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Environmental Impact Assessment for Concrete Additive Manufacturing in Construction: A Unified Framework for Particle bed and Deposition-based technologies

Sophie Viktoria Albrecht
sophie.albrecht@oth-regensburg.de

OTH Regensburg
Charlotte Thiel
OTH Regensburg

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Abstract

Concrete additive manufacturing (AM) is rapidly evolving and encompasses a growing range of processes. However, existing Environmental Life Cycle Assessment (E-LCA) studies are often shaped by data availability rather than a consistent methodological structure. Combined with process-specific assessment approaches, this results in inconsistent system boundaries, assessment parameters, and inventory modelling approaches. Consequently, current approaches do not adequately capture the environmental impacts associated with the production and construction processes of concrete AM, particularly across technologies beyond extrusion-based processes. First, a literature review is conducted to identify assessment parameters considered in existing E-LCA studies. These parameters are then integrated with a previously proposed E-LCA approach and incorporated into a unified cradle-to-site E-LCA framework. Its applicability is evaluated through a case study of a selective paste intrusion produced bridge. Results show that the framework's additional parameters enable a more transparent and comprehensive assessment of concrete AM processes. Accounting for up to 37 % of the total Global Warming Potential, they reveal previously unaccounted-for impacts and opportunities to optimise concrete AM production. The proposed framework provides a methodological basis for harmonised cradle-to-site E-LCA studies of concrete AM technologies. By improving transparency, completeness, and comparability, it supports more consistent environmental assessments and identifies hotspots across the concrete AM process chain. This enables the comparison of different concrete AM production technologies, supports the development of more sustainable production processes and lower-impact technological alternatives, and identifies the process stages with the greatest potential for environmental impact reduction.

1. Introduction

The transition toward more sustainable construction practices has intensified the need for robust and comprehensive methods to quantify environmental impacts across the entire life cycle of building products and processes. Environmental Life Cycle Assessment (E-LCA) has emerged as a standardized and widely accepted methodology for this purpose. By providing a holistic perspective on environmental burdens, including greenhouse gas emissions, energy consumption, and resource depletion, E-LCA supports informed decision-making in both research and industrial applications (Sala et al. 2016).

In parallel, additive manufacturing (AM) technologies for concrete construction have attracted increasing research attention due to their potential to support material-efficient, automated, and geometrically flexible production compared with conventional construction methods (Placzek and Schwerdtner 2023). AM applications range from in-situ construction of structural elements to the prefabrication of building components and comprise a variety of process technologies rather than a single manufacturing method (Buswell et al. 2020). Construction AM is commonly categorized into two main process families: deposition-based processes and particle-bed-based processes (Kloft et al. 2021). Despite their different manufacturing principles, both process families are governed by the interaction between material properties and process parameters, making their environmental assessment increasingly important as AM technologies continue to diversify within the construction industry.

The increasing diversity of AM processes in construction highlights the need for a common environmental assessment framework. A fundamental challenge in the current literature is the limited comparability and transferability of results, as many studies develop tailored E-LCA models for individual processes or case studies. Key methodological choices, including functional units, system boundaries, cut-off criteria, assessment parameters, and inventory modelling approaches, vary considerably due to differences in data availability and process-specific requirements (Khan et al. 2021; Tinoco et al. 2022; Mastropasqua et al. 2026; Alokshiya et al. 2026). These variations complicate comparisons both within and across processes and limit the identification of generalisable insights for decision-making. Moreover, the frequent use of cradle-to-gate system boundaries may exclude relevant environmental contributions from subsequent production and construction activities, thereby reducing the completeness of the assessment (Khan et al. 2025; Mastropasqua et al. 2026).

This study develops a unified framework for assessing the environmental impacts of concrete AM in construction. The framework builds on the cradle-to-gate calculation approach for extrusion-based concrete AM introduced by Kuzmenko (2021) and extends it to a cradle-to-site perspective, covering life cycle stages A1–A5. It also broadens the scope of the original approach to include different process families, particularly deposition- and particle-bed-based technologies.

First, a systematic literature review is conducted to identify the parameters, system boundaries, functional units, cut-off criteria, and inventory modelling approaches applied in existing E-LCA studies of concrete AM. The review is used to examine methodological inconsistencies and determine relevant material-, process-, production- and construction-related parameters. These parameters are subsequently defined, justified based on the literature, and integrated into a unified environmental impact model.

By incorporating both common and process-specific parameters, the framework represents different concrete AM technologies within a shared E-LCA equation, thereby improving transparency and comparability within and across process families. The applicability of the framework is then demonstrated through a particle bed process case study. The environmental impacts calculated using the proposed framework are compared with those obtained using the original Kuzmenko (2021) equation to assess the influence of the methodological extensions and newly incorporated parameters.

The framework addresses researchers conducting E-LCAs of concrete additive manufacturing, researchers developing concrete AM technologies, and construction companies by providing a consistent basis for assessing and comparing the environmental performance of concrete AM technologies. By combining an established modelling approach with literature-based methodological extensions, the study contributes to a more comprehensive, transparent, and comparable assessment of concrete AM in construction. The resulting environmental impact assessment also supports the identification of environmental hotspots and indicates where alternative technologies, resource-efficient strategies, and targeted process improvements offer the greatest potential for reducing impacts throughout the production and construction process.

2. Literature review

A systematic literature review was performed using the search string *("Life Cycle Assessment" OR "Environmental Life Cycle Assessment") AND ("Additive Manufacturing" OR "3D Printing") AND ("Concrete" OR "Cement" OR "Mortar")* across the databases Scopus, ScienceDirect, Web of Science, and Google Scholar. Duplicate records were removed, and publications not aligned with the scope of this study were excluded during the screening process. This resulted in a final dataset of 43 publications, which was analysed to identify methodological approaches, system boundaries, functional units, and parameters considered in previous studies (Albrecht 2026).

2.1. Methodological approaches to the environmental assessment of concrete additive manufacturing

The reviewed studies were examined regarding their approaches to assessing the environmental impacts of concrete AM. Existing studies indicate that the environmental performance of 3D concrete printing is primarily influenced by both material consumption and operational energy demand (Kuzmenko 2021; Roux et al. 2023). However, the proposed assessment approaches differ considerably in their system boundaries, level of process detail, and representation of material and energy flows.

Kuzmenko (2021) proposed one of the first process-oriented equations by expressing the environmental impact as the combination of material-related and time-dependent operational impacts. This approach highlighted that, beyond the environmental burden of the material itself, the duration of the manufacturing process and the operation of production equipment contribute to the overall environmental performance. Similarly, Roux et al. (2023) described the impact of a 3D-printed element as the sum of material and process contributions. Their formulation considers the amount of material used, the duration of the printing process, the robotic operation and the electricity consumption during manufacturing. By establishing relationships between material flow, printing speed and printing cross-section, the approach links environmental impacts directly to relevant production parameters rather than solely to the final component (Roux et al. 2023).

While these approaches provide valuable insights into the printing stage, other studies have focused on individual subprocesses. Ye et al. (2024) investigated the electricity demand associated with concrete mixing and demonstrated the relevance of mixer performance and production rate for the overall energy consumption. At a broader scale, Meng et al. (2023) adopted a life-cycle framework in which environmental impacts were allocated to the construction, use, and end-of-life stages, following a structure that reflects the life-cycle modules defined in EN 15804 (Deutsches Institut für Normung (DIN) e.V. 2022).

Overall, the literature indicates that the environmental impacts of concrete AM originate from three principal sources: the embodied impacts of the material, the energy demand of material preparation, and the energy required for robotic deposition. Nevertheless, these contributions are typically assessed separately and are often limited to specific process stages. Existing models commonly focus either on the printed element itself or on individual production steps, resulting in a fragmented representation of the manufacturing process.

Notably, all identified assessment approaches focused exclusively on extrusion-based concrete AM, indicating a lack of comparable approaches for other AM process categories.

2.2. System boundaries and functional units

Considerable variation was observed in the definition of system boundaries across reviewed studies (Albrecht 2026). The majority of publications employed a cradle-to-gate approach (n = 23) (Kuzmenko et al. 2019; Long et al. 2019; Mohammad et al. 2020; Weng et al. 2020; Yao et al. 2020; Sinka et al. 2020; Muñoz et al. 2021; Abu-Ennab et al. 2022; Liu et al. 2022; Mir et al. 2022; Roux et al. 2023, 2024; Zhang et al. 2023; Sambucci et al. 2023; Khan et al. 2023; Ramesh et al. 2024; Genc et al. 2024; Motalebi et al. 2024; Baytak et al. 2024; Ye et al. 2024; Albrecht et al. 2025; Patel and Raphael 2025; Raza et al. 2025) (see Fig. 1a), focusing primarily on raw material extraction, material transport, and production stages. Eight studies extended the assessment to cradle-to-site (Alhumayani et al. 2020; Abdalla et al. 2021; Han et al. 2021; Salandin et al. 2022; Fernandez et al. 2023; Khalili Tari et al. 2023; Pons-Valladares et al. 2023; Bianchi et al. 2024; Zhang et al. 2024), while only a limited number considered broader life cycle stages, including cradle-to-grave (n = 3) (Gislason et al. 2022; Jones and Li 2023, 2024; Meng et al. 2023), cradle-to-cradle (n = 2) (Khan et al. 2024; Moghayedi et al. 2024), or intermediate boundary definitions such as life cycle phases A–B (n = 2) (Ebrahimi et al. 2022; Khadka et al. 2024), A1 (n = 1) (Long et al. 2021), A1–A2 (n = 1) (Skibicki et al. 2024) and gate-to-gate (n = 1) (Alonso-Cañon et al. 2024). In several cases, the system boundary was not explicitly stated and was therefore assigned based on the life cycle stages and processes reported in the publication.

Figure 1 Distribution of (a) System boundaries and (b) Functional units in the reviewed literature

A high degree of heterogeneity was identified in the selection of functional unit (FU) (see Fig. 1b). Since the FU serves as the reference basis for environmental assessment in each study, differences in FU selection directly influence the interpretation and comparability of the reported results. Area-based (n = 11) (Kuzmenko et al. 2019; Alhumayani et al. 2020; Mohammad et al. 2020; Abdalla et al. 2021; Ebrahimi et al. 2022; Salandin et al. 2022; Zhang et al. 2023; Khalili Tari et al. 2023; Bianