. This allows for an overall single score to be made to evaluate and compare the overall environmental impact of product systems. This usually involves input from stakeholders. Even weighting was applied to the normalised scores in the current research. This was done because input from the relevant stakeholders for devising specific weighting factors for each impact category was unobtainable given the time-frame of the research. Instead the normalised scores were simply added to calculate a single score. It is important to note that this single score is not representative of an order of magnitude but rather a simple quantified indication of which alternative has the lowest and highest impacts. Therefore the normalised single score is unitless with lower scores indicating better performance.

VS design	*RS design*	*50 PC design*	*35 PC design*
27182	23422	16300	22702

Table 5. (Even-weighted) normalised single scores (marine ecotoxicity not accounted for).

Overall the *VS design* had the greatest (non-weighted) normalised environmental impacts in the baseline scenario. 50 MPa Portland concrete by far outperformed all other alternatives while the *RS design* and *35 PC design* were relatively even with the latter outperforming the former by 3% in the baseline scenario. However, before the dimensions of the concrete substructures were amended it was seen that the *RS design* actually outperformed the *35 PC design* by 2%. See Appendix D.

6.3.3 Contribution analyses

An initial contribution analysis was performed for each substructure design to highlight which lifecycle stages were the most impactful to each impact category. Following the initial contribution analyses a secondary contribution analysis of the highlighted lifecycle stages themselves was performed to find which flows and processes were responsible for the larger contributions.

6.3.3.1 Initial contribution analyses

Figures 7-10 showing the initial contribution analyses can be found below. For all substructure designs the raw materials held the largest share of the impacts. This was expected because the operation phases of the designs require little maintenance and no operational energy. For all substructure designs the stages ‘transport to site’ (A4) and ‘EoL transport’ (C2) also contributed considerably (> 20% of total impact) to the impact categories: acidification, eutrophication: terrestrial, eutrophication: marine, and photochemical oxidant formation. In the concrete designs the impact of A4 + C2 amounted to > 20 % of the total impact in an additional six impact categories (see *figures 9-12*). The contributions of transporting the substructures was much greater in the concrete designs due to their much heavier mass in comparison with the steel designs. For the VS and *RS design*s it was also found that the majority of the marine ecotoxicity impact came from the use phase (B1). This was 65 and 63%, respectively. For both concrete designs the EoL disposal (C4) of the materials accounted for 33% of the marine ecotoxicity impact.

Overall between material designs the lifecycle stage contributions were quite similar i.e. the contributions for the steel designs shared similar patterns to each other and the contributions of the concrete designs were similar to each other too. This is especially true for the concrete designs because there is a low amount of variation in their life cycle inputs.

Figure 7-10. Contribution analyses of the substructures at the lifecycle stage level. (From top left running clockwise

figures: 7. VS design, Figure 8. RS design, Figure 9. 35 PC design , Figure 10. 50 PC design

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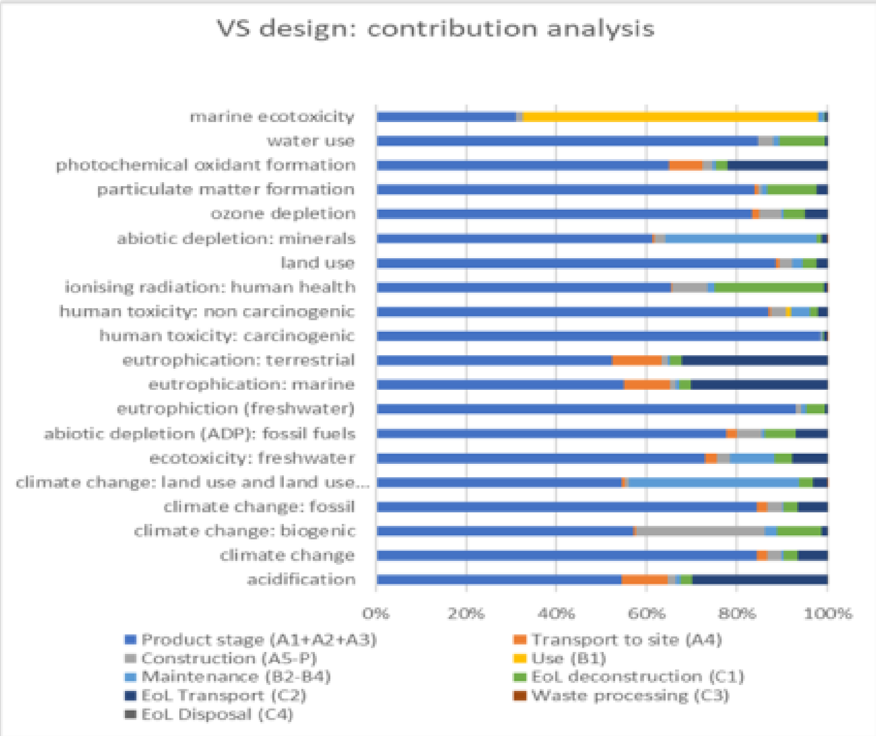
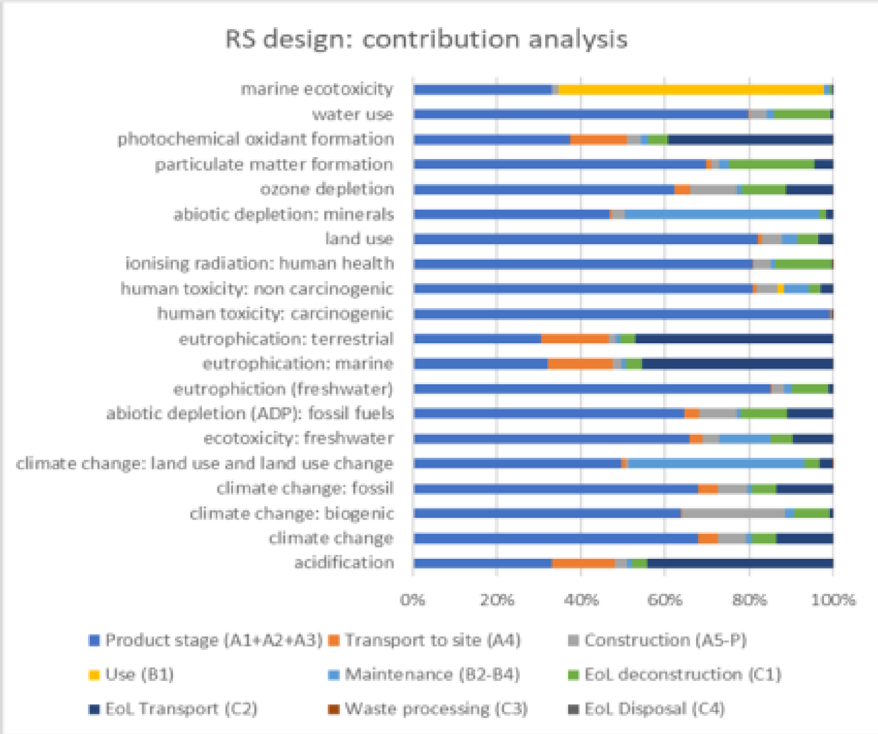
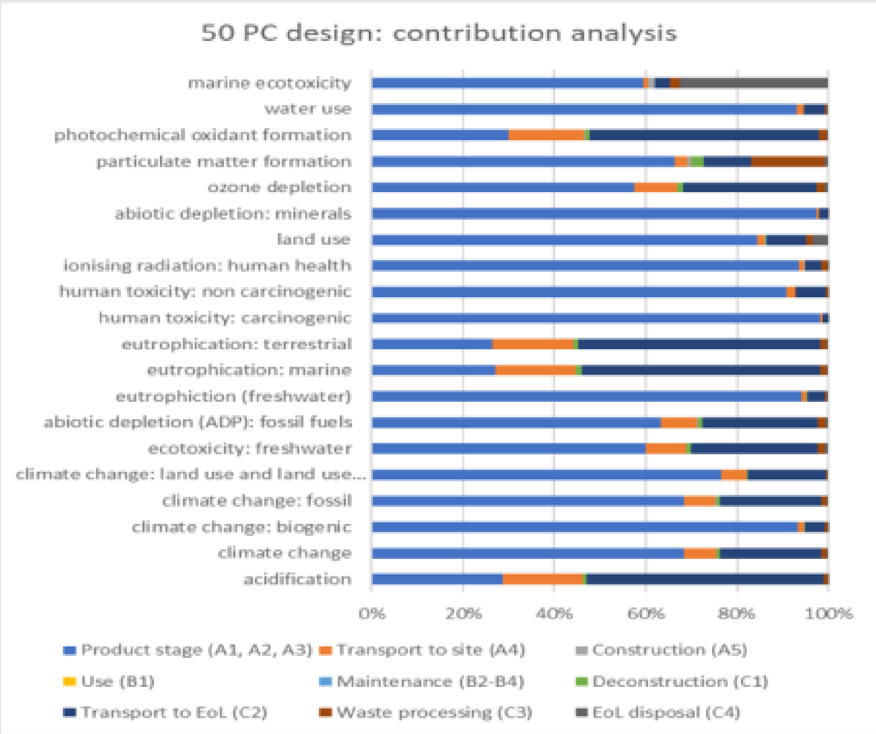
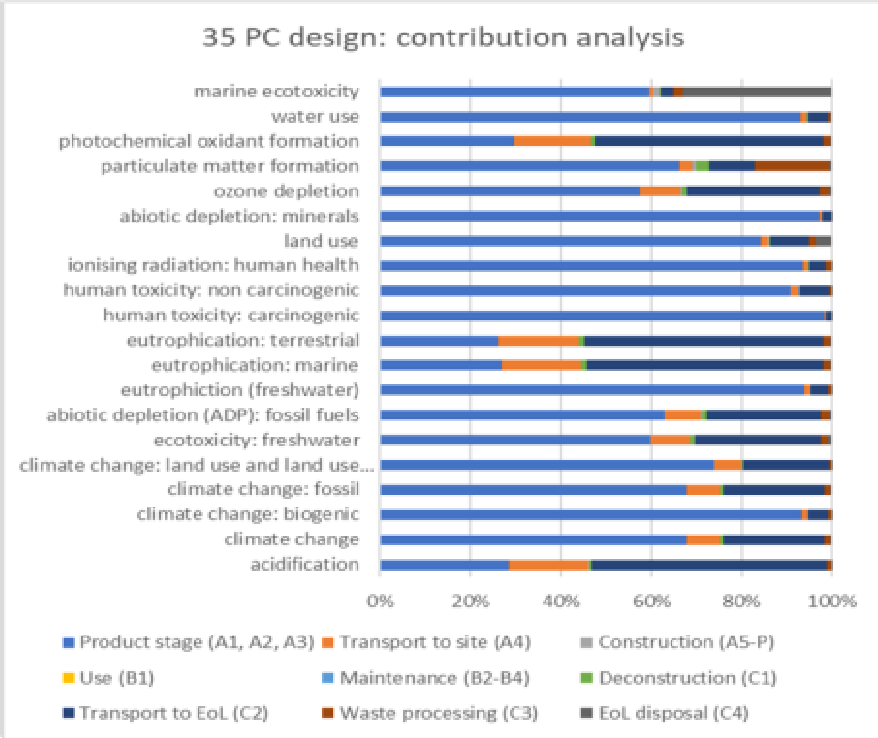


