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Stahlbau

- Zukunftsfähiger Stahlbau – Gamechanger zugunsten der Nachhaltigkeit
- Leitfaden zur Wiederverwendung von Stahlbauteilen
- Zum Einsatz von emissionsreduzierten Stahlprodukten in der Gebäudehülle
- Vergleichende Ökobilanzstudie von Varianten einer Hallenkonstruktion
- Stahl-Energiepfähle aus der Erde ins Labor
- **Life cycle assessment of an underground car park's retaining walls**

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Life cycle assessment of an underground car park's retaining walls

In 2020, the construction sector contributed to 37 % of global CO_2e emissions. While efforts have primarily targeted reducing environmental impacts related to building operations through enhanced energy efficiency, the significance of addressing embodied impacts (arising from materials/products) has recently garnered attention. Underground car parks (UCPs) mitigate the scarcity of parking space in densely urbanized regions, though they pose unique design and construction challenges not encountered in above-ground structures. This paper seeks to compare the environmental performance of retaining walls within the excavation pit of an UCP associated with an office building in Berlin, Germany, over a service life of 50 years through a life cycle assessment (LCA). Four structural alternatives are evaluated: (a) permanent steel sheet pile, (b) temporary steel sheet pile with a permanent reinforced concrete wall, (c) permanent concrete secant pile, and (d) permanent concrete diaphragm wall. Utilizing the life-cycle framework outlined by EN 15798, the LCA encompasses the product stage, construction process, repair, end-of-life, and benefits and loads beyond the system boundary. Predominantly based on environmental product declarations in accordance with EN 15804+A2, the LCA meets ISO 14044 requirements and has successfully undergone critical review by an independent panel comprising three German experts.

Lebenszyklusanalyse der Stützmauern einer Tiefgarage
Im Jahr 2020 trug der Bausektor zu 37 % der globalen CO_2e-Emissionen bei. Während sich die Bemühungen i.d.R. darauf konzentrieren, die Umweltauswirkungen im Zusammenhang mit dem Gebäudebetrieb durch verbesserte Energieeffizienz zu verringern, hat die Bedeutung der grauen Emissionen (die sich aus Baumaterialien und -produkten ergeben) kürzlich Aufmerksamkeit erlangt. Tiefgaragen entschärfen den Mangel an Parkplätzen in dicht besiedelten Gebieten, wobei sie einzigartige Herausforderungen in Bezug auf den Entwurf und die Ausführung mit sich bringen, die bei oberirdischen Strukturen im geringeren Ausmaß auftreten. Diese Arbeit zielt darauf ab, die Umweltauswirkungen von Stützwänden innerhalb der Baugrube einer Tiefgarage, die mit einem Bürogebäude in Berlin, Deutschland, verbunden ist, über eine Nutzungsdauer von 50 Jahren durch eine Ökobilanzierung (LCA) zu vergleichen. Vier technische Varianten werden bewertet: (a) permanente Stahlspundwand, (b) temporäre Stahlspundwand mit permanentem Beton, (c) permanente Bohrpfahlwand und (d) permanente Schlitzwand. Unter Verwendung des Lebenszyklusrahmens gemäß EN15798 umfasst die LCA die Produktionsphase, den Bauprozess, die Reparatur, die Entsorgungsphase sowie Nutzen und Lasten über die Systemgrenze hinaus. Überwiegend basierend auf Umweltproduktdeklarationen gemäß EN15804+A2, erfüllt die LCA die Anforderungen der ISO14044 und wurde von einem unabhängigen Gremium bestehend aus drei deutschen Experten kritisch überprüft und validiert.

Keywords life cycle assessment; LCA; sheet piles; embodied carbon; retaining walls; environment; underground car park

Stichworte Ökobilanzierung; LCA; Spundwand; graue Emissionen; Stützwände; Umwelt; Tiefgarage

1 Introduction

In 2020, compared to other sectors, 37 % of the global share of energy-related CO_2e emissions were attributed to buildings and the construction sector [1]. So far, most of the efforts have been brought to reduce the operational carbon footprint of buildings by improving their energy efficiency. In addition, recently, awareness has also been raised on embodied carbon: emissions from materials/products must be urgently addressed to ensure sustainable constructions, optimized as low CO_2e emission solutions.

In response, European countries are accelerating their efforts to comply with climate change commitments and regulations as pressure grows for the construction sector to reduce its impact rapidly. While a common EU policy on whole-life carbon is still in the making, some European countries have introduced policies to reduce whole-life CO_2e emissions from buildings and construction.

An LCA can be applied to assess the environmental impacts of constructions: it is a science-based and standardized, [2, 3] methodology for quantifying and reporting on environmental impacts. Amongst several other purposes, it is used to measure and provide insights to reduce the CO_2e emissions of constructions over their life cycles: before the use of the building, during the use of the building, and at the end-of-life (EOL) of the building. To improve the effectiveness of the process, LCA should, as far as possible, be performed at the earliest stage of a construction project [4]. In this context, emissions from materials/products must be urgently addressed by LCAs to ensure that constructions being built today are

Tab. 1 Functional unit definition
Definition der funktionellen Einheit

Functional unit definition	
Functional unit	One retaining wall of a total length of 112 m spanning two underground levels for a total excavation height of 9.5 m over a 50-year analysis period. The excavation pit is squared-shaped with sides equal to 28 m.
Reference unit	One retaining wall with a total length of 112 m.
Location	Berlin (DE).
Quantification	Material content as defined by the design office GRBV.

optimized for low CO_2e emission solutions across their entire life cycle. This involves evaluating each design choice using a whole life-cycle approach to minimize upstream greenhouse gas emissions (e. g., low CO_2e emission materials) and taking steps to avoid downstream greenhouse gas emissions (e. g., circularity).

Underground car parks (UCPs) target parking issues in cities, but are complex and costly. ArcelorMittal is innovating sustainable underground construction using steel sheet piling for retaining walls. This method speeds up construction, reduces material use and waste by eliminating the need for permanent walls in excavations.

The present report details the LCA of the retaining walls within the excavation pit of an underground car park associated with a specific building (e. g., commercial, residential, office use, etc.) assumed to be constructed in Berlin (DE) with 50 years of required service life (RSL).

The structural design of the retaining walls was conducted by the German design office GRBV Ingenieure im Bauwesen. Four retaining wall options for the underground car park: permanent steel sheet piles, temporary steel sheet piles with RC walls, secant pile walls, and diaphragm walls. These options were selected because they suited the project's requirements and were common in the German market for underground car park construction.

The boundaries of the LCA are the product stage (modules A1–A3), the construction process (modules A4–A5), repair (B3), the EOL (modules C2–C4), and the benefits and loads beyond the system boundary (module D).

The LCA calculations were performed using the commercial software One Click LCA [5]. This choice was driven by the assessor's previous experience with the tool, and the accessibility to most of the datasets used in the study.

2 Goal and Scope

2.1 Goal

The goal of this study is to assess the life cycle environmental impacts associated with four different types of retaining wall systems within the excavation pit of an underground car park. The study observes impacts over a 50-year analysis period at one location: Berlin, Germany.

The results of this study are intended to support different construction chain players (e.g.: engineers, architects, design offices, etc.) in the construction decision-making process by providing comparisons of the potential environmental performance improvement.

