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LIFE CYCLE ASSESSMENT OF AN UNDERGROUND CAR PARK CONSIDERING DIFFERENT RETAINING WALL SOLUTIONS

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Abstract. *In 2020, buildings and the construction sector accounted for 37% of global energy-related CO_2e emissions, surpassing other sectors. A life-cycle assessment is a science-based and standardized, 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. This research involves a life cycle assessment of an underground car park in Rio de Janeiro, Brazil. It compares a steel sheet pile and a reinforced concrete diaphragm retaining walls. The life cycle assessment examines stages from product to end-of-life, along with loads and benefits beyond the system boundary. Environmental product declarations compose the environmental database, and calculations are performed using One Click LCA software. The objective is to provide an understanding of the Global Warming Potential associated with the underground car park and compare the different structural configurations and materials considered. The results indicate that the steel sheet pile wall reduced the global warming potential by 48% compared to the reinforced concrete diaphragm wall solution.*

1 INTRODUCTION

In 2020, compared to other sectors, 37% of the global share of energy-related CO_2eq. 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. More recently, awareness has also been raised on embodied carbon: emissions from materials and products must be urgently addressed to ensure sustainable constructions, optimized as low-carbon emission solutions.

An LCA can be applied to assess the carbon emissions 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 carbon 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 and products must be urgently addressed by LCAs to ensure that constructions being built today are optimized for low-carbon emission solutions across their entire life cycle. This involves evaluating each design choice using a whole life-cycle approach to minimize upfront carbon impacts (e.g., low-carbon emission materials) and taking steps to avoid future embodied carbon during the EOL.

The present report details the LCA of the retaining walls within the underground car park of a commercial building assumed to be constructed in Rio de Janeiro (Brazil) with 60 years of required service life (RSL). In addition to a steel sheet pile retaining wall, a reinforced concrete diaphragm wall is considered. Although various construction solutions for retaining walls, such as secant piles or cutter soil mixing, could have been analyzed, the diaphragm wall was chosen due to its better alignment with the characteristics of the Brazilian construction market for the retaining walls of underground car parks.

The structural design of the retaining walls was conducted by the Brazilian design office ABS, according to Brazilian national standards for safety and performance of structural elements. The boundaries of the LCA are the product stage (modules A1-A3), the construction process (modules A4-A5), repair (B3), the end-of-life (EOL) (modules C2-C3-C4), and the benefits and loads beyond the system boundary (module D). The life cycle inventory (LCI) is composed of environmental product declarations (EPDs) according to EN 15804 [5][6]. The commercial software One Click LCA [7] was used for the LCA calculations.

The primary objective is to evaluate the environmental impact of the retaining walls within the underground car park of a commercial building, considering different structural configurations and materials. Additionally, by conducting this LCA, the aim is to provide a comprehensive understanding of the Global Warming Potential (GWP) associated with the UCP's retaining walls and compare the different structural configurations and materials considered. The LCA underwent a critical review process by LCA specialists of "*CTE Centro de tecnologia de edificações*" in Brazil.

2 METHODOLOGY

According to EN 17472 [2] a LCA is carried out in four distinct phases. The phases are often interdependent in that the results of one phase will inform how other phases are completed.

- Goal and scope;
- Life cycle inventory;
- Life cycle impact assessment;
- Results and interpretation.

2.1 Goal and scope

The goal of the present LCA is to quantify the environmental performance of equivalent structural options, composed of different materials, of the retaining walls surrounding a commercial building's UCP located in Rio de Janeiro, Brazil. This case study will specifically address the retaining walls of the underground car park in the commercial building. Other components of the commercial building and its underground levels are not included in the object of assessment.

This comparative study can support the different construction chain players (e.g.: engineers, architects, design offices, etc.) in the decision-making process by providing comparisons of the environmental performance of different design options and by indicating the potential for environmental performance improvement.

2.1.1 Functional unit

The functional unit for this LCA encompasses a total of 200 meters in length of a retaining wall with a maximum excavation depth of 7,5 meters, situated in an underground car park of a commercial building located in Rio de Janeiro in the region of Botafogo with a RSL of 60 years. The building has a square shape measuring 50 m by 50 m and two levels below grade (refer to Figure 1).