VS design: contribution analysis
marine ecotoxicity
water use
photochemical oxidant formation
particulate matter formation
ozone depletion
abiotic depletion: minerals
land use
ionising radiation: human health
human toxicity: non carcinogenic
human toxicity: carcinogenic
eutrophication: terrestrial
eutrophication: marine
eutrophiction (freshwater)
abiotic depletion (ADP): fossil fuels
ecotoxicity: freshwater
climate change: land use and land use...
climate change: fossil
climate change: biogenic
climate change
acidification
0%
20%
40%
60%
80%
100%
Product stage (A1+A2+A3)
Transport to site (A4)
Construction (A5-P)
Use (B1)
Maintenance (B2-B4)
EoL deconstruction (C1)
EoL Transport (C2)
Waste processing (C3)
EoL Disposal (C4)



RS design: contribution analysis
marine ecotoxicity
water use
photochemical oxidant formation
particulate matter formation
ozone depletion
abiotic depletion: minerals
land use
ionising radiation: human health
human toxicity: non carcinogenic
human toxicity: carcinogenic
eutrophication: terrestrial
eutrophication: marine
eutrophiction (freshwater)
abiotic depletion (ADP): fossil fuels
ecotoxicity: freshwater
climate change: land use and land use change
climate change: fossil
climate change: biogenic
climate change
acidification
0%
20%
40%
60%
80%
100%
Product stage (A1+A2+A3)
Transport to site (A4)
Construction (A5-P)
Use (B1)
Maintenance (B2-B4)
EoL deconstruction (C1)
EoL Transport (C2)
Waste processing (C3)
EoL Disposal (C4)


50 PC design: contribution analysis
marine ecotoxicity
water use
photochemical oxidant formation
particulate matter formation
ozone depletion
abiotic depletion: minerals
land use
ionising radiation: human health
human toxicity: non carcinogenic
human toxicity: carcinogenic
eutrophication: terrestrial
eutrophication: marine
eutrophiction (freshwater)
abiotic depletion (ADP): fossil fuels
ecotoxicity: freshwater
climate change: land use and land use...
climate change: fossil
climate change: biogenic
climate change
acidification
0%
20%
40%
60%
80%
100%
Product stage (A1, A2, A3)
Transport to site (A4)
Construction (A5)
Use (B1)
Maintenance (B2-B4)
Deconstruction (C1)
Transport to EoL (C2)
Waste processing (C3)
EoL disposal (C4)

35 PC design: contribution analysis
marine ecotoxicity
water use
photochemical oxidant formation
particulate matter formation
ozone depletion
abiotic depletion: minerals
land use
ionising radiation: human health
human toxicity: non carcinogenic
human toxicity: carcinogenic
eutrophication: terrestrial
eutrophication: marine
eutrophiction (freshwater)
abiotic depletion (ADP): fossil fuels
ecotoxicity: freshwater
climate change: land use and land use...
climate change: fossil
climate change: biogenic
climate change
acidification
0%
20%
40%
60%
80%
100%
Product stage (A1, A2, A3)
Transport to site (A4)
Construction (A5-P)
Use (B1)
Maintenance (B2-B4)
Deconstruction (C1)
Transport to EoL (C2)
Waste processing (C3)
EoL disposal (C4)

6.3.3.2 Secondary contribution analyses

In the ‘transport to site’ (A4) and ‘EoL transport’ (C2) lifecycle stage oceanic transport accounts for the majority of the contributions across all impact categories. At the process and flow levels it was found that the emission of ‘zinc, to ocean’ accounted for all of the marine ecotoxicity impacts in the use phase (B1). This implies that the cathodic protection of the steel designs leads to the majority of marine ecotoxicity impacts. In the concrete designs all of the marine ecotoxicity impact associated with the EoL disposal (C4) came from the treatment of scrap steel. The majority of the remaining impact came from the production of the stainless steel rebars. In fact, for the concrete substructure designs the greatest contributions, for most impact categories, came from the production of stainless steel (specifically the alloy materials chromium and nickel) and not the concrete.

7 Consistency and completeness checks

7.1 Consistency check

Consistency in LCA refers to the adherence of the LCA study to the goals and scope set at the beginning of an LCA study (Guinée, 2002). In the present research this means that the methods, data, and assumptions should be valid for calculating the environmental impacts of the prospective MFS substructure designs and that the separate product systems should be comparable.

7.1.1 Consistency between alternatives

All alternatives had the same boundaries and overarching life cycle. Furthermore a conservative approach was taken throughout all product-systems for assumptions without exception. Also, the same impact assessment methods were applied to all systems. Inconsistency between alternatives was found in the level of detail of the product-systems. The steel based substructures, while intrinsically having a more complex system due to their use of coatings and cathodic protection, did have a disproportionately greater level of detail than the concrete based substructures, especially in the deconstruction stage (C1), due to data gaps regarding concrete deconstruction. A further example of the discrepancy in detail is the cut-off applied to the energy inputs for the pouring of concrete in the construction of the concrete based product-systems (see section 5.1.2).

7.1.2 Consistency of data

The data collection methods were consistent throughout for the most part. Literature being the primary source. It should be noted however that the data source for the requirements of base material, steel or reinforced concrete, were disparate between the steel and concrete designs. For the steel substructures the figure was taken directly from the literature (Wang et al., 2019) where the specific requirements had been extensively calculated. For the concrete designs however the figure was calculated by the researcher as described in Appendix A. Other considerations regarding the data is that the quality of data sources was consistent amongst product-systems and while it was entirely secondary data it is deemed to be consistent with the goal and scope of the study given its prospective nature. As previously mentioned the data used regarded the relevant industries and came from reputed sources (literature, governmental and organisational reports e.g. EU, OECD etc.).

An inconsistency was found in the geographical representativeness of the data. Rather than representing one geography the data sources refer to international practices (Kaneyama et al., 2007; Florin-Nicolae et al., 2014; Harish & Sunil, 2015; Dong & Cai, 2020), general practices in the European Union (Gervasio & Dimova, 2018) and other European nations (Jiven & Mariterm, 2004, Rees et al., 2017; Rees et al., 2018; Cucinotta et al., 2021). This is also true for the datasets used to model the system. As previously mentioned only one dataset, ‘market for electricity, medium voltage’ used in construction, specifically refers to

Italy. All other datasets used are representative of aggregations: Europe, global, rest of world (see Appendix C for all data inputs and their respective geographical representation). A final inconsistency between the data and the temporal scope of the research was found in the EoL stages of the substructures. All the datasets used represent current day practices and environmental impacts while the EoL stages (C1-C4) are to take place in the future. Therefore developments in technology such as marine transport and EoL waste treatment are not accounted for in the model.

The inconsistencies regarding geography are deemed acceptable because the current research aims to provide insight into the likely environmental impacts of MFS substructures in a general sense, while the case study of Italy was chosen simply to provide the necessary data inputs as explained in section 4.2.1. However the inconsistency between the EoL treatment datasets used and the temporal scope of the research are expected to result in an overestimation of the impacts because these treatment processes are expected to improve in the future through more efficient practices and use of renewable energy.

7.2 Completeness check

Completeness in LCA refers to having used appropriate and sufficient methods and data in order to draw justifiable conclusions from the LCA results all while keeping in line with the goal and scope of the study. The data and assumptions should also be available and complete (Guinée, 2002). The research encountered several data gaps however these were circumvented using assumptions, proxies, and cut-offs (when lacking all other options).

7.2.1 Cut-offs and assumptions

The full list of cut-offs can be seen in section 5.1.2 and all assumptions made are described in section 5.2.2 and Appendix B. While the cut-offs were deemed acceptable due to their predicted low impact on the overall results they are nonetheless instances of incompleteness. The validity of the decision to apply cut-offs for the energy needed for air-spraying paint coats and welding anodes in the steel substructure designs is bolstered by the fact that the energy inputs for the building of the steel substructures themselves, which was far greater than that needed for welding and painting, had such a low share of the overall impacts.

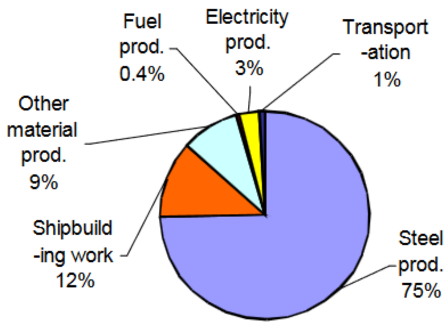
7.2.2 Proxies

The proxies used are highlighted in the inventory analysis (see section 5.2.3). Only one proxy, the use of 'GLO: transport, freight, sea, ferry' in place of a process specific to tugboat or heavy lift vessel transport was predicted to have a significant impact on the results. This is because the differing mass and dimensions of the substructure designs would lead to differing drag, resistance between the vessel and the ocean, when the substructures are transported through the ocean (Munson et al., 2013). At equal velocity greater drag means greater fuel consumption. However because drag *is* a product of the velocity the structure is towed through the sea, fuel can be saved by towing at slower speeds (Munson et al., 2013). Nonetheless the proxy used does not account for the differences in drag and consequently the use of this proxy misrepresents the deviation in impacts between the product systems, especially regarding the impact categories most affected by marine transport e.g. photochemical oxidant formation, acidification, ozone depletion, and eutrophication. The proxy regarding the specific emissions to the ocean from the paint being sandblasted is a further instance of incompleteness.