2.2 Functional unit

The construction work analysed in this report concerns a retaining wall. The functional unit is described in Tab. 1.

2.3 Product description

The present LCA considered 4 technical solutions (VARIANTS) for a retaining wall:

- VARIANT 1: Permanent steel sheet pile (SSP) wall;
- VARIANT 2: Temporary steel sheet pile wall in combination with a permanent reinforced concrete (RC) wall;
- VARIANT 3: Permanent Secant Pile wall (RC);
- VARIANT 4: Permanent Diaphragm wall (RC, also known as "slurry wall").

Each of these variants will be presented in detail in this section.

Fig. 1 presents the plan view of the retaining wall, the excavation pit, and the location of the neighbouring buildings.

The adopted soil properties are typical for the Berlin region as depicted in Fig. 2 and Tab. 2.

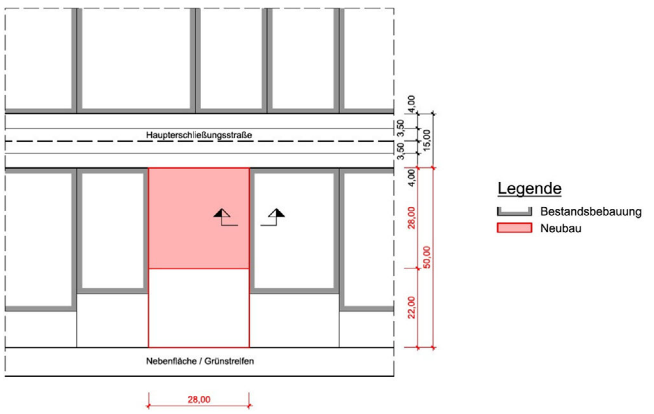

Fig. 1 Plan view of the building and its surroundings
Gebäude- und Umgebungsplan

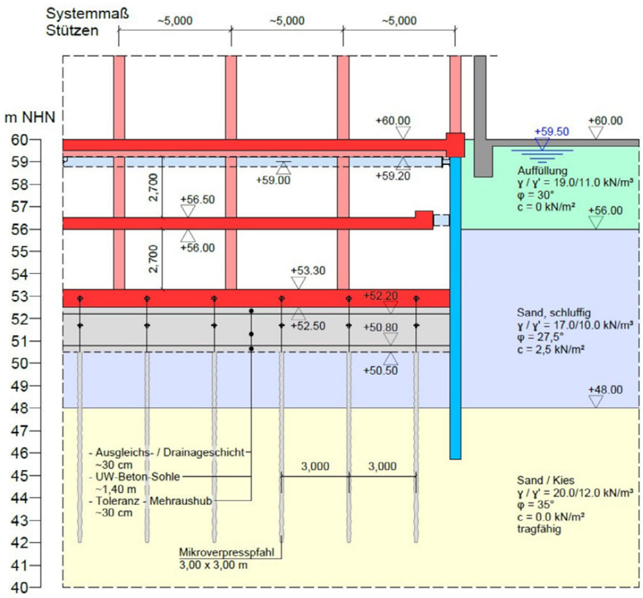

Fig. 2 Underground car park cross-section
Querschnittplan der Tiefgarage

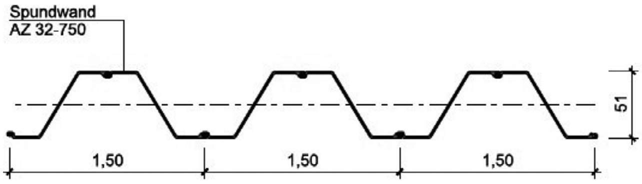

Fig. 3 ArcelorMittal's AZ 32–750
ArcelorMittal's AZ 32–750>

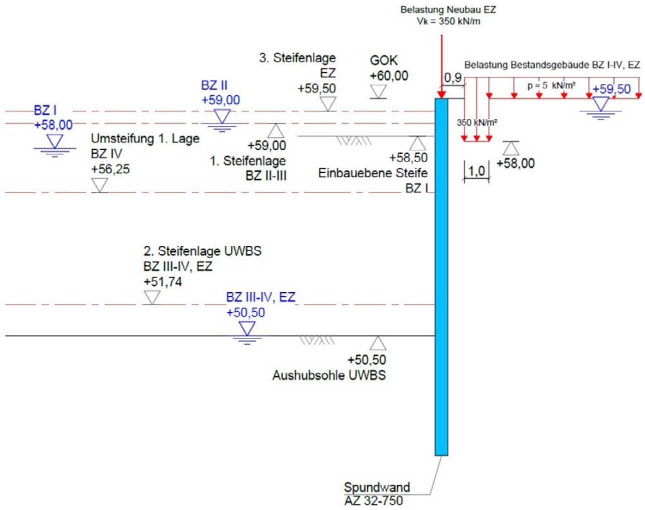

Fig. 4 Permanent steel sheet pile wall system
Dauerhaftes Spundwandsystem aus Stahl

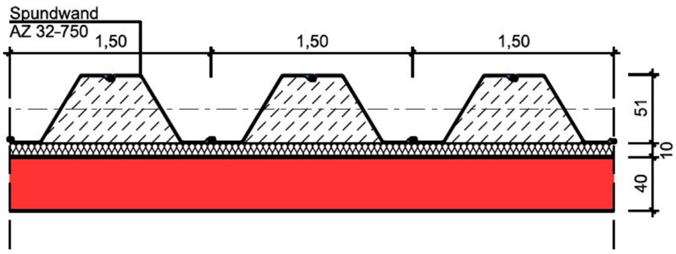

Fig. 5 Temporary steel sheet pile wall
Temporäre Stahlspundwand

Structural design solutions are functionally equivalent due to equivalent boundary conditions (design assumptions, building situation, soil, safety, and actions) based on German and European standards. The retaining wall designs ensure structural integrity for a 50-year RSL and R90 fire resistance, while maximizing utilization ratios for economical solutions.

2.3.1 VARIANT 1: Permanent Steel Sheet Pile

For the steel sheet pile permanent solution (Variant 1), the profile AZ 32–750 was selected (Fig. 3).

The final scheme of the steel sheet pile wall solution is presented in Fig. 4. The total height of the steel sheet pile is 14.50 m.

2.3.2 VARIANT 2: Temporary Steel Sheet Pile

As the governing design phase is the temporary phase, the design of the temporary sheet pile wall is identical to Variant 1. The schematic cross-section of the temporary steel sheet pile wall (Variant 2) is presented in Fig. 5.

The final scheme of the temporary steel sheet pile wall solution is presented in Fig. 6. The total height of the steel sheet pile is 14.50 m and the total height of the permanent reinforced concrete wall is 7.50 m.

2.3.3 VARIANT 3: Reinforced Concrete Secant Pile Wall

Overlapped secant piles of 1.18 m diameter were proposed for the reinforced concrete secant pile walls (Variant 3) with its schematic cross-section presented in Fig. 7.