Two distinct yet functionally equivalent alternatives for retaining walls were considered by the design office ABS Engenharia: the use of steel sheet piles and a reinforced concrete diaphragm wall. In terms of structural design, the functional equivalency of these solutions is ensured by adopting the same design assumptions, such as soil condition, safety requirements, and actions on the structure as prescribed by Brazilian standards. Both retaining wall solutions were designed for their maximum utilization ratio.

To ensure relevance to the case study, ABS Engenharia utilized an actual soil profile from Rio de Janeiro in the structural design. This soil profile is derived from investigations conducted in Botafogo-RJ and is assumed to be representative of the region.

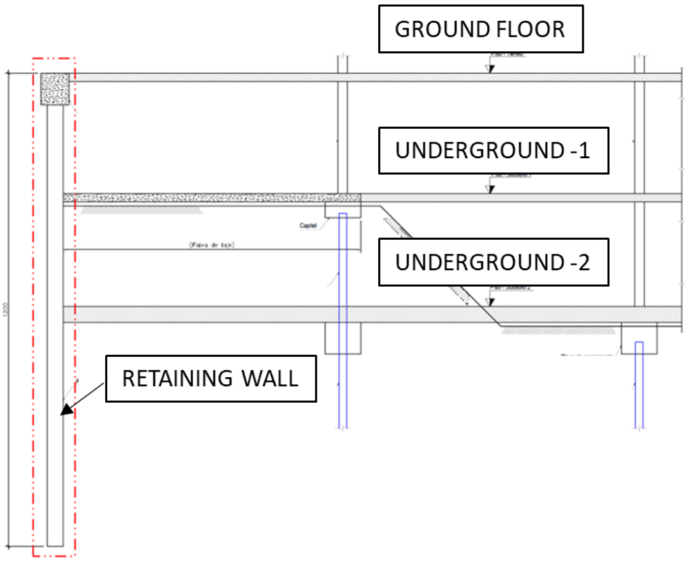
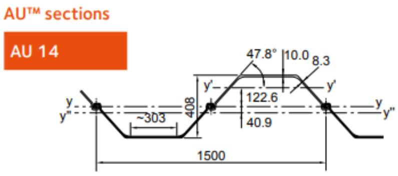


Figure 1 Underground car park cross-section with two underground levels (with execution phases).

- Steel sheet pile:

For the steel sheet pile solution, the design used a 12,0 meter long steel sheet pile. The profile AU 14 (refer to Figure 2) from ArcelorMittal in steel grade S 355 GP was selected.



Per S	99.2	**77.9**	6590	**457**	8.15	0.96
Per D	198.5	**155.8**	43020	**2110**	14.73	1.91
Per T	297.7	**233.7**	59550	**2435**	14.15	2.86
Per m of wall	132.3	**103.8**	28680	**1405**	14.73	1.27

Figure 2 ArcelorMittal steel sheet pile AU 14.

From the structural design the bill of materials (BOM) of the steel sheet pile wall for the full length was extracted and is presented in the Table 1.

Table 1 BOM for the steel sheet pile solution.

Item	Quantity	Unit
Steel sheet pile AU14, S 355 GP, L=12m	247104	kg
Waterproofing plates e=5mm	13923	kg
Steel reinforcement 16mm CA50 – connection with slabs	3719	kg
Waterproofing tape	264	m
Ready-mix concrete f_{ck} 30 – Capping beam	108	m³
Steel reinforcement CA50 – Capping beam	12960	kg
Fire protection coating Class 1 EI60	1300	m²
Welding	1986	m
Sheet pile driving	2376	m²
Non contaminated soil – Excavation	15875	m³
Disposal non contaminated soil – Transport	19050	m³

The corrosion of the steel sheet piles was considered in the LCA, eventhough estimating corrosion losses is complex, influenced by factors during both use and deconstruction. Predicting deposit adherence adds uncertainty. The corrosion assumption selected is according to Eurocode 3 Part 5, for 50 years: 1,00 mm + 1,75 mm = 2,75 mm

- Reinforced concrete diaphragm wall:

For the reinforced concrete diaphragm wall, a typical cross section of the panels adopted is presented in Figure 3. The designed diaphragm wall is 40 centimeters wide and 12,0 meters long.

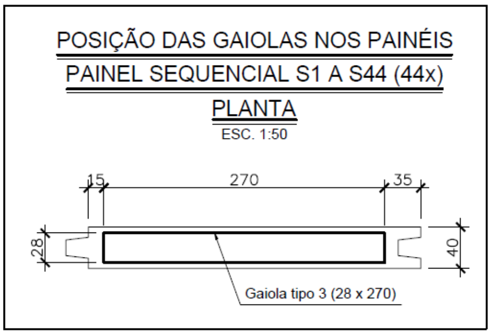


Figure 3 Typical reinforced concrete diaphragm wall cross-section.