7.2.3 Comparison with literature

Because there is no known instance of an MFS substructure in reality the results of the current research were not fully comparable with the existing literature. However, for the steel based substructures comparisons of contributions could be drawn with LCA studies of ships. Only the contributions are comparable and not the absolute impacts because of the variance between the size and shapes of the ships and substructures. For the reinforced concrete substructures the results were in line with those of modern buildings which have low operational phase impacts, that is to say that material procurement and construction are the chief contributors to most environmental impacts (Goldstein & Rasmussen, 2018).

Below in *figures 11 & 12* integrated indexed results from Kameyama et al. (2007) can be seen. For the shipbuilding process it can be seen that, like the current research, the majority of the impacts were embodied in the steel used to produce the ships. When looking at the aggregated lifecycle stage contributions Kameyama et al. state the operational phase to be the greatest contributor to environmental impacts. This is mainly from fuel consumption. The product systems in the current research do not consume fuel, or much else, in their operational phase and consequently this stage has low impacts for the MFS substructures. However, disregarding the use phase it can be seen that, similar to the results from the current study, Kameyama et al. found the shipbuilding/construction phase (stages A1-A5 in the current research) to be by far the greatest contributor. Note that Kameyama et al. took credits for recycling which in the current research are awarded outside the system boundaries (see <u>section 5.1.2</u>).



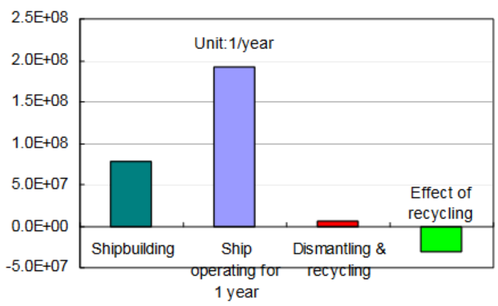


Figure 11. (left) Integrated index contributions to environmental impacts of shipbuilding.

Figure 12. (right) Integrated index contributions of environmental impacts of ship over lifetime (taken from Kameyama et al., 2007).

In *figure 13* the climate change impacts of the steel substructures are compared with that of another LCA of a ship over its lifetime (Florin-Nicolae et al., 2014). Consistency can be found in that the materials used are the greatest contributor to climate change. The shipbuilding phase (i.e. energy used and construction waste disposal) contributes considerably more in Florin-Nicolae et al. (23%) than in the *VS design* (3%) and *RS design* (7%).

The use phase in Florin-Nicolae et al. is inconsistent itself with Kameyama, however it is more important to understand why it is inconsistent with the results of the current research. This again can be explained by the MFS substructures having low requirements and consequently impacts in their use phase. Instead the EoL phase contributes more significantly in the results of the present research. This is largely due to C2 (transport to end of life) being contained in the EoL phases.

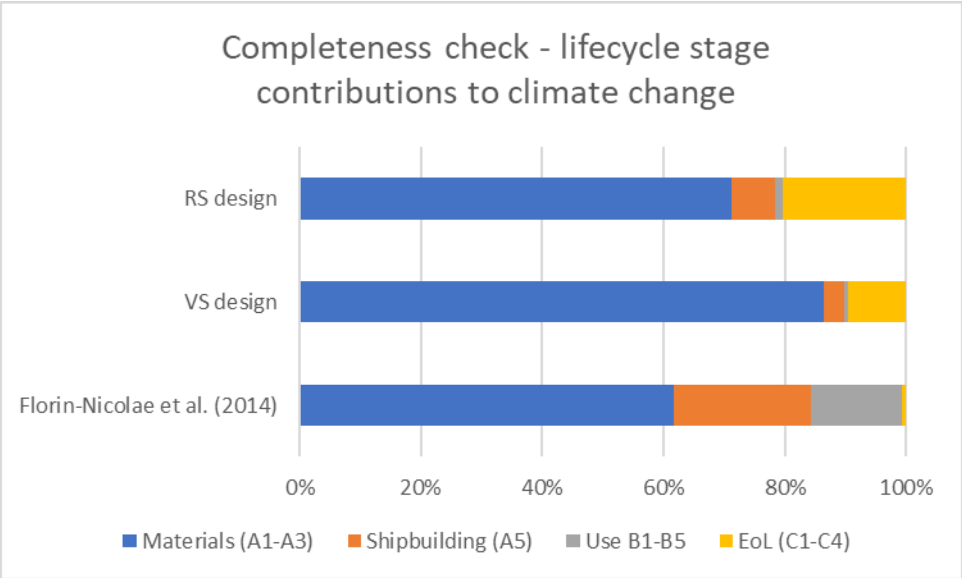


Figure 13. Comparable lifecycle stage contributions to climate change.

7.2.4 Consistency and completeness conclusion

All in all the models face several issues regarding consistency and completeness. This is due to the lack of resources (specific data, expertise, and time). However, the trend of results is aligned with the comparable literature. Furthermore the present research aims to provide *academic* insight into the environmental impacts of the substructure designs, highlight the hotspots and make recommendations where likely improvements in design choices can be made. The model can do this however it shall be reiterated that absolute claims of environmental performance should not be made.

8 Sensitivity analyses

Throughout the model there are various instances of uncertainty. These are largely due to a lack of data. The robustness of the results was improved by running sensitivity analyses on various variables (Guinée, 2002). This was done to (a) test the sensitivity of the model and (b) provide better recommendations for optimisation of the substructure design choices. The following section discusses the sensitivity analyses devised and performed

Hotspots in the contribution analysis were used to identify variables suitable for the sensitivity analyses. These hotspots revealed that the majority of environmental impacts were embodied within the raw materials and the oceanic transport of the MFS substructures. The LCA already accounted for several suitable raw material variations. Therefore a sensitivity analysis was devised for further investigating the oceanic transport. As mentioned in the consistency check uncertainty arises in the model from the disparate methods of calculating the bulk requirements of steel and concrete in the respective designs. Therefore a second sensitivity was done to investigate this. A more specific but nonetheless significant impact was found in the use phase, specifically zinc emissions, of the *VS* and *RS designs* for the marine ecotoxicity impact category and this was cause for a further sensitivity analysis.

8.1 Sensitivity 1: oceanic transport distances

At the baseline it was assumed that the substructures would be constructed at Messina and deconstructed at Genoa (a total oceanic transport distance of 1898 km). It was decided to test how changing the locations of the construction (shipbuilding yards) and deconstruction (shipbreaking yards) and consequently the distances of oceanic transport would affect the product-systems. Three scenarios were created for this sensitivity analysis.

- In the first scenario it is assumed that the MFS is not limited to EU approved shipbreaking sites. Instead, deconstruction at the port of Taranto or any other suitable point on the shoreline within 1km of where the MFS is stationed. This means there is a total oceanic transport distance of 482 km (construction still takes place in Messina).

- The second scenario assumes that the substructures are built at the port of Taranto and that this port has shipyards with the facilities to construct MFS substructures when scaled up to entire MFS blocks. This means there is a total oceanic transport distance of 1418 km (deconstruction still takes place at Genoa).

- In the third scenario it is assumed that the construction of the substructures occurs at the port of Monfalcone, which contains the Fincantieri Monfalcone shipyard, one the biggest shipyards in Italy (OECD, 2024). For this scenario there is a total transport distance of 2467 km (deconstruction still occurs at Genoa).

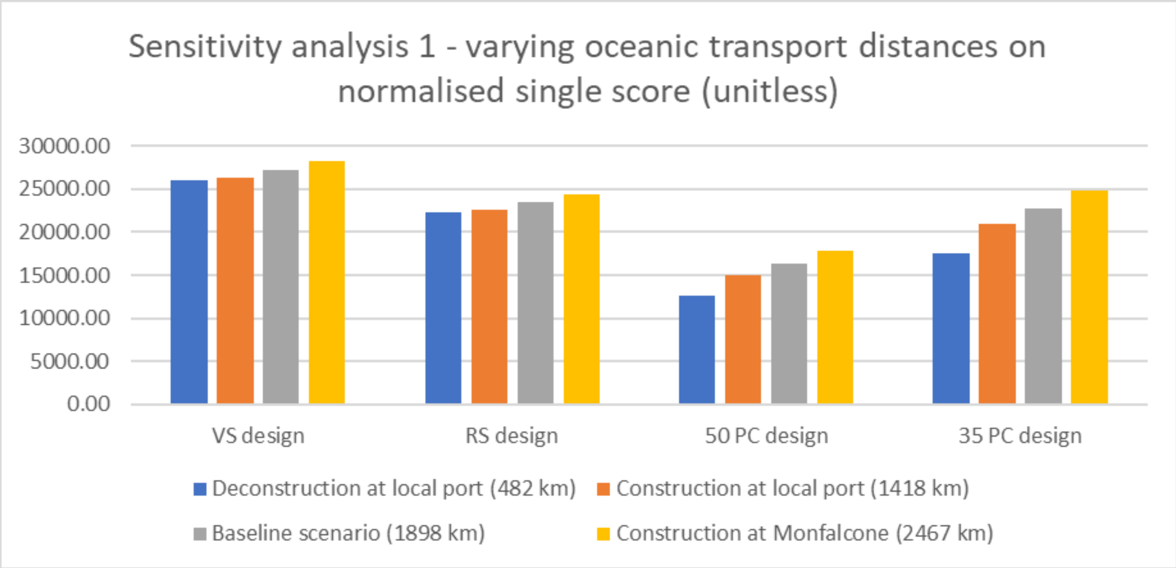


Figure 14. Sensitivity analysis 1 results. Overall normalised scores.

As was expected based on the contribution analyses, the effect of the oceanic transport distance changing is much more pronounced in the concrete designs than in the steel designs. Again this is due to the concrete designs' much heavier mass which gives them far higher ton-kilometre values than the steel designs. It can be seen in *figure 14* that the the *VS design* is by far the worst performing design, regardless of the oceanic transport distance while the *50 PC design* is by far the best performer. The *RS design* begins to outperform the *35 PC design* between the baseline 1898 km oceanic transport distance and 2467 km oceanic transport distance. This finding is significant as it implies that the overall environmental impacts of the concrete substructures are only lower than the steel substructures up to a certain distance.