The final scheme of the reinforced concrete secant pile wall solution is presented in Fig. 8. The total height of the

Tab. 2 Soil profile
Untergrundprofil

Layer	N°	Layer Bottom Elevation [mNHN]	Unit Weight [kN/m³]	Submerged Unit Weight [kN/m³]	Friction Angle [°]	Cohesion [kN/m²]	Tip Resistance (CPT) [MN/m²]
Fill	1	+56	19	11	30	-	5
Silty Sand	2	+48	17	10	27.5	2.5	5
Sand & Gravel	3	from +48	20	12	35	-	15

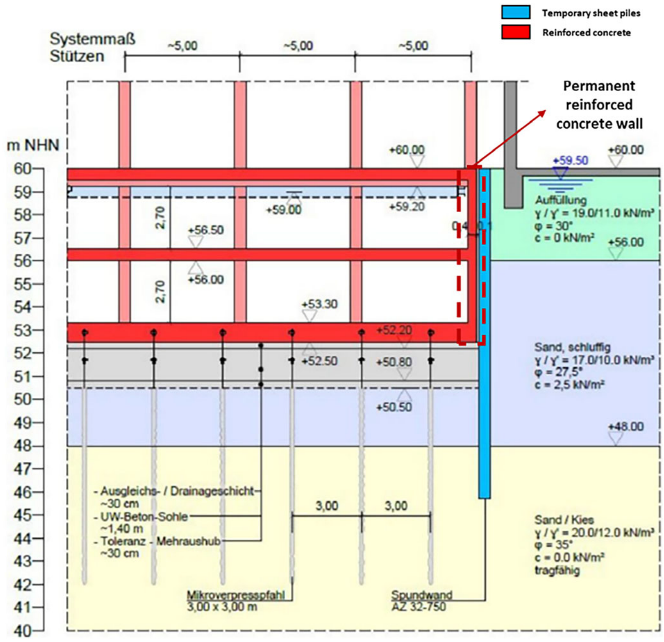

Fig. 6 Temporary steel sheet pile wall and reinforced concrete permanent wall
Provisorische Stahlspundwand und permanente Stahlbetonwand

reinforced concrete secant pile is 14.50 m.

2.3.4 VARIANT 4: Reinforced Concrete Diaphragm Wall

A reinforced concrete wall of 1 m was proposed as a diaphragm wall solution (Variant 4). The retaining wall solution cross-section is presented in Fig. 9.

The final scheme of the reinforced concrete diaphragm wall solution is presented in Fig. 10. The total height of the reinforced concrete diaphragm wall is 16.00 m.

2.4 System boundaries

The International Standard ISO 21930 [6], the EN 15978 [7] based on the European Standard EN 15804 [8] set out a common life cycle model for building and construction works. Fig. 11 highlights in green colour all the life cycle stages included in the LCA analysis.

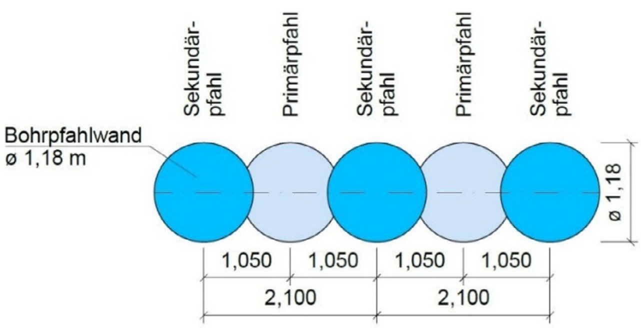

Fig. 7 Reinforced concrete secant pile
Sekantenpfahl aus bewehrtem Beton

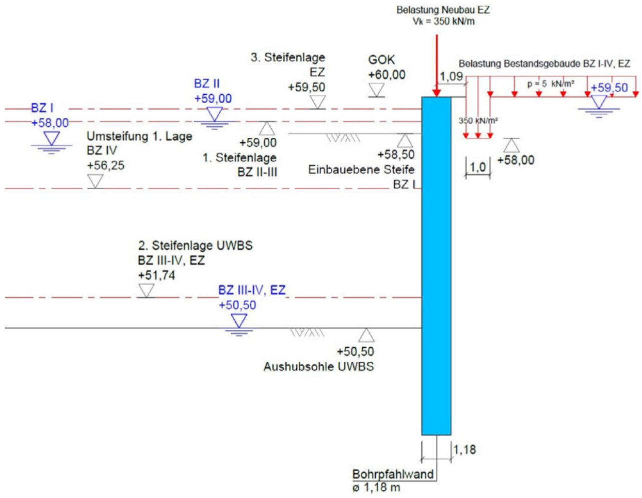

Fig. 8 Reinforced concrete secant pile wall system
Sekantenpfahlwand aus Stahlbeton

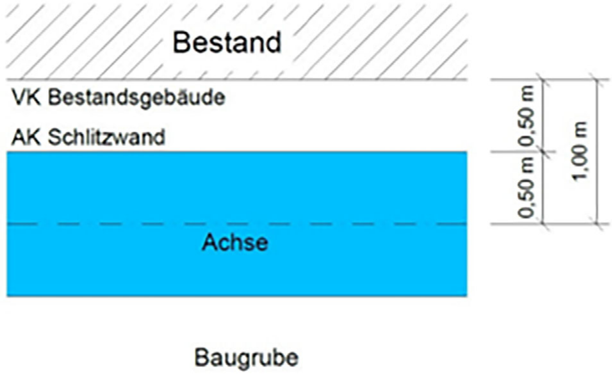

Fig. 9 Reinforced concrete diaphragm wall
Schlitzwand aus Stahlbeton

Stages B1, B2, B5, B6, B7, and B4 are not included in this LCA. Stages B1, B2, B5, B6, and B7 are deemed irrelevant to the goal and scope (structural material/products), and B4 is omitted because replacements of structural elements are unlikely during the wall's lifespan.

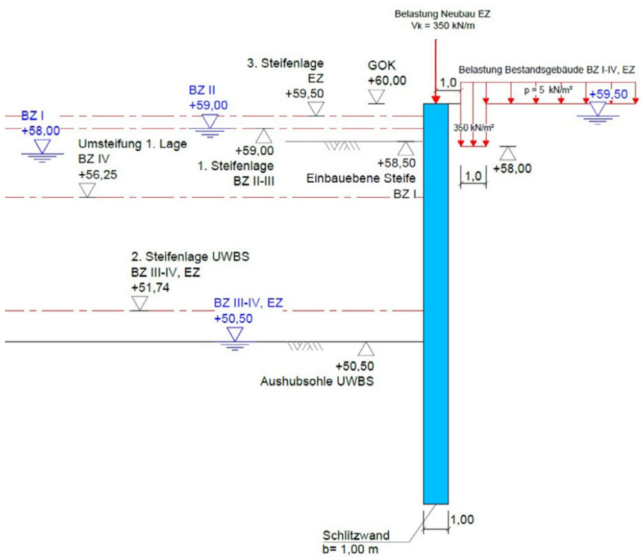

Fig. 10 Reinforced concrete diaphragm wall system
Schlitzwandsystem aus Stahlbeton