Likewise, from the structural design the BOM of the total length of the reinforced concrete diaphragm wall was extracted and is presented in the Table 2.

Table 2 BOM for the reinforced concrete diaphragm wall solution.

Item	Quantity	Unit
Steel reinforcement 16mm CA50 – connection with slabs	3719	kg
Waterproofing tape	264	m
Ready-mix concrete f_{ck} = 30 MPa – Capping beam	164	m³
Steel reinforcement CA50 – Capping beam	19680	kg
Ready-mix concrete f_{ck} = 30 MPa – wall panel	960	m³
Steel reinforcement CA50 – Wall panel	126	t
Non contaminated soil – Excavation	15875	m³
Disposal non contaminated soil – Transport	19050	m³
Bentonite	20	t
Disposal contaminated soil waste – excavation	1920	m³

Item	Quantity	Unit
Disposal contaminated soil waste – transport	2304	m³
Steel reinforcement CA50 – guide wall	3000	kg
Formwork OSB 12 mm – guide wall	740	m²
Joint treatment	406	m

2.1.2 System boundaries of the LCA

The International Standard ISO 21930 [8] and the European Standard EN 15804 [5] set out a common life cycle model for building and construction works. The life cycle model includes modular definitions for the life cycle stages, allowing each stage to be compared in isolation with other projects.

Depending on the purpose of the LCA, some life cycle stages can be omitted or replaced with a scenario in the absence of detailed information. The present UCP LCA considers the following life cycle stages:

- A1-A3, Product stage;
- A4-A5, Construction process stage, information modules;
- B3, Use stage, information modules related to the building fabric;
- C2-C4, End-of-life stage, information modules;
- D, Benefits and loads beyond the system boundary, information module.

Figure 4 highlights in green color all the life cycle stages included in the LCA analysis.

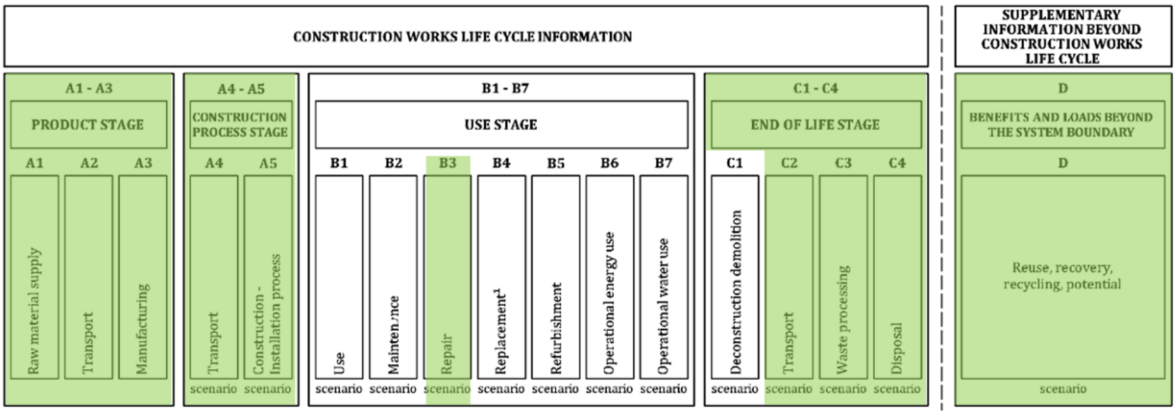


Figure 4 UCP LCA system boundaries.

2.1.3 Scenario definition (A4, A5, B3, C2, C4 and D)

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

- Tranport A4:

Table 3 outlines the transportation scenarios selected for various materials and products. In the case of providing the steel sheet piles, three transportation legs were considered. The initial leg encompasses a train journey from Luxembourg to the port of Antwerp, followed by the subsequent leg involving transport by ship from Belgium to Brazil and finally a leg involving the transportation by truck in Brazil from the port of arrival in Santos-SP to Rio de Janeiro-RJ.

Table 3 Transport scenarios.