8.2 Sensitivity 2: concrete requirements

The second sensitivity aimed to investigate the uncertainty in the model arising from the method of calculating the concrete requirements for the concrete based alternatives. To do this the results were rerun with the concrete based alternatives' models assuming +20% concrete requirements and -20% concrete requirements. This was applied to all the scenarios in sensitivity 1. As can be seen in *figure 15,* given the uncertainty, the *RS design* may begin to outperform the *35 PC design* as soon as ~500 km. The construction at Monfalcone scenario (2467 km total oceanic travel) is considered the most conservative reasonable scenario for the current case study and therefore the uncertainty range is capped at 2400 km oceanic travel.

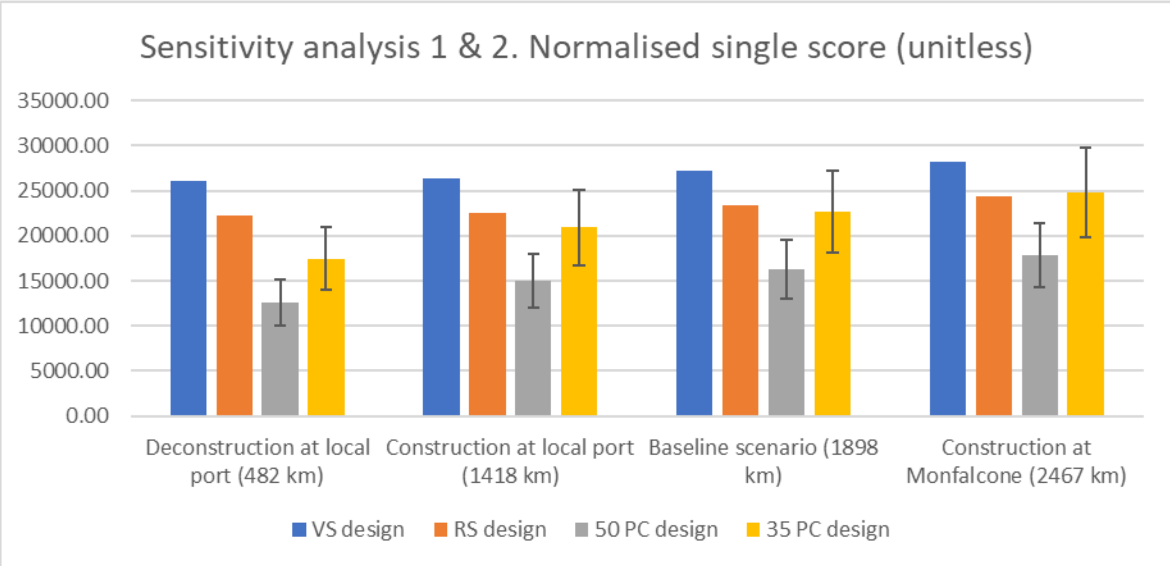


Figure 15. Sensitivity analysis 2 results. Overall normalised scores with 20% margin of error for the Portland concrete designs.

8.3 Sensitivity 3: sacrificial zinc anodes

As stated earlier, the 'zinc, to ocean' emissions were the greatest contributing flow to marine ecotoxicity in the steel substructure designs. The baseline assumptions regarding the sacrificial zinc anodes were 50% dissolution before replacement and an average replacement rate of once every five years. Given that there is evidence of sacrificial zinc anodes lasting up to 30 years on stationary structures in marine environments (see Appendix B) it was decided to perform a sensitivity extending the lifetime of the zinc anodes. The 50% dissolution of the anodes before replacement was kept constant because higher variability was seen in lifetime length and therefore the effect of lower/higher dissolution rates would fall within the range imposed by altering anode lifetime. A lifetime of 30 years was not taken as a scenario for the anodes because, in reality, the rate of corrosion and dissolution is subject to several factors (see again Appendix B) and this level of detail was not feasible within the context of the current research. Therefore more conservative scenarios were devised assuming anode lifetimes of 15 years and 20 years.

Lifetimes shorter than the baseline (5 years) were not added as scenarios because 5 years was already a very conservative assumption and a shorter lifetime was not seen as realistic. This sensitivity was not applicable to the concrete designs as they did not have sacrificial anodes.

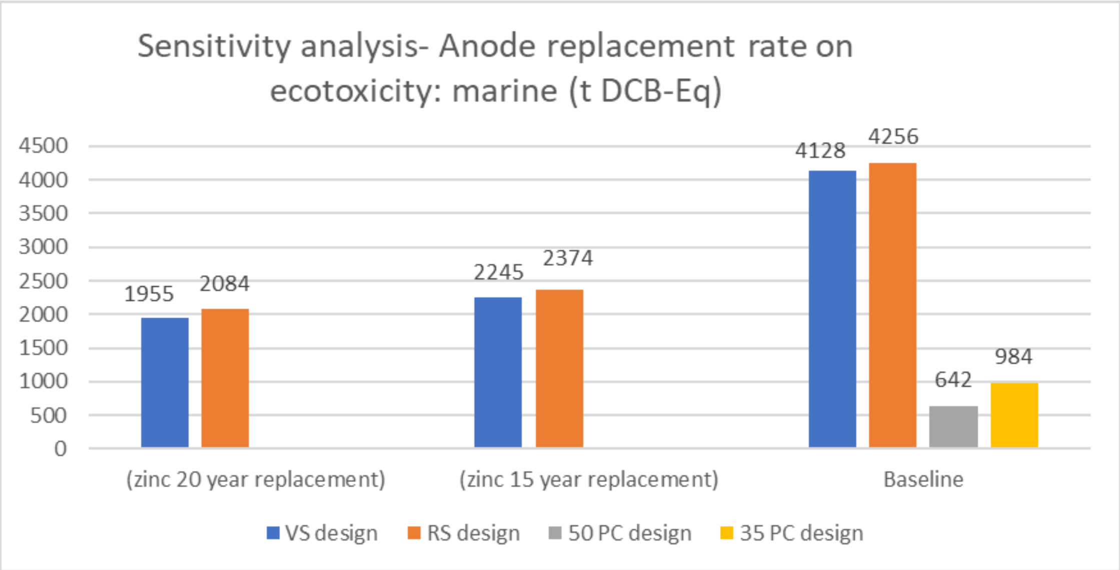


Figure 16. Sensitivity analysis 2 results for the ecotoxicity: marine impact category.

It was seen that extending the replacement frequency to every 20 years could more than half the marine ecotoxicity impacts of both steel design substructures. While a lifetime of up to 15 years led to reductions of 44% and 46% for the VS and *RS designs*, respectively. This is a positive finding for the steel designs, however even with these reductions the marine ecotoxicity impacts of the steel substructures are still much higher than those of the concrete design substructures (more than double the *35 PC design* and over triple that of the *50 PC design*).

8.4 Conclusion to sensitivity analyses

The highest uncertainty for overall impacts was found in the *35 PC design* where it ranged from - 38% to + 31% while the lowest uncertainty was exhibited in the *VS design* where it ranged from – 4% to + 4%. The implications of the sensitivity analysis for substructure design will be discussed in depth in section 9 and section 10.2.

9 Discussion of the results

The full lifecycle inventory of each product-system, from cradle-to-grave has been assessed in the inventory analysis. The environmental impacts of each system are shown in section 6.3.1. In sections 7 & 8 the validity and uncertainty of the results is explained. In the following section the implication of the results is discussed.

It is important to note that the *50 PC design* outperforms all other designs on paper however towards the end of this thesis research, literature demonstrating issues associated with the useability of 50 MPa Portland concrete were discovered. Higher strength concrete such as 50 MPa Portland concrete has issues regarding useability. This comes from an increased risk of cracking (American Concrete Institute, 2001) and difficulty regarding workability (Prem et al., 2020). Therefore for a project of the scale of an MFS substructure it is unclear if 50 MPa Portland is technically suitable for use. However, provided it can be used on the requisite scale it is the front running material for MFS substructure design.

As shown in the results the *VS design* performed by far the worst overall, and in most impact categories. When compared with the *RS design* it is seen that the *RS design* outperforms the *VS design* in virtually all impact categories except marine ecotoxicity and human toxicity: carcinogenic. The marine ecotoxicity impacts of the steel designs, given the current design, as highlighted in section 6.3.1 are far higher than that of the concrete designs. This is an important factor to bear in mind when making substructure design choices. Considering these observations it is clear that the argument for design choice lies between the *RS design* and the *35 PC design*.

From the results it is also clear that the proximity of construction and deconstruction sites is central to the improving environmental performance. The choice of material relates is crucial here. As shown by the normalised single score, the *35 MPa design* performs better overall than the *RS design* up to ~2467 km. It would be simple to say that using the *35 MPa design* and ensuring oceanic transport distances under ~2467 km is preferential. However in reality there are many factors to consider. In addition to the possibility of EoL deconstruction of the substructures being dictated by regulation, a further consideration is the capabilities of the shipbuilding yards and ports. In Wang et al. (2020) an arbitrary MFS layout of 53 twin-hull modules is considered as one block. This has an area of ~0.8 km^2 and can house approximately 19,000 people (Bikker, 2023). While a given port may have the capabilities to produce an MFS substructure they may not have the capabilities to produce, in a timely fashion, on the scale required by an entire floating urbanisation. In reality construction in multiple shipyards across several ports may be necessary. If this were the case then mixing the use of *RS design* and *35 PC design* substructures may reduce the environmental impacts of the overall floating urbanisation.

On this note, it is interesting to look at the reductions that could be made by choosing one substructure design over another when the application is upscaled. Taking the MFS block from Wang et al. (2020) when considering the baseline scenario, using the *RS design* over *35 PC design* would lead to CO_2-Eq savings of 131 kilotonnes per MFS block. Considering the fact that most of the datasets used pertained to the European region, rather than Italy, it can be reasonably assumed that these results will translate roughly to the general European context, assuming the oceanic distances travelled by the substructures are the same/similar.

If the use of MFS blocks is further scaled up to meet the requirements of a significant amount of Europe's coastal urban area expansion then CO_2-Eq savings grow accordingly. However the trade-offs should also be considered. A block of *RS design* substructures, given the current system design (notably sacrificial zinc anodes) would be far more toxic to the marine environment with greater DCB-Eq emissions of 171 kilotonnes. This highlights the importance of decision makers deciding early on which environmental impact categories are to be prioritised as there is no 'one-size fits all solution'.