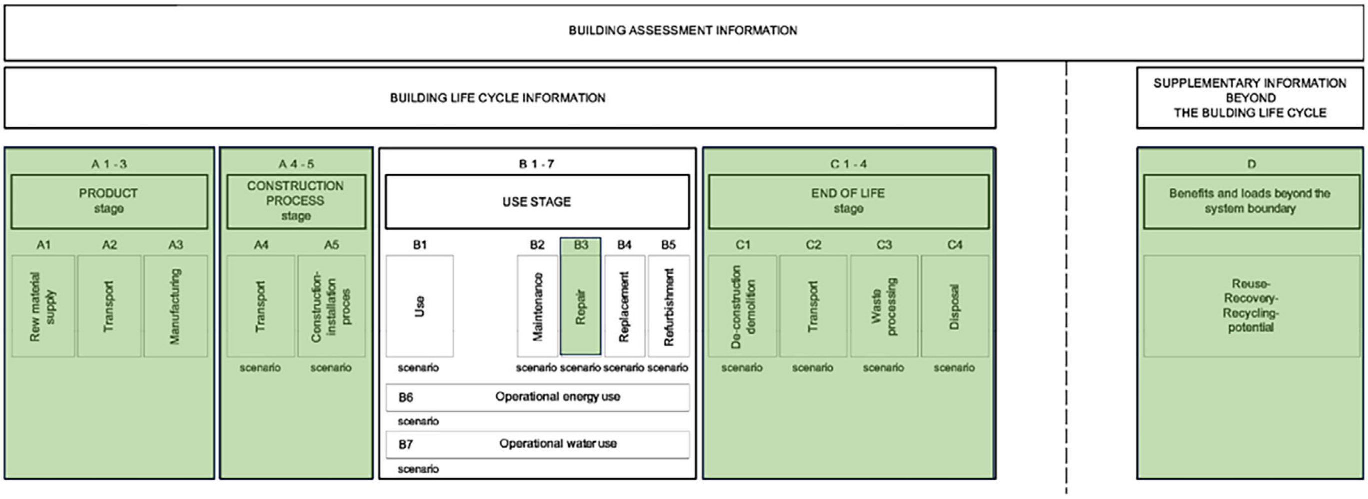

Fig. 11 LCA system boundaries [7]
Systemgrenzen der Ökobilanz [7]

2.5 Allocation

Co-product allocation was not necessary in the foreground processes, as there are no co-products known or considered in the construction of the retaining wall. Below it is listed the allocation principles of the background data for the most relevant structural materials/products employed in the construction of the different variants:

– Hot rolled steel sheet pile:

Scrap inputs in module A1–A3, including pre-consumer scrap, are treated as 'burden free'. Externally sourced pre-consumer scrap was treated as post-consumer scrap meaning that the only burdens considered are a transport burden, taken into account in A2.

– Ready-mix concrete:

For granulated ground blast furnace slag (GGBS), an economic allocation of the loads of steel production was applied. Fly ash was considered to be free of loads, but internal transport expenses were considered.

2.6 Selection of Life Cycle Impact Assessment Methodology and Types of Impacts

A set of impact assessment categories considered to be of high relevance to the goals of the project are shown in Tab. 3.

For all indicators mentioned in the Tab. 3, the characterization factors from EC-JRC were applied. (Environmental Footprint (EF).

Life cycle impact assessment (LCIA) results should be understood as relative expressions of potential environmental impacts, not as definitive predictions of actual consequences, threshold exceedances, safety margin violations, or risks, as they are estimates based on assumed emission pathways and specific environmental conditions, and only represent a portion of the total environmental burden related to the functional unit.

2.7 Assumptions

In this section, it is presented the various assumptions tied to specific scenario-dependent life cycle stages, which include A4, A5, B3, C2, C3, C4, and D.

2.7.1 Transport scenarios (A4)

Tab. 4 outlines the transportation scenarios selected for various materials/products.

2.7.2 Construction – installation process (A5)

During construction, it was established assumptions regarding material/product waste at the construction site (referred to as $A5_{material}$), as well as the impacts of the assembly of materials/products (referred to as $A5_{installation}$). Tab. 5 and Tab. 6 outline $A5_{material}$ and $A5_{installation}$ respectively.

2.7.3 Repair (B3)

The fire protection coating on steel sheet piles is the only product considered for repair, with a scenario assuming 25 % of the coating needs reapplication every 25 years.

2.7.4 Deconstruction (C1)

Deconstruction is only assessed for the steel sheet pile in the permanent and temporary retaining wall variants, as the remaining retaining wall variants are left in place (refer to section 2.7.6). The scenario for the deconstruc-

Tab. 3 Core environmental indicators, units and models as per EN 15804+A2 [8]
Kernumweltindikatoren, Einheiten und Modelle gemäß EN 15804+A2 [8]

Impact category	Indicator	Unit	Model
Climate change – total	Global Warming Potential total (GWP-total)	kg CO_2e	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change – fossil	Global Warming Potential fossil fuels (GWP-fossil)	kg CO_2e	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change – biogenic	Global Warming Potential biogenic (GWP-biogenic)	kg CO_2e	Baseline model of 100 years of the IPCC based on IPCC 2013
Climate change - land use and land use change	Global Warming Potential land use and land use change (GWP-luluc)	kg CO_2e	Baseline model of 100 years of the IPCC based on IPCC 2013
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC 11 eq.	Steady-state ODPs, WMO 2014
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H+ eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al. 2008
Eutrophication aquatic freshwater	Eutrophication potential, fraction of nutrients reaching freshwater end compartment (EP-freshwater)	kg P eq.	EUTREND model, Struijs et al. 2009b, as implemented in ReCiPe
Eutrophication aquatic marine	Eutrophication potential, fraction of nutrients reaching marine end compartment (EP-marine)	kg N eq.	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP-terrestrial)	mol N eq.	Accumulated Exceedance, Seppälä et al. 2006, Posch et al.
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP);	kg NMVOC eq.	LOTOS-EUROS, Van Zelm et al. 2008, as applied in ReCiPe
Depletion of abiotic resources – minerals and metals	Abiotic depletion potential for non-fossil and metals resources (ADP-elements)	kg Sb eq.	CML 2002, Guinée et al. 2002, van Oers et al. 2002.
Depletion of abiotic resources – fossil fuels	Abiotic depletion potential for fossil resources (ADP-fossil)	MJ, net calorific value	CML 2002, Guinée et al. 2002, van Oers et al. 2002.
Water use	Water (user) deprivation potential, deprivation-weighted water consumption (WDP)	m^3 world eq. deprived	Available WAter REmaining (AWARE) Boulay et al. 2016

Tab. 4 Transport scenarios
Transportszenarien

	Leg 1		Leg 2	
Material/Product	Distance (km)	Type	Distance (km)	Type
Ready-mix concrete	30	Truck 32 t	-	-
Steel sheet piles	790	Truck 20–26 t	-	-
Temporary steel sheet piles	659	Truck 20–26 t	-	-
Steel plates	2209	Bulk Carrier Coast	316	Rail
Welding material	370	Truck 20–26 t	-	-
Fire protection coating	110	Truck 20–26 t	-	-
Temporary bracings	2209	Bulk Carrier Coast	316	Rail
Steel rebars	600	Truck 20–26 t	-	-
Sealing material: Beltan	790	Truck 20–26 t	-	-
Drilling template foam	430	Truck 20–26 t	-	-
Bentonite	200	Truck 20–26 t	-	-
Exterior wall insulation	430	Truck 20–26 t	-	-

Tab. 5 Material wastage scenarios
Szenarien der Materialverschwendung

Material	Wastage (%)
Ready-mix concrete	4
Steel sheet piles	1
Steel plates	3.3
Fire protection coating	2
Temporary bracings	3.3
Steel reinforcement	4.85
Drilling template foam	4
Exterior wall insulation	4

tion of the permanent sheet pile is outlined in Tab. 6 "Removal – steel sheet piles" above.

2.7.5 EOL transport (C2)

Tab. 7 outlines the transport distances for the structural materials/products from the construction site to a waste treatment centre or disposal. Road transport type (truck) was selected.

2.7.6 Waste Processing, Disposal and Benefits Outside the System Boundaries (C3–C4, D)

Different EOL assumptions were attributed to each retaining wall solution. They were:

Tab. 6 Material assembly scenarios
Szenarien zur Materialzusammenstellung

Material	Unit	Type	Quantity
Installation – steel sheet piles	l/t	Diesel	11.22
Removal – steel sheet piles	l/t	Diesel	8.77
Installation/removal – temporary bracings	MJ/kg	Diesel	0.0511
Installation/removal – struts	MJ/kg	Diesel	0.0511
Installation – reinforcement cage	MJ/kg	Diesel	0.0511
Excavation – diaphragm wall panels	l/m	Diesel	2.12
Preaugering – steel sheet piles	l/m	Diesel	2.5
Drilling and casing placement – secant pile	l/m	Diesel	3.375
Pumping – ready-mix concrete	MJ/m^3	Diesel	128.40
Pumping – bentonite solution	MJ/m^3	Diesel	128.40
Welding – plates	kWh/m	Electricity	2.40

Tab. 7 Transport scenarios C2
Transportszenarien C2

Material/Product	Distance (km)
Ready-mix concrete	50
Steel sheet piles (recycling)	100
Steel sheet piles (disposal)	300
Steel plates (recycling)	100
Steel plates (disposal)	300
Welding material	100
Fire protection coating	50
Temporary bracings	100
Steel rebars	50
Sealing material: Beltan	50
Drilling template foam	50
Bentonite	50
Exterior wall insulation	50

– Permanent steel sheet pile wall (VARIANT 1) is recovered and recycled in its EOL (50 years);

Tab. 8 outlines the EOL scenarios of Variant's 1 materials/products.

To accommodate the steel loss resulting from corrosion, it is assumed that the lost steel is left in place. However, about transportation (C2) and disposal (C4), a zero assumption is made, and the loss of scrap burden is considered in module D.

– The temporary steel sheet pile in (VARIANT 2) is to be reused (a total of 5 uses) with the reinforced concrete wall structure left in place in its EOL;

Tab. 9 outlines the EOL scenarios of Variant's 2 materials/products.

Retaining walls and foundation elements constructed from reinforced concrete, are often left in place beyond their designated service life yielding no impacts in the EOL. In contrast to concrete, the steel reinforcement, if left in place, might be viewed as contributing to an environmental load in module D. This is due to the possibility that the Net_{scrap} could yield a negative value equivalent to the $Scrap_{input}$.

– The reinforced concrete secant pile (VARIANT 3) and the reinforced concrete diaphragm wall (VARIANT 4) are assumed to be left in place in its EOL;

Tab. 10 outlines the EOL scenarios of Variant's 3 & 4 materials/products.

As assumed in VARIANT 2, materials left in place, namely ready-mix concrete, and steel rebars, there are no impacts at the EOL and the steel rebars showcase a burden in module D.

Tab. 8 Variant 1 EOL scenarios
Variante 1 EOL-Szenarien

Material/Product	Recycling %	Downcycling %	Reuse %	Landfilling %	Left in place %
Sealing material: Beltan	-	-	-	100	-
Hot rolled steel heavy plates	93	-	7	-	-
Steel reinforcement	95	-	-	5	-
Ready-mix concrete C30/37	-	75	-	25	-
Fire protection coating	-	-	-	100	-
Permanent steel sheet pile	100	-	-	-	-
Permanent steel sheet pile (corroded steel)	-	-	-	-	100
Temporary bracings	-	-	100	-	-

Tab. 9 Variant 2 EOL scenarios
Variante 2 EOL-Szenarien

Material/Product	Recycling %	Downcycling %	Reuse %	Landfilling %	Left in place %
Sealing material: Beltan	-	-	-	100	-
Ready-mix concrete C30/37	-	-	-	-	100
EPS insulation	-	-	-	-	100
Temporary steel sheet pile	18	-	80	2	-
Steel reinforcement	-	-	-	-	100
Temporary bracings	-	-	100	-	-
Sealing material: Beltan	-	-	-	100	-

3 Life cycle inventory

3.1 Material Quantities

The material quantities for each of the Variants are calculated from the structural design and are represented by the chart in Fig. 12.

3.2 Datasets

Fuel, energy (A5), and transport (A4) process datasets, sourced from the ÖKOBAUDAT online database in Germany, are not detailed in this report; however, material/product (A1–A3) datasets are presented in Tab. 11.

4 Life Cycle Impact Assessment

The life cycle impact assessment is focused on the environmental impact indicators described in EN 15804+A2 (refer to section 2.6). Calculations for the environmental impact indicators within each life cycle stage were derived through a matrix calculation approach, as illustrated in Fig. 13.

For i = to the assessed life cycle stages [A1–A3, A4, A5, B3, C1, C2, C3, C4] and [D].

The calculation consists of multiplying each product and service quantified in a module of the life cycle of the building with its respective value for any environmental indicator.

5 Results

5.1 Climate change – GWP-total

The following figures show the total lifetime GWP (A-C) of the four VARIANTs. In Fig. 14 VARIANT 1 has the lowest GWP-total followed by VARIANT 2.

Tab. 10 Variant 3 EOL scenarios
Variante 3 EOL-Szenarien

Material/Product	Recycling %	Downcycling %	Reuse %	Landfilling %	Left in place %
EPS Insulation: drilling template foam	-	-	-	-	100
Ready-mix concrete C20/25	-	-	-	-	-
Ready-mix concrete C25/30	-	-	-	-	-
Steel reinforcement: drilling template	-	-	-	-	-
Steel reinforcement	-	-	-	-	-
Temporary bracings	-	-	100	-	-