Item	Leg 1 Distance (km)	Leg 1 Type	Leg 2 Distance (km)	Leg 2 Type	Leg 3 Distance (km)	Leg 3 Type
Steel sheet piles AU 14	300	Train	11308	Ship	510	Trailer 40t
Steel plates	370	Trailer 40t	-	-	-	-
Steel plates - XCarb®	300	Train	11308	Ship	510	Trailer 40t
Bentonite	200	Trailer 40t	-	-	-	-
Steel reinforcement	370	Trailer 40t	-	-	-	-
Hydro-expansive tape	470	Truck 9t	-	-	-	-
Ready-mix concrete	25	Concrete mixer truck	-	-	-	-
Fire protection (spray)	110	Trailer 40t	-	-	-	-

- Construction A5:

During the A5 life cycle stage, it was established assumptions regarding material and product waste at the construction site during installation processes (referred to as "$A5_{material}$"), as well as the impacts of installation itself during the assembly of materials and products (referred to as "$A5_{installation}$"). These installation impacts predominantly come from machinery fuel and electricity consumption. Table 4 and Table 5 outline $A5_{material}$ and $A5_{installation}$ respectively.

Table 4 Material wastage scenarios.

Item	Wastage	Source
Steel sheet piles AU 14	3,3%	One Click LCA
Steel plates	3,3%	One Click LCA
Reinforcement steel (rebars)	4,9%	One Click LCA
Hydro-expansive tape	10,0%	One Click LCA
Ready-mix concrete	3,0%	[9]
Fire protection coating	13,0%	One Click LCA

Table 5 Material assembly scenarios.

Item	Unit	Fuel type	Quantity	Source
Steel sheet piles AU 14	l/t	Diesel	11,22	ArcelorMittal
Ready-mix concrete	MJ/m^3	Diesel	128,40	INIES - FR
Bentonite solution	MJ/m^3	Diesel	128,40	INIES - FR
Excavator, wheeled 88kW	h/m^3	Diesel	0,0114	SINAPI
Welding	kWh/m	Electricity	2,40	[10]

- Repair B3:

Concerning life cycle stages during the use of the building B3 repair, the sole product for which a scenario was considered is the fire protection coating applied to the steel sheet pile. The scenario assumed was that 25% of the fire protection coating requires reapplication every 25 years of usage, as referenced in [11].

- Waste processing C3, disposal C4 and benefits outside the system boundaries D:

Different end-of-life scenarios were assigned to the steel sheet pile and reinforced concrete retaining walls. It was assumed that the steel sheet pile wall will be recovered and recycled at its EOL (60 years). On the other hand, it was assumed that the reinforced concrete diaphragm wall will be left in place at its EOL.

In the analysis of the steel sheet pile wall, it was assumed that corroded steel is lost and treated as landfill material, with the difference that impacts reported in modules C2, C3, and C4 were neglected. However, in module D, the environmental burden from scrap loss due to corrosion of the steel is considered

Retaining walls and foundation elements constructed from reinforced concrete, like the studied reinforced concrete diaphragm wall, are often left in place beyond their designated service life. This EOL scenario was simulated, and the associated GWP impacts linked to modules C2, C3, and C4 were adjusted to zero. The same approach was employed for module D.

In contrast to concrete, the steel reinforcement, if left in place, might contribute to an environmental load in module D. This is because there is a chance that the net scrap available in the system could result in a negative value, which is equivalent to the scrap input. This is particularly relevant for the steel reinforcement used in the LCA, as it involves scrap input in steel production (i.e.: Electric Arc Furnace steel production).

Table 6 and Table 7 depict the EOL scenarios for the materials and products used in the steel sheet pile and reinforced concrete diaphragm wall, respectively.

Table 6 Steel sheet pile wall: EOL scenario for recovered sheet piles

Item	Recycling %	Reuse %	Landfilling %	Source
Steel sheet piles AU 14	99	0	1	ArcelorMittal
Corroded steel	0	0	100	ArcelorMittal
Steel plates	88	11	1	[12]
Steel reinforcement	85	0	15	[13]
Ready-mix concrete	5	0	95	[9]
Hidro-expansive tape	0	0	100	[14]
Fire protection coating	0	0	100	OneClick LCA
Welding	99	0	1	[10]

Table 7 Reinforced concrete diaphragm wall EOL

Item	Recycling %	Reuse %	Landfilling %	Left in place %	Source
Bentonite	0	0	100	0	OneClick LCA
Steel reinforcement	0	0		100	-
Ready-mix concrete	0	0		100	-
Hidro-expansive tape	0	0		100	-
Formwork OSB	0	0	100	0	-
Waterproofing tape	0	0		100	-

2.2 Life cycle Inventory LCI

EPDs offer quantified insights into the environmental impacts of products as valuable resources for LCAs. In accordance with EN 15804:2012+A1:2013 [6], diverse EPDs were employed. Furthermore, the environmental database was enriched by integrating internally verified data provided by One Click LCA. The main EPDs and environmental data used in the UCP LCA are presented in Table 8.