A further point of discussion is that this research provides an indication of which design to take based solely on environmental performance as calculated by LCA. However, in practice other nuances should be considered when making design choices. These include pricing of materials, material availability. The *35 PC design* had by far the largest impact on abiotic depletion: minerals. While concrete and cement materials are abundant, the rules and regulations surrounding the mining of the required materials are growing more stringent, lowering availability. Furthermore concrete is not generally recycled and is instead usually landfilled or downcycled as aggregate material, mainly for road building (Lotfi et al., 2013; Gebremariam et al., 2020). This is due to the uncompetitive price of recycling compared to downcycling (Gebremariam et al., 2020). Downcycling only accounts for 9.4% of waste concrete in the EU due to the EoL concrete availability far outweighing the requirements of the road building industry (Lotfi et al., 2013). Steel on the other hand has a high recyclability potential and scrap steel can be smelted to form new steel of equivalent material properties endlessly. The *RS design* had by far the lowest abiotic depletion: minerals impact meaning that it requires the least raw mineral resources. This is a strong argument for choosing steel over concrete when constructing MFS substructures in the present day context, however future developments in concrete recycling (Lotfi et al., 2013) may negate this.

10 Limitations and recommendations

10.1 Limitations

10.1.1 Lack of primary data and high uncertainty

An outstanding limitation of the research was the lack of primary data in addition to the lack of data specific to the technology at hand. This was due to the prospective nature of the product systems understudy. The data used can be considered as best fit seeing as the substructures are designed to be constructed using conventional methods and facilities for shipbuilding (in the case of steel design) or regular construction and marine construction (concrete design). However representativeness suffers. For example, due to the differing shapes of the substructures and that of a ship, not to mention the higher intricacy in a ship hull than an MFS substructure there are likely discrepancies in the energy/t steel required in the construction of a ship and an MFS substructure. Furthermore, the cut-offs applied and proxies used (see sections 5.1.2; and 5.2.3; and section 7) are a limitation of the research.

Two main limitations were previously highlighted in the consistency and completeness section. The first being the different calculation methods for the requirements of concrete and steel. As previously stated the requirements of steel in a steel based MFS substructure were taken from Wang et al. (2019) where the value was rigorously calculated. The calculations to find requirements in a concrete-based MFS substructure done by the researcher in the present study are quite simplified compared to what would be required in real-life practice. Consequently they are less accurate. While a sensitivity analysis of the concrete requirements (+/-20%) was performed if, in reality, the requirements fall outside this range then it is not accounted for in the model. The second main limitation is the differential effect of drag for each substructure design. Accounting for this would likely increase the impacts of the concrete based substructures, and certainly would if equal velocity of towing were assumed for all alternatives. This would mean that steel substructures begin to outperform concrete substructures when the required oceanic transport distances of the substructure are less than 2400 km.

10.1.2 Variety of alternatives and their scope

In this thesis four alternative material designs for MFS substructures were considered. Two steel and two steel-reinforced concrete. This does not cover all the material types available on the market. For instance other materials which could be used such as fibre-reinforced concrete (Cejuela et al., 2020) or epoxy coated steel-reinforced concrete (Life Consortium II, 2020). Therefore it is important to note that the current research can only provide conclusions of the difference in performance of the materials analysed and cannot provide a conclusive recommendation on the best possible material choice.

Another limitation is the geographic coverage. The datasets used were a mix of European and World averages. This means that the results are not in reality fully representative of the case study selected. However because the choice of case study was relatively arbitrary and the goal was to draw conclusions on MFS substructures in a more general sense then the use of European and World datasets in fact increases the generalisability of the results. However then the inconsistency between European and World datasets becomes a limitation.

10.2 Recommendations

10.2.1 Recommendations for researchers

Future research akin to (Wang et al., 2019; Wang et al., 2020) should be done on concrete substructure designs to test its technical suitability and to accurately estimate the concrete requirements. Research should also be done to see how the drag and the consequent difference in fuel consumption is affected by the differing substructure designs.

Future LCA specific research should investigate the environmental impacts of other material alternatives such as concrete substructures reinforced with: (a) epoxy coated steel; or (b) plastic fibres. This is recommended given the surprising finding that the impacts in the concrete designs were largely from the stainless steel modelled rather than the concrete. This was especially unexpected due to the far greater mass of concrete than stainless steel used in the designs (156 kg stainless steel / 2315 kg concrete). The impacts in several categories came from the non-iron constituents (namely chromium) of the stainless steel.

The current research quantifies the environmental impacts of different MFS substructure designs. A further recommendation is to compare the environmental implications of MFS technology against other urban expansion methods in coastal cities such as:

- building upwards
- classic urban sprawl
- building on reclaimed land

A final recommendation is to investigate how the use of MFS would impact the local marine ecosystems. For instance MFS (substructures) could block out sunlight from reaching lifeforms in the sea such as macroalgae (seaweeds) and phytoplankton. However they could provide a substrate for which seaweeds to attach to. A fouling community would also form, likely consisting of multiple life forms. These organisms would even sequester carbon, nitrogen and phosphorus (Layman & Allgeier, 2020).

10.2.2 Recommendations for MFS developments

It is important to consider that the recommendations given are not absolute. Rather they are dynamic and liable to change depending on the specific environmental goals and concerns of parties who may be involved in the use of the MFS technology.

As mentioned in section 9 the proximity of construction and deconstruction sites is paramount for design choices to improve environmental performance. Therefore these locations should be clarified at the beginning of a project using MFS. For scenarios where the combined oceanic transport will be =/>2467 km it is recommended that the *RS design* is taken. However for shorter distances it is recommended that the *35 PC design* be used. This recommendation is based on the overall normalised environmental impacts however weighting should be applied depending on the interests of the stakeholders/actors involved. This weighting will have an influence on the overall environmental performance of the substructures and consequently would alter the oceanic transport distance at which *RS design* will outperform the *35 PC design*.

A final recommendation for the design is that, when the *RS design* is deemed best to use, rather than using sacrificial anodes an impressed current cathodic protection system (ICCP) system be employed. ICCP systems incur less damage to their local environment than sacrificial cathodic protection systems (Mohamed & Martin, 2023) and can last up to 75 years with proper upkeep (Brueckner et al., 2022).

11 Conclusion

This research aimed to investigate how the environmental performance of MFS substructures could be improved. To achieve this alterations to the substructure design were made. The primary alteration was using alternative materials: virgin steel, recycled steel, 50 MPa Portland concrete (reinforced), and 35 MPa Portland concrete (reinforced). Due to the varying density of these materials the concrete designs had to be amended in order for them to perform with a comparable buoyancy to the steel substructures. For the *35 PC* and *50 PC designs* the beams were extended to 34.5 m and 32 m, respectively. This meant that the design no longer conformed with industry minimum standards regarding ship beam lengths (30 m). The *50 PC design* had by far the greatest environmental performance of all designs. However 50 MPa Portland concrete entails some issues of workability and usability. In terms of present-day usability and environmental performance the two forerunning designs were the *RS design* and the *35 PC design* but the design choice is not black and white as trade-offs exist. For example the *RS design* had 7292 t CO_2-Eq emissions. This was significantly lower than the *35 PC design* 9769.55 t. However the latter design far outperforms the former in terms of marine ecotoxicity 984 t DCB-Eq vs 4256 t DCB-Eq, respectively. For the *35 PC design* most of these impacts are not to the local environment. However in the case of the *RS design* 63% of these emissions are to the local environment from sacrificial zinc anodes corroding into the sea. This could be lowered by using alternative cathodic protection, e.g. ICCP.

Normalisation and even weighting were applied to compare the overall impacts of the designs. When total oceanic transport distance of the substructures is 482 km the *35 PC design* outperforms the *RS design* by 22%. At 1898 km this decreases to 3%. At longer distances the *RS design* performs better due to its lighter mass and subsequent lower impacts from oceanic transport. At 2467 km the *RS design* outperforms the *35 PC design* by 1.6%. These findings highlight the importance of oceanic transport distance when considering the environmental performance of MFS substructures. This is subject to the weight and dimensions of the substructure thus making the density of the material used and the geometry of the substructure design (based on the materials properties) other important factors to consider when amending MFS substructure design in order to lower their life cycle environmental impacts.

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Appendix A

Geometric and mechanical properties

Buoyancy

To test the suitability of the substructure it had to be ensured to float at an acceptable height above sea level. In a typical vessel the freeboard is the height above the waterline of the vessel's main deck. Given the flat top of an MFS substructure, in the current system the freeboard refers to height above the waterline of the substructure's top plane.

For the freeboard to be found the draft of the substructure had to be calculated. The draft of a vessel refers to the maximum depth of said vessel below the waterline. In the case of the MFS substructure the structure has a horizontal bottom plane so the draft is uniform throughout. The amount of water displaced from the MFS pushing downwards into the sea is used to calculate a structure's draft. This is calculated using the formula:

$$draft = \frac{m}{swd * l * b}$$ where:

m = the total mass of the MFS including substructure, superstructure, outfitting, and payload.
swd = average saltwater density (1.025 t/m3)
l = the substructure length (100 m)
b = substructure beam (*x* m)

Given the default dimensions the concrete designs had a higher displacement of water due to the greater mass of their designs. A change in the dimension designs was necessitated to ensure that the concrete designs floated with more similar height above the water to the steel design proposed in Wang et al. (2019).