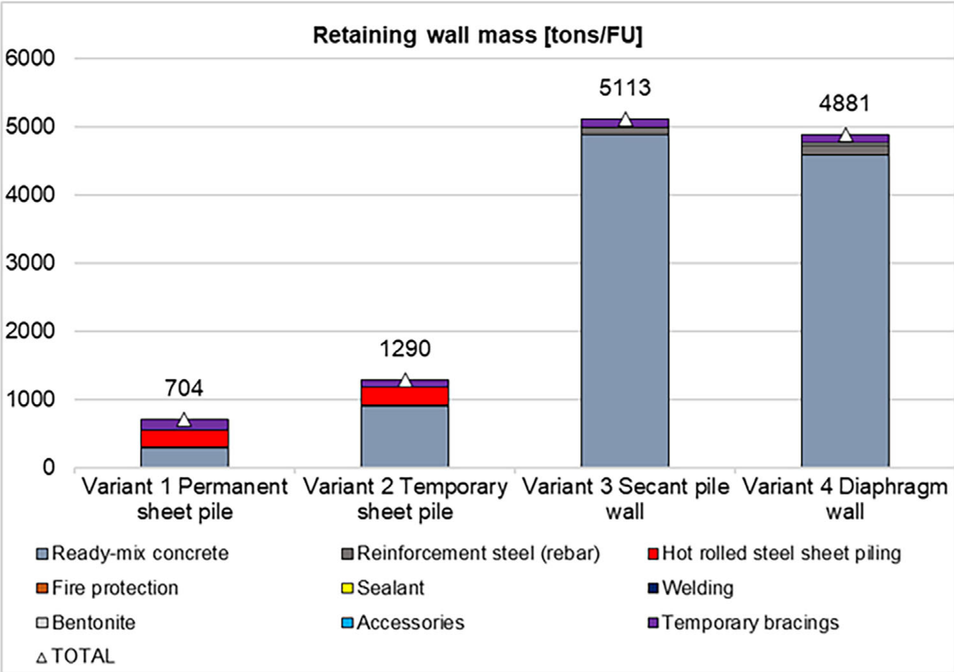

Fig. 12 Variants' total mass
Gesamtmasse der Varianten

LCIA results for GWP-total are also presented based on the contribution of the materials/products utilized in the different VARIANTs (Fig. 15). The hot rolled steel sheet pile emerges as the predominant contributor to GWP in VARIANT 1 and VARIANT 2. Similarly, the ready-mix concrete emerges as the biggest contributor to GWP for VARIANT 3 and VARIANT 4.

Fig. 16 and Fig. 17 display the LCIA of Ozone Potential Depletion (ODP), Acidification Potential (AP),

Tab. 11 Materials/products datasets
Materialien/Produkte-Datensätze

Product/Material	Dataset name	Source	Compliance system name	Year	Geography	Upstream database
Hot rolled steel sheet piles	EcoSheetPile™ Plus – Steel Sheet Piles	EPD	EN 15804+A2	2023	RER	GaBi
Sealing material for interlocks: Beltan	Bitumen cold adhesive	ÖKOBAUDAT	EN 15804+A2	2022	DE	GaBi
Hot rolled steel plates	XCarb® Heavy Plates from ArcelorMittal	EPD	EN 15804+A2	2022	RER	GaBi
Ready-mix concrete C30/37	Ready-mix concrete C30/37	ÖKOBAUDAT	EN 15804+A2	2022	DE	GaBi
Steel rebars	Betonstahl in Ringen und Betonstabstahl Badische Stahlwerke GmbH	EPD	EN 15804+A2	2022	DE	GaBi
Fire protection coating	PROMASTOP®-CC Etex Germany Exteriors GmbH	EPD	EN 15804+A2	2022	DE	GaBi
EPS insulation: exterior wall	EPS-Hartschaum –Industrieverband Hartschaum e.V. (IVH)	EPD	EN 15804+A2	2022	DE	GaBi
EPS foam: drilling template	EPS-Hartschaum – Industrieverband Hartschaum e.V. (IVH)	EPD	EN 15804+A2	2022	DE	GaBi
Ready-mix concrete C25/30	Ready-mix concrete C20/25	ÖKOBAUDAT	EN 15804+A2	2022	DE	GaBi
Bentonite	Bentonite {DE} | market for bentonite | No transport | Cut-off	Ecoinvent	EN 15804+A2	2021-2022	DE	Ecoinvent

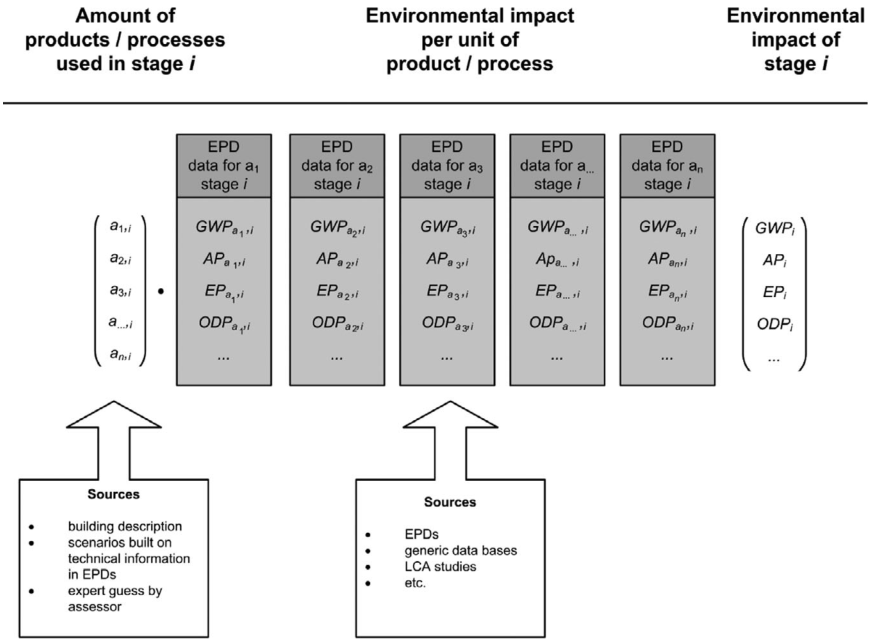

Fig. 13 Principle of the matrix calculation of the environmental impacts for module *i* of the building life cycle and relevant data sources [7]
Prinzip der Matrixberechnung der Umweltauswirkungen für Modul *i* des Gebäudelebenszyklus und relevante Datenquellen [7]

Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Abiotic Depletion Potential (ADP) and Water Deprivation Potential (WDP).

ODP entails high uncertainty, particularly for VARIANT 4, due to the dataset used to characterize the Bentonite. This dataset originates from Ecoinvent, whereas all other datasets are sourced from GaBi. It is recognized that these two databases exhibit significant variability in results for assessing the ODP impact category. In Fig. 16, the graph on the left incorporates bentonite in the ODP impact assessment, while the graph on the right neglects its contribution

For better visualization in Fig. 17 ADP-elements is presented with and without the contribution of the module D.

5.2 Sensitivity Analyses

Sensitivity analyses were performed to test the robustness of the results towards uncertainty and main assumptions. Different ready-mix concrete datasets were used to consider low carbon emission ready-mix concrete. These datasets (Tab. 12) consider the replacement of clinker by supplementary cementitious materials such as fly ash, GGBS, or silica fume by up to 33.18 %.

Fig. 18 compares the GWP-total of the total lifetime (A–C) of the four VARIANTs when low carbon emission ready mix concrete was considered.