Table 8 GWP A1-A3 emission factors.

Item	FU	A1-A3 $kgCO_2eq./FU$	Source
Reinforcement steel (rebar) - XCarb®	kg	0,300	[13]
EcoSheetPile™ Plus (ArcelorMittal)	kg	0,370	[15]
Ready-mix concrete C12/15	m³	196,1	One Click LCA
Oriented strand board (OSB)	m³	200,6	One Click LCA
Bentonite, activated	kg	0,48	One Click LCA
Sealing tapes	m	0,14	[14]
Ready-mix concrete C30/37 CEM II/A	m³	247,5	One Click LCA
Gypsum based fire resistant mortar	m²	2,45	[11]
Welding (filler material)	kg	1,85	[10]

2.3 Life cycle impact assessment: GWP

The life-cycle impact assessment is focused on the global warming potential (GWP) as the designated indicator for quantifying environmental impact. Calculations for the GWP values within each life cycle module are derived through a matrix calculation approach, as illustrated in Figure 5.

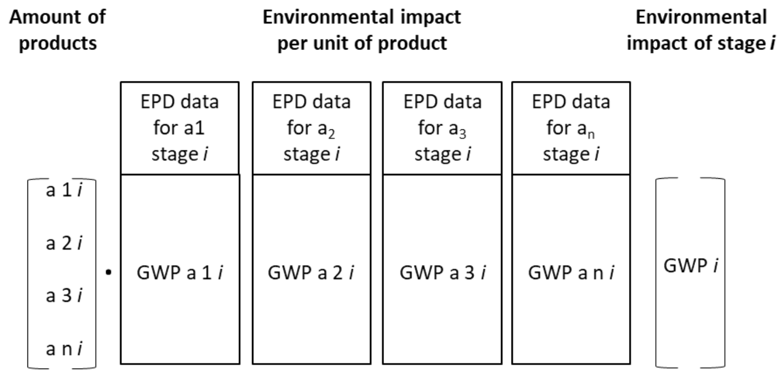


Figure 5 Principle of the matrix calculation of the environmental impacts for module i of the building life cycle and relevant data sources.

For i = [A1-A3, A4, A5, B4, C2, C3, C4] and [D].

2.4 Result and interpretation

Figure 6 compares the environmental impact of the reinforced concrete diaphragm wall and the steel sheet pile wall in terms of GWP. This figure highlights the intensity of emissions at each stage of the construction's life cycle.

Notably, the product stage A1-A3 emerges as the most influential phase, followed by the construction stage (A5) and the transportation stage (A4).

When compared to the reinforced concrete diaphragm wall, steel sheet pile wall:

- Reduced the overall GWP by 48%;
- Reduced the GWP related to the production of materials (module A1-A3) by 60%;
- Reduced the GWP related to the installation of structural elements and material wastage during construction (module A5) by 32%;
- Increased the GWP related to transport (module A4) by 80%.

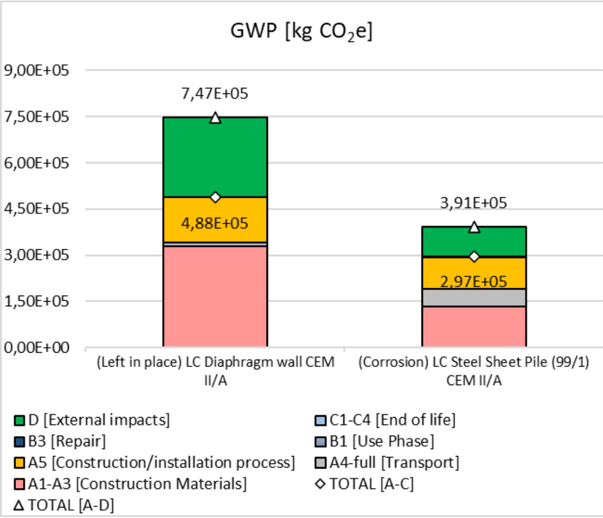


Figure 6 GWP comparison reinforced concrete diaphragm wall vs. steel sheet pile wall.