Material	Displacement (t)	Beam (m)	Draft (m)	Freeboard (m)
VS & *RS designs*	15,700	30	5.1	2.9
35 PC design	18,721	30	6.1	1.9
50 PC design	17,007	30	5.5	2.5

Table A.1.Substructure properties given original dimensions
Table A.1. 1

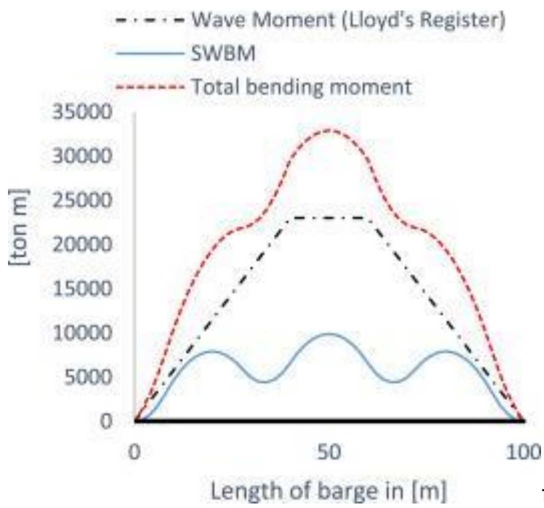
Material	Displacement (t)	Beam (m)	Draft (m)	Freeboard (m)
VS & *RS designs*	15,700	30	5.1	2.9
35 PC design	18598	34.5	5.26	2.74
50 PC design	16967	32	5.17	2.84

Table A.2. Properties given amended dimensions

The freeboard is acceptable so the theoretical designs of both concrete substructures is valid in terms of technical feasibility for the purposes of this LCA study (personal communication with G. Wang, May 9, 2024)

Bending moment

Bending moment is a measure of torque, due to an external load, within a structural element. The required bending moment, 35,000 ton m (343.25 million Nm) was taken from Wang et al. (2019). The 'total' bending moment is used to calculate the stress (see below for an explanation of stress) at any given point on the beam.



total

Figure A.1. Module9000 Longitudinal Bending Moment diagram (including total bending moment, still water bending moment and Wave Moment). Taken from Wang et al. (2019).

As stated in section 2.2.1 steel used in shipbuilding should have a yield strength of 235 MPa. A concrete compressive strengths, as stipulated in section 4.3, of 35 MPa and 50 MPa was taken in the current research. Furthermore a design with concrete of 50 MPa was investigated.

Bending stress of beam section

Bending stress (σ) is the internal tension/pressure which mounts in a material when it is being bent. The point of greatest stress occurs at the point farthest from the neutral axis. Using the box dimensions of: length 100 m; beam 30 m; depth 8 m (see *table 1*) and specific material strengths (see *table 9*), suitable material thickness can be determined using the bending stress of the object. A minimum safety factor of 3 was required to ensure that the substructure designs exceeded any potential stress they would hypothetically face (personal communication with G. Wang, January 25, 2024). In practice a safety factor of 3.06 was used. Ie the beam of each design could withstand 3.06 the amount of stress as calculated using the bending stress formula.

The bending stress formula is as follows:

$$\sigma_{bend} = \frac{My}{I} \text{ where:}$$

M = the internal bending moment about the neutral axis of the section (343.25 million Nm)

y = the perpendicular distance between the neutral axis and a point on the section (4 m)

I = the moment of inertia about the neutral axis of the section area

M and *y* were taken from Wang et al. (2019) however *I,* the moment of inertia, still contained unknowns.

Second moments of area

Also known as the moment of inertia (*i)* about the x-axis is a geometric property of a cross-sectional shape. It is required to calculate the bending moment of the substructure. It quantifies how the shape's mass is distributed in relation to a given axis. This indicates the beam's resistance to bending about the x-axis and is dependent on the beam's cross sectional geometry.

Given that the desired bending moment was already known, the moment of inertia about the *x-axis* was used to find the required material thickness of the substructure walls. Considering the present MFS substructure, i.e. a hollow rectangle with an in inner rectangle which has width (beam) b_1 and height h_1, the moment of inertia is given by the formula:

$$I_x = \frac{bh^3 - b_1 h_1^3}{12}$$

See *figure A.2.* below for a graphical representation of the cross-sectional structure.

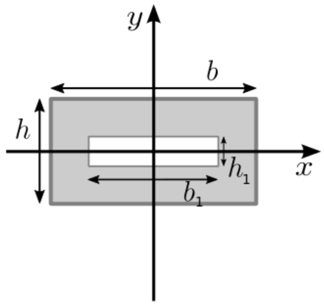


Figure A.2. Cross section of hollow rectangular structure.

Considering that the structure has an equivalent thickness (*t*) all around:

$$t = b - b_1 = h - h_1$$

Suitable values were found for *t* in all substructure designs by employing the aforementioned 'total' bending moment and the safety factor. Knowing all dimensions of the substructures allowed for the volume of the materials required to be calculated which was in turn used to find the mass of material required.

Material	**Strength (MPa)**	**Average thickness (m)**	**Inner beam (b_1)(m)**	**Inner height (h_1)(m)**
VS & *RS designs*	235	0.0172	29.97	7.97
35 PC design	35	0.1190	29.76	7.76
50 PC design	50	0.0824	29.84	7.84

Table A.3. Geometric properties of MFS substructures given the original default dimensions. The outer beam and height dimensions were equivalent for the steel and RS designs.

Material	**Strength (MPa)**	**Average thickness (m)**	**Inner beam (b_1)(m)**	**Inner height (h_1)(m)**
VS & *RS designs*	235	0.0172	29.97	7.97
35 PC design	35	.104	34.29	7.79
50 PC design	50	0.0775	31.85	7.85

Table A.4. Geometric properties of MFS substructures with amended dimensions.

Material mass required

The differential factor (*df*) between the material requirements of the steel-based MFS described by Wang et al. (2019) and the steel-based MFS devised in the current research using the calculated bending moment was applied to find the theoretical and acceptable (personal communication with G. Wang, January 25, 2024) requirements of concrete MFS substructures. This factor was calculated using the formula:

$$df = \frac{m_a}{m_{bm}}$$ where:

m_a= the twin-hull substructure mass as stated in Wang et al. (2019)

m_{bm} = the twin-hull substructure initial mass calculated as described above

In addition to the required material from the calculations described above m_{bm} also contains caps to seal the structures. These caps are of equivalent thickness to their respective design.

The final mass of the substructures is given by the equation:

$$M_{final} = df * m_{bm} + c$$ where:

c = the hull connection

Additional material is required for connecting the monohull Module9000 substructures. Each monohull-module was connected using three connectors each of 20 m width (see *figure A.3.* below). Given the total twin-hull beam length of 75 m the length measure of each connector varied between designs depending on the substructure's beam. The buoyancy of the connectors was not a concern as they are not designed to be loaded with a payload. The thickness of each connector and the material used was respective to its design.

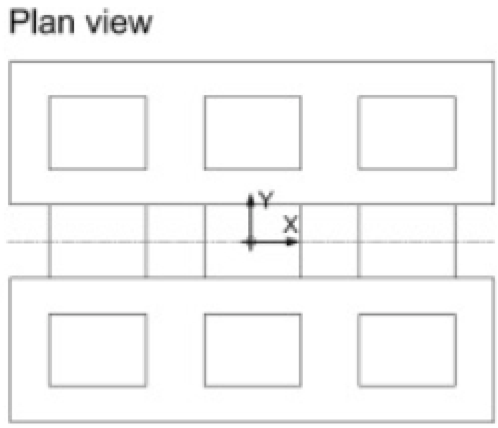


Figure A.3. Plan view of twin-hull MFS (From Wang et al., 2019)

Material	**Density (t/m3)**	m_{bm} **(t)**	$m_{df} + c$ **(t)**
VS & *RS designs*	7.874 (Bohnenkamp & Sandström, 2000)	2186.73	5647.4
35 PC design	2.471 (Younis et al., 2018; Ecoinvent, 2024)	4631.65	12286.56
50 PC design	2.488 (Younis et al., 2018; Ecoinvent, 2024)	3271.03	8938.62

Table A.5. Material density (including steel rebars), the initial mass (excluding df), the final mass used in model (including the connectors)

Appendix B

Description of substructure designs

Steel design

Construction

Energy and bulk material inputs

As mentioned in the main text, only energy inputs, raw materials and losses were considered in this research. For these inputs data from the shipbuilding industry was used.
The data found (Kameyama et al., 2007; Nicolae et al., 2014; Harish and Sunil, 2015; Cucinotta et al., 2021) was averaged to provide the resource input/net t of steel.

Coating & Protection

Multiple layers of coating are commonly used for protecting marine vessels. The primer (base layer) is often a coating based on epoxy, polyurethane or acrylic. This coat acts as a protective barrier between the hull and the environment. Often two layers are used (American Bureau of Shipping, 2018). A layer of antifouling coat is used in conventional vessels to reduce the occurrence of bioforms attaching to ship hulls which cause the ship to drag against the ocean thus increasing fuel consumption (Devanny & Riastuti, 2019; Gelengenis, 2022). In the model antifouling was not included because the substructure is not intended to travel with the frequency of a ship. It is only intended to travel when being taken to site of operation and, after its lifetime, to its end of life (personal communication with G. Wang, March 7, 2024). It is still worth noting, however, that currently available antifouling products are highly toxic to the environment however research into environmentally sound antifouling products based on zosteric acid is well underway (Jendresen & Nielsen, 2019; Zhang et al., 2023; European Commission, 2023).

Paint and coatings are not the only protection steel structures need in the marine environment. Cathodic protection is an electrochemical process required for slowing down the rate of corrosion of steel in vessels and marine infrastructures. It ensures longevity of steel structures. This is most commonly achieved by inducing galvanic corrosion on another metal (zinc). Zinc and steel have different electrical potentials when they are placed within an electrolyte (sea water). When the two metals are in contact with each other a small electrical current is applied to the structure. Zinc acts as the anode (positive electrode) while steel becomes the cathode (negative electrode). The steel receives electrons from the zinc, this is known as reduction, and oxidation occurs at the zinc when these electrons are released (Hussain et al., 2021). Ie. the zinc corrodes instead of the steel. This is quite commonly and simply achieved by placing pieces (anodes) of zinc spread out across the steel surfaces (Rees et al., 2017; Rees et al., 2020). The amount of zinc required is estimated at 0.147 kg/t steel (Cucinotta et al., 2021). It should be noted that this assumption is highly simplified because in reality the rate of corrosion of structural steel and sacrificial anodes in the marine environment is a result of several factors: pH, flow velocity, temperature, salinity (chloride content) of the seawater, marine organisms present and dissolved oxygen content (İz & Köylüoğlu, 2023). Furthermore the exposure of the steel is a factor i.e. if it is submerged, in a tidal zone (sometimes submerged sometimes not), in a splash zone, or in an atmospheric zone.