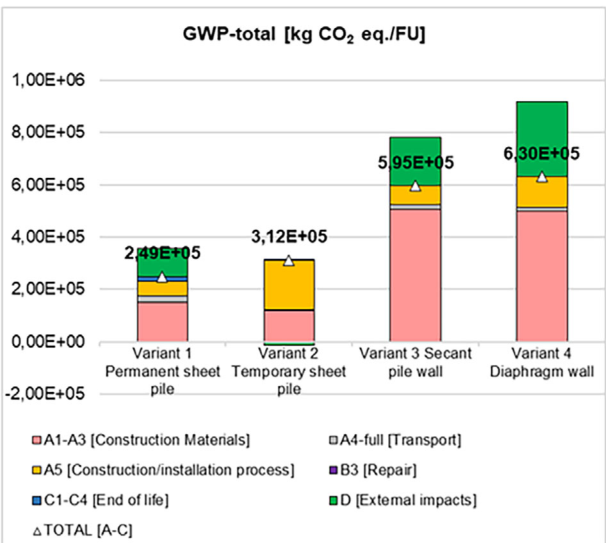

Fig. 14 Total life cycle (A-C) GWP-total for all VARIANTs
Gesamter Lebenszyklus (A-C) GWP-Gesamt für alle VARIANTen

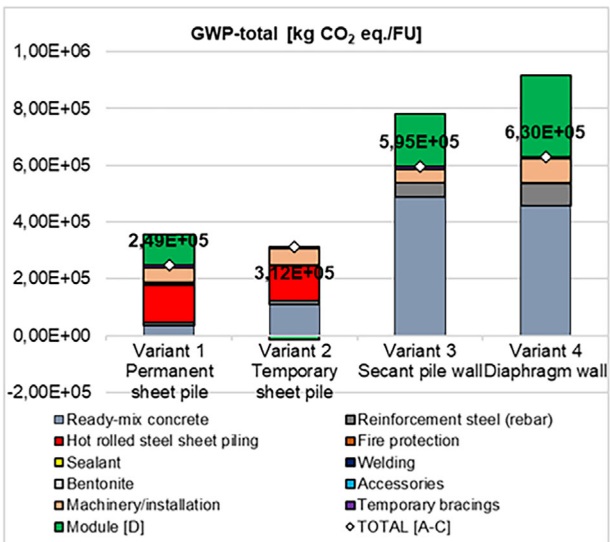

Fig. 15 Material and product contribution to GWP-total in the total life cycle assessment A–C
Material- und Produktbeitrag zum GWP-Gesamt in der Gesamtökobilanz A-COther impact categories: ODP, AP, EP, POCP, ADP and WDP

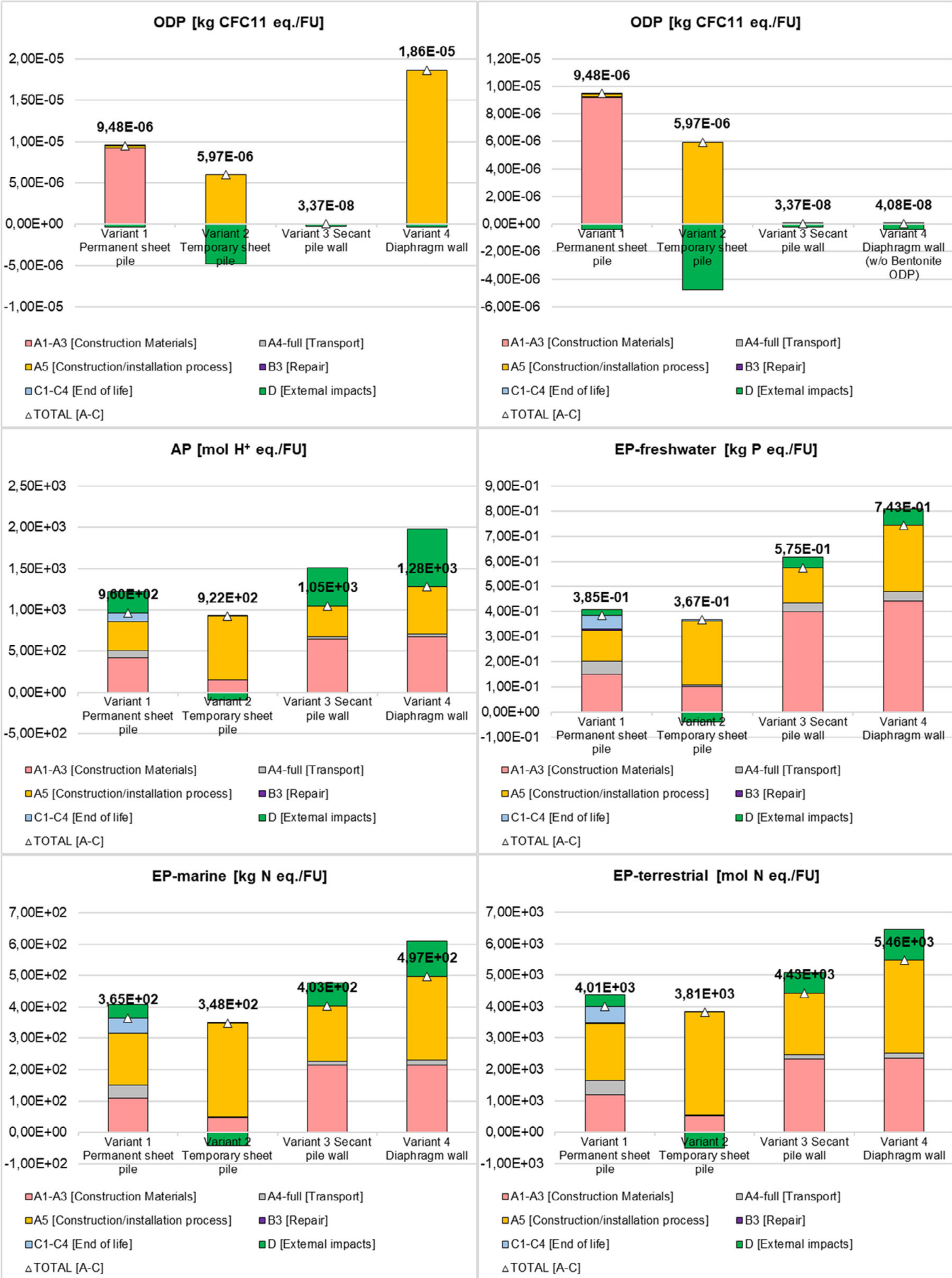

Fig. 16 Total life cycle (A-C) ODP, AP, and EP for all VARIANTs
Gesamtlebenszyklus (A-C) ODP, AP und EP für alle VARIANTen

6 LCA Interpretation

6.1 Identification of Relevant Findings

The following conclusions can be made based on the LCA results:

1. VARIANT 1 and VARIANT 2 lead to lower environmental impacts when compared to VARIANT 3 and VARIANT 4 with the exception of ODP, ADP-elements and WDP;
2. VARIANTs 1 and 2 result in lower GWP-total compared to VARIANTs 3 and 4. Specifically, GWP-total is reduced by up to 60 % when comparing VARIANT 1 with VARIANT 4 over their total lifetime (A-C):

- The majority of GWP-total savings can be attributed to the production of materials/products, with VARIANTs

Fig. 17 Total life cycle (A–C) POCP, ADP, and WDP for all VARIANTs
Gesamtlebenszyklus (A-C) POCP, ADP und WDP für alle VARIANTen

1 and 2 benefiting from lower material consumption (refer to Fig. 12).

- The steel sheet piles utilized in VARIANT 1 and VARIANT 2 are manufactured in an electric arc furnace (EAF) using 100 % recycled steel and renewable electricity.