Figure 7 displays the embodied carbon of the materials and products employed in both structural designs. As anticipated, the embodied impact of the steel sheet pile wall construction is significantly shaped by the hot rolled steel sheet piles. The utilization of machinery and installation procedures emerges as the second-largest contributor to CO_2e emissions.

In the case of the diaphragm wall, reinforced concrete exerts the most significant influence on embodied carbon. This indicates the heightened sensitivity of this construction solution to the utilization of low-carbon emission concrete and low-carbon emission rebars.

In accordance also with previous findings related to the construction site stage, the steel sheet pile wall scenario GWP impacts related to machinery use and fuel consumption during the construction phase is lower by 22% (2,58E+04 kgCO_2e) when compared to the diaphragm wall solution.

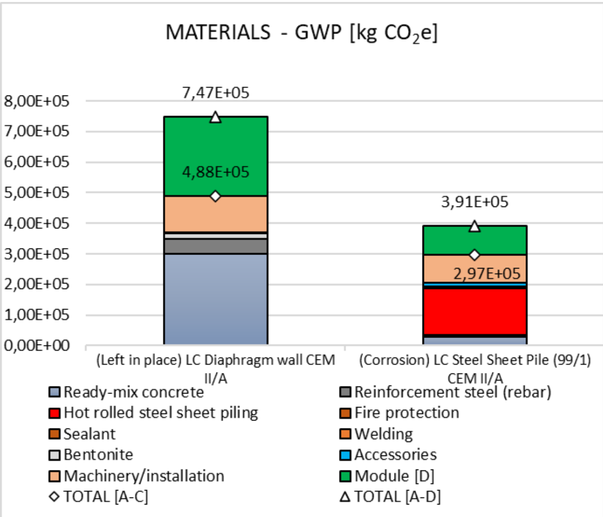


Figure 7 Embodied carbon of products and materials.

3 CONCLUSION

In conclusion, the study offers valuable insights into the environmental impacts of two equivalent retaining wall solutions for underground car parks: steel sheet piles and reinforced concrete diaphragm walls. The GWP outcomes, as depicted in Figure 6, provide a clear perspective on the life cycle stages that significantly impact each solution's carbon footprint.

In the context of the steel sheet pile wall, the product stage (A1-A3), transportation (A4) and construction (A5) are pivotal, as they reflect the majority of emissions. Similar dynamics apply to the reinforced concrete diaphragm wall in terms of the production stage (A1-A3) and construction stage (A5). However, unlike the steel sheet pile wall, the transport stage (A4) show lower contribution as the materials and products are sourced locally in Brazil.

Overall, the steel sheet pile alternative reduced the GWP by 48% when compared to the reinforced concrete diaphragm wall alternative. Several factors contributed to this reduction such as:

- The use of low carbon emission sheet piles: EcoSheetPile^{TM} Plus produced from almost 100% recycled steel with the source of 100% renewable electricity, reducing the production stage A1-A3 GWP by 60%;
- Lighter solution reducing the GWP for construction installation and lower material wastage in the construction site (A5) by 32%.

The study examines two End-of-Life (EOL) scenarios for different retaining wall systems. In these scenarios, the steel sheet pile wall is intended for recovery, while the reinforced concrete diaphragm wall is intended to remain in place. A higher recycling ratio and lower landfilling prove advantageous for the GWP of the steel sheet pile wall solution. The reinforced concrete diaphragm wall is left in place after its service life, a practice that is very detrimental to the environment due to the scrap loss burden.

The embodied carbon analysis, as shown in Figure 7, highlights the role of different components in influencing embodied impacts. Machinery use and installation procedures emerge as significant contributors, emphasizing the need for sustainable energy sources.

In conclusion, the comprehensive assessment of both retaining wall solutions reveals the steel sheet pile wall as the standout performer in terms of environmental impact mitigation. Its significant GWP reduction, intrinsic efficiency in material utilization, emphasize its superiority as an environmentally conscious choice. This study underscores the importance of considering the broader environmental impacts of construction choices and supports the notion that the steel sheet pile wall is not only a practical engineering solution but also a responsible one that aligns with the imperatives of a greener future.

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