Maintenance

In ship maintenance the old paint in the exposed surfaces must be fully stripped before applying fresh layers (Kaddour, 1990). However, in the model, the below waterline surfaces were not stripped of their layers as it was assumed that the sea life which attaches itself to these underwater surfaces will act as further protection against corrosion. Furthermore the substructure is intended to be as non-invasive to the local ecosystem as possible and the function of the substructure as a habitat for sea-life is an encouraged element of its design (personal communication with G. Wang, February 29, 2024).

A coating maintenance of every five years was assumed (personal communication with G. Wang, February 8, 2024). And sandblasting is the method of choice for stripping old paint from ship hulls. Sandblasting involves spraying small particles, usually grit or sand, at speed against the surface to be stripped of paint. The abrasive force of these particles strip paint from the surface. Fine particulate matter forms as a result and this is a pollutant to air while the solid remains of the paint, grit and oxidised (rusted) iron are a solid waste which in, shipyards, can be gathered to be disposed of properly (Kaddour, 1990; Dong & Cai, 2020). In the current system, because maintenance is assumed to take place out at sea (personal communication with G. Wang, March 15, 2024). Therefore it is assumed that the remains from the sandblasting are emitted directly to the sea as ‘solids, inorganic’.

Zinc anodes need to be replaced once they are worn to 40-60% of their original mass. This is based on the replacement of zinc anodes in small leisure crafts (Rees et al., 2017; Rees et al., 2020) however it is assumed that this holds true for vessels and structures of any size. Based on this 50% of the zinc which entered the system boundaries was modelled as direct zinc emissions to the ocean. The rest of the zinc was returned to the economy as zinc scrap. Regarding the replacement rate (frequency over time) of the zinc anodes there was a data gap for anodes on stationary steel structures. Assuming a similar replacement rate as ships, which constantly move and thus increase the rate of anode corrosion, was considered an overestimation. Therefore the longevity of sacrificial zinc anodes on other stationary structures was investigated. There is evidence of protection from zinc anodes on bridges and other stationary steel-reinforced concrete structures lasting up to twenty and even thirty years (Rafdinal, 2016; Brueckner et al., 2022). Considering a sacrificial anode replacement rate range of 1-30 years for various vessels and structures, a conservative assumption was made with the replacement modelled as occurring every five years.

End of Life

The steel based substructure is also sandblasted at its EoL in order to prepare the steel for recycling (Wang et al., 2018). The energy inputs for shipbreaking (excluding sandblasting) from Harish & Sunil (2015) were assumed for the steel-design substructure. Gervasio & Dimova (2018) stated a recycling rate of 90% for structural steel in the EU. No source was found to indicate the fate of the remaining 10% so it was assumed that this was split evenly between incineration and landfill.

Reinforced concrete design

Construction

Energy and bulk material inputs

Concrete losses in the European construction industry are estimated to be 1-4% (Correia et al., 2009). For the current research a conservative approach was taken and 4% concrete losses were assumed. The mass of steel rebars needed, 156 kg/m3 concrete, was assumed to be equivalent to those of a ten-storey building (Younis et al., 2018). The MFS substructures are designed to hold ten-storey suprestructures (Wang et al., 2019). A combustion of 5.74 l/m3 concrete was also assumed for the mixing truck mixing in the transportation of the concrete mixture (Ecoinvent, 2024). As mentioned in the main text the energy required for the pumping of the concrete was cut-off due to a data gap.

Coating & Protection

The concrete designs were assumed to not use coatings or cathodic protection. Instead it was assumed that sufficient reinforcement depth and stainless steel rebars were ample protection against the corrosion of the rebars (Mistry et al., 2016).

The software Life-365 (www.life-365.org) as used by Mistry et al. (2016) was furthermore used to investigate if the concrete designs were suitable. For this the dimensions of the concrete slabs were input and the exposure (<1.5km out in ocean in a Mediterranean climate) was accounted for. A minimum reinforcement depth of 4.5 cm was found to be necessary for the designs to last long enough. In the Ecoinvent v3.9.1 (2024) datasets 'RoW: concrete production, 50MPa, with cement, Portland' and 'RoW: concrete production, 35MPa, for civil engineering, for exterior use, with cement, Portland' a 24% fly ash/silica fume/blast furnace slag content in the cement is stated. Given a 24% fly ash or slag content in cement, it was seen that stainless steel rebars were suitable for periods of 100 years or longer without maintenance while black/ungalvanised steel rebars and epoxy coated steel rebars were not. Epoxy coated steel rebars could last to nearly 100 years provided the cement mix had a 15% silica fume content however an epoxy coated rebar design was not investigated.

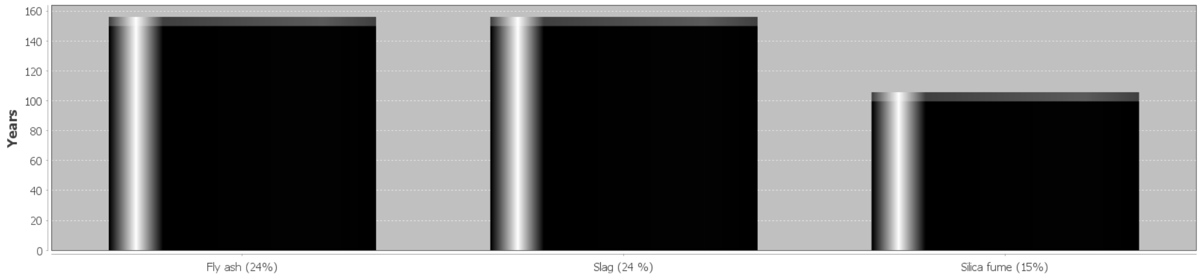


Figure B.1. Stainless steel reinforced concrete substructure lifetime (estimated using Life-365 software)

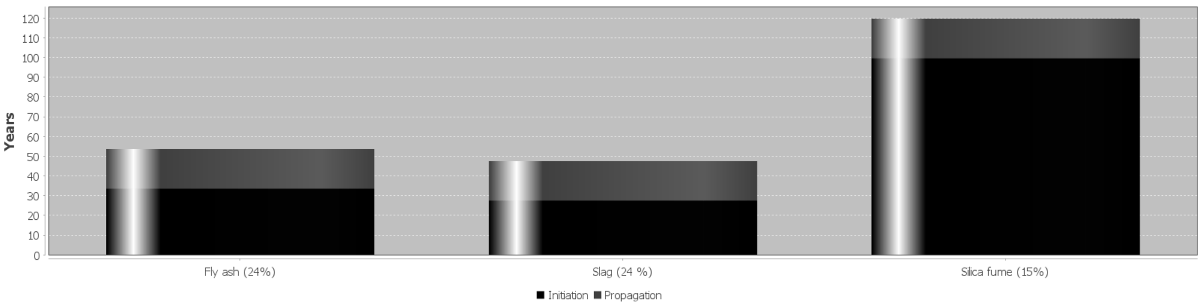


Figure B.2. Epoxy coated steel reinforced concrete substructure (not modelled) lifetime (estimated using Life-365 software)

Maintenance

As stated in section (inventory analysis baseline scenario) no structural maintenance was required for any substructure design. Given that the concrete design does not have coatings or cathodic protection no required maintenance was assumed.

End of Life

It was assumed that the energy required for the deconstruction of the concrete substructures was 0.070 Mj/kg (Gervasio & Dimova, 2018). Concrete is usually deconstructed with diesel powered machines e.g. jackhammers, demolition machines so it was assumed that deconstruction made use only of diesel fuel.

In Italy concrete is recycled at a rate of ~60% while steel rebars are recycled at 70% (Gervasio & Dimova, 2018). These figures were assumed for the current research. Furthermore a concrete landfill rate of 40% was assumed because concrete is not often incinerated. For the remaining 30% of rebars it was assumed that the EoL fate is split evenly between incineration and landfill.

Appendix C

See Excel file 1 for inventory analysis inputs and calculations

See Excel file 2 for raw results

Appendix D

Additional results

Default concrete designs

Amending the designs of the *35 PC* and *50 PC* substructures based on their buoyancy led to reductions of the concrete total concrete requirements of 5% and 2% respectively. This is because beam length was a variable for the total bending moment of the substructures and increasing the beam led to a higher resistance to bending. This meant that thinner slabs (i.e. requiring less concrete) could be used to achieve equivalent strength. The overall difference in environmental performance between the amended and default designs was proportional to the amount of concrete saved and can be seen in *figure D.1.* below.

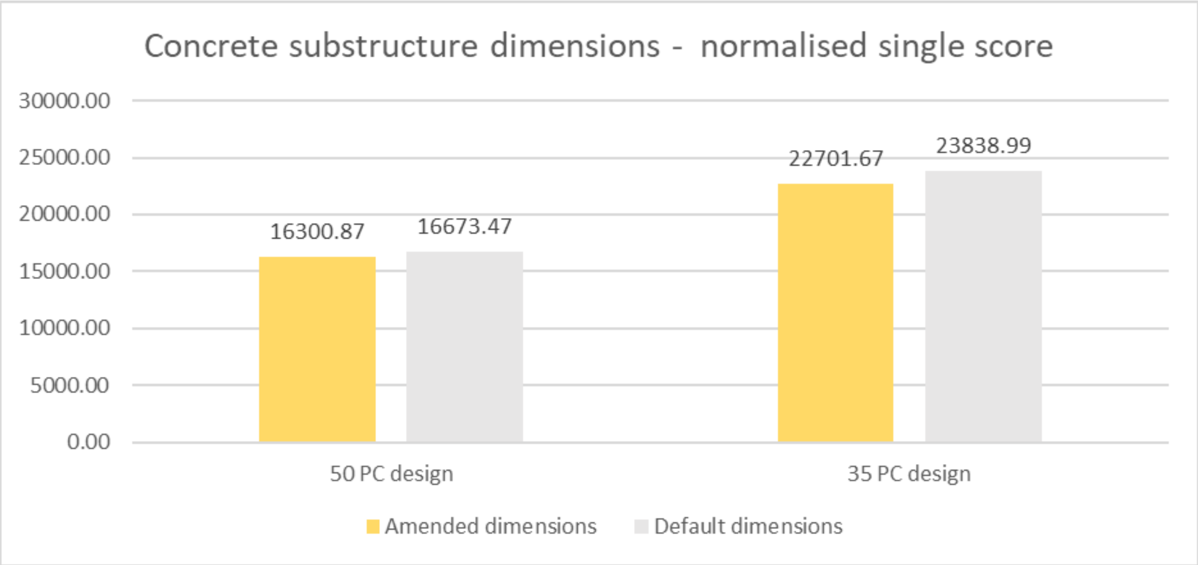


Figure D.1. The effect of the concrete substructure dimensions on the normalised single score (overall impact)

Analysis of human toxicity: carcinogenic

Human toxicity: carcinogenic was the impact category which had the highest normalised score in each substructure design. As can be seen in *figure D.2.* below the *RS design* had by far the greatest normalised result (9795), and implicitly the highest characterised result. Implying that over its lifetime the *RS design* substructure expose people to as many carcinogenic toxic as all the activities incurred by 9795 people worldwide in the year 2010.

The contribution analysis revealed that, in the *RS design,* a 92% contribution was found coming from the landfilling of electric arc furnace slag which results from the production of smelting of the scrap steel. In the *VS design* the greatest contribution (55%) came from the coke used for smelting in the steel production. For the concrete designs 70% of the impacts derived from the production of ferrochromium which was used to make the stainless steel. Stainless steel usually has a chromium content of ~18% (United States Geological Survey, 2010) while the stainless steel modelled had a chromium content of 19%. Chromium is essential to the anti-corrosive properties of stainless steel and therefore lowering the content chromium is not a feasible way to lower carcinogenic impacts of the concrete substructures.

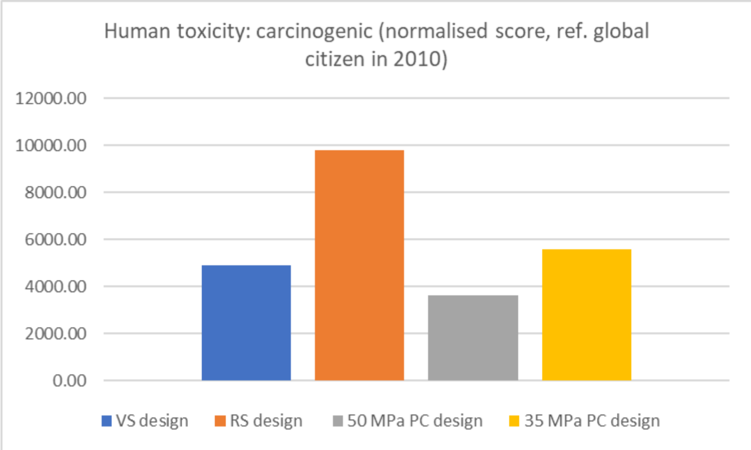


Figure D.2. Normalised results of human toxicity: carcinogenic (unitless measure).

A final sensitivity analysis was conducted due to the high human toxicity: non-carcinogenic impacts associated with the landfilling of slag born from the recycling of steel in the recycled steel substructure design. In this final sensitivity scenario the sensitivity for the *RS design*, the design with the highest human toxicity: carcinogenic score, was tested. At the baseline only 4% of the slag associated with the production of recycled steel was recovered while the rest ended up in residual landfill. In the EU recovery of slag from steel production was 76% in 2010 (European Commission, 2019) and there are even claims of recovery up to 94% in Germany (Teo et al., 2020). In this sensitivity a recovery rate of 76% for electric furnace slag was tested.

Devising this sensitivity involved the remodelling of the Ecoinvent datasets ‘Europe without Switzerland: steel production, electric, low-alloyed’ and ‘Europe without Switzerland: market for electric arc furnace slag’. While electric furnace slag was a flow in all substructure designs the *RS design* is the only one where there are large quantities of this slag. Furthermore the human toxicity impacts were well spread out across several flows in the other designs rather than concentrated as is the case in the *RS design*. Given these factors and the time constraints of the research this additional sensitivity was only applied to the *RS design* because it was not anticipated to make a large difference to the remaining designs proportionate to the time investment of remodelling the several necessary datasets to test each design.

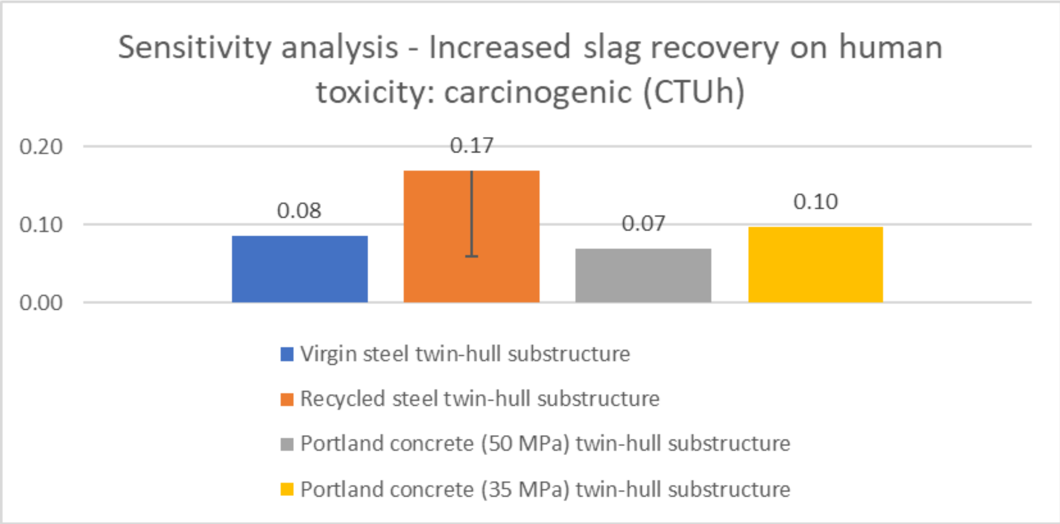


Figure D.3. Sensitivity analysis results (represented by the error bar) for the human toxicity: carcinogenic impact category.

Increasing the slag recovery reduced the impacts in human health: carcinogenic to lower than that of the other substructure designs. It also decreased the impacts in several other categories however in some categories, including climate change, the impact increased. This is mainly due to higher energy use in the higher recovery scenario. These findings imply that, in reality, the carcinogenic impacts of the *RS design* may be far lower than initially calculated. In fact it may perform closer to the other substructure designs in this regard, however it is pertinent to keep in mind that the carcinogenic effects of the other substructures would also be reduced slightly by increasing slag recovery rate in their modelling.

Appendix E

Additional information

LCA typology

Firstly, LCA can be classified at the level of depth that the product system will be studied at: simple/simplified or detailed. Detailed LCA provides the most in-depth and rigorous analysis. For example, simple LCA abides mostly by the ISO standards but not fully while detailed LCA is completely in-line with the ISO standards (Guinée, 2002). There are additional dimensions along which one can classify LCA. Arvidsson et al. (2023) state these to be real time, maturity, and causality. Sandén & Karlström (2007) state two dimensions: time and responsibility.

Real time (measured in years): This dimension encapsulates the time difference between the operationalisation of the modelled technology (i.e. the temporal state of its environmental impacts) and the LCA study (Arvidsson et al., 2023.; Sandén & Karlström, 2007). If the modelled technology is currently operational, and the LCA is conducted presently, then the LCA can be called *contemporary* (Arvidsson et al., 2023; Sandén & Karlström, 2007). If the modelled technology will be operational at a future point in time it can be called *prospective* (Arvidsson et al., 2023; Sandén & Karlström, 2007).

Maturity: This refers to the technology readiness levels and manufacturing readiness levels (MLR) of technology/product. In *figure E.1.* below the different time and maturity dimensions of various LCA sub-types can be seen.

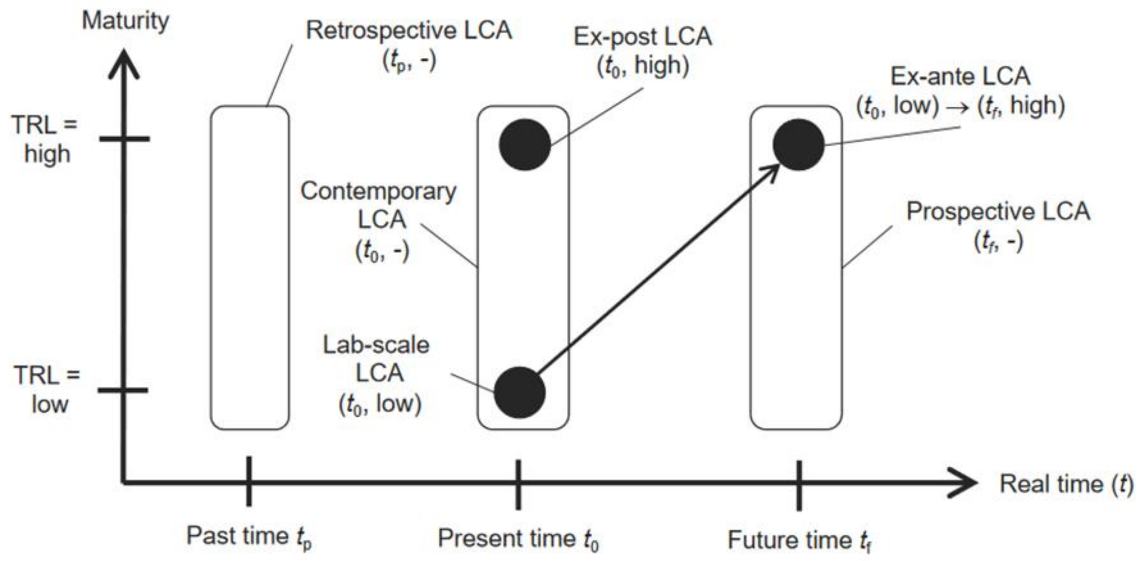


Figure E.1. Schematic illustration of the dimensions of real time and maturity with numerous LCA types labelled (source: Arvidsson et al., 2023)

Causality/responsibility: This dimension is divided into two classifications, attributional and consequential. Attributional LCA considers the upstream effects of the combinations of products and processes which result in the technology/product system studied. Consequential LCA considers all that attributional LCA considers in addition to the downstream effects of a technology such as marginal market effects, rebound effects, and efficiency improvements from learning and economies of scale. In short, consequential LCA also encompasses the environmental implications of the use of the technology (Ekvall, 2019).