3. Hot rolled steel sheet piles and the steel reinforcement used in the analysis are produced via a EAF route and use 100 % recycled steel. Consequently:

- In VARIANT 1, Module D reflects a scrap burden concerning scrap loss: the amount of scrap input to production exceeds the scrap recovered at the EOL through recycling of the steel reinforcement and the hot rolled steel sheet piles. This burden outweighsthe benefits of recovering other materials, such as downcycling of the ready-mix concrete, resulting in a net positive Module D.
- In VARIANT 2, Module D accounts for the scrap burden caused by the rebars left in place. However, the

Tab. 12 Low carbon emission ready-mix concrete datasets
Datensätze für kohlenstoffarmen Transportbeton

Material/Product	Dataset name	Source	Compliance system name	Year	Geography	Upstream database
Ready-mix concrete C25/30	Beton C25/30 XC4 XF1 XA1 F3 16 M ECOPact	EPD	EN 15804+A2	2023	DE	GaBi
Ready-mix concrete C30/37	Beton C30/37 XC4 XF1 XA1 F3 16 M ECOPactR	EPD	EN 15804+A2	2023	DE	GaBi

advantage of reusing the temporary steel sheet piles five times outweighs this burden, resulting in a net negative Module D.

- For VARIANT 3 and VARIANT 4, Module D captures the burden from the rebars left in place at EOL, resulting in a net positive Module D.

4. Low carbon emission ready-mix concrete reduces the GWP-total of VARIANT 2, VARIANT 3 and VARIANT 4 by 14 %, 24 % and 21 % respectively:

- VARIANT 2, VARIANT 3, and VARIANT 4 demonstrated high sensitivity to the use of low carbon emission ready-mix concrete, driven by their higher consumption of this material (refer to Fig. 12). VARIANTs 1 and 2 result in lower GWP-total compared to VARIANTs 3 and 4. Specifically, GWP-total is reduced by up to 53 % when comparing VARIANT 1 with VARIANT 4 over their total lifetime (A–C) (refer to Fig. 18).

7 Critical review

As required by ISO 14040/44 [9, 2] ArcelorMittal commissioned iPoint-systems gmbh to set up a panel of 3 experts and conduct a critical review of this comparative LCA study with reference to EN 15978, and ISO 14040/44.

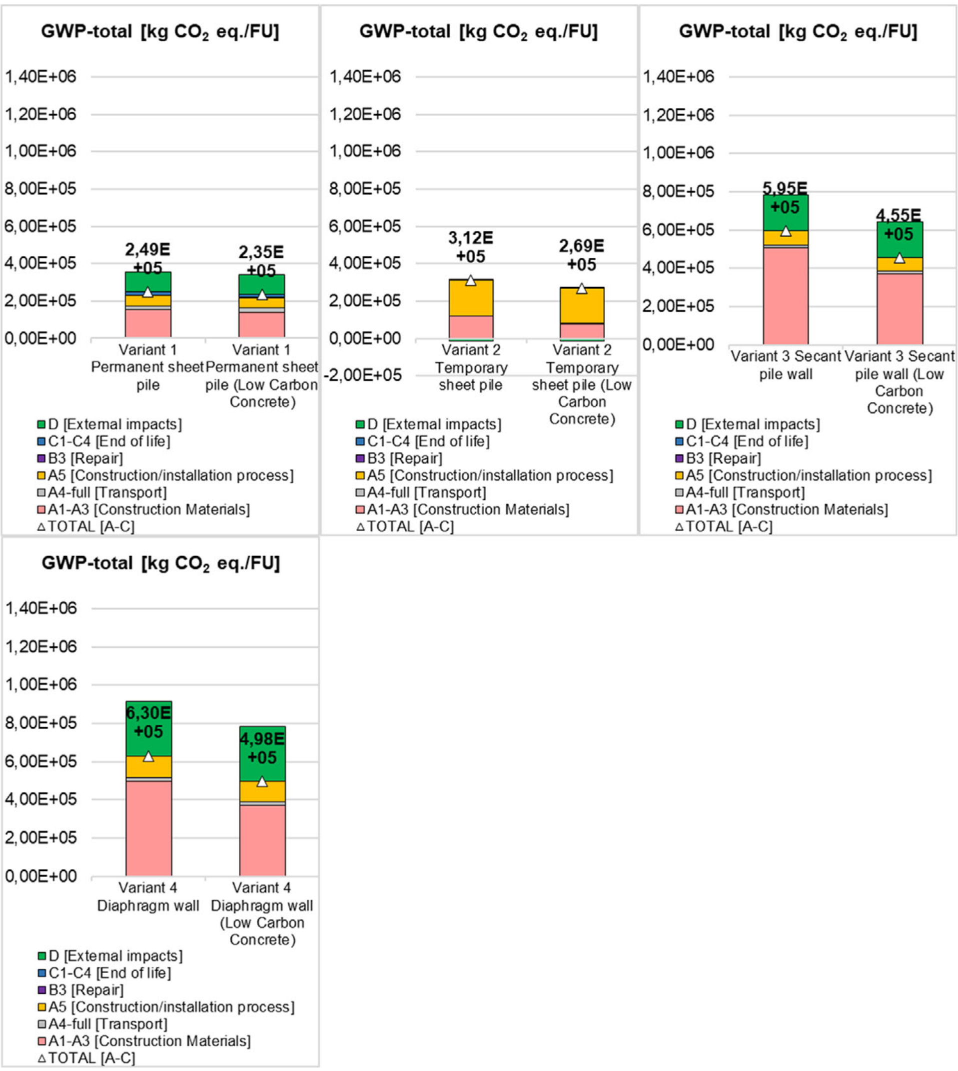

Fig. 18 GWP-total comparison (Low Carbon Emission Ready-mix Concrete)
GWP-Gesamtvergleich (kohlenstoffemissionsarmer Transportbeton)

Reviewers concluded that the study's approach, data, assumptions, results, and interpretations were all sound, reasonable, and consistent with the study's objectives and scope, as well as compliant with ISO 14040/44 standards.

8 Conclusions

The present report details the LCA which the goal is to assess the environmental impacts associated with four different types of retaining wall systems within the excavation pit of an underground car park associated with a specific building (e. g., commercial, residential, office use, etc.) assumed to be constructed in Berlin (DE) with 50 years of required service life.

The four technical solutions for the retaining wall designed by an independent design office (GRBV Ingenieure im Bauwesen) were:

- VARIANT 1: permanent steel sheet pile (SSP) wall;
- VARIANT 2: temporary steel sheet pile wall in combination with a permanent reinforced concrete (RC) wall inside the excavation;
- VARIANT 3: permanent Secant Pile wall (RC);
- VARIANT 4: permanent Diaphragm wall (RC, also known as "slurry wall").

The LCA results reveal that VARIANTs 1 and 2 offer environmental advantages over their life cycle when compared to VARIANTs 3 and 4. Specifically in terms of climate change, GWP-total is reduced by up to 60 % when comparing VARIANT 1 with VARIANT 4 over their total lifetime (A–C). This can be attributed to their lower material consumption compared to VARIANTs 3 and 4 (Fig. 12). Additionally, the use of 100 % recycled steel and renewable electricity for the manufacturing of sheet piles further contributes to the reduction of environmental impacts.

The investigation into the use of low-carbon emission concrete demonstrated a reduction in environmental impacts, particularly for VARIANTs 3 and 4, as these variants exhibited higher consumption of ready-mix concrete. While adopting low carbon emission concrete, GWP-total is reduced by 53 % when comparing VARIANTs 1 and 4.

Datasets with different upstream databases (GaBi and Ecoinvent) were used. This combination of databases introduces uncertainties in the LCIA of certain environmental indicators, such as ODP, ADP, and WDP. Future studies may consider exploring the variation and uncertainty associated with the consideration of datasets and mixing datasets from different upstream databases.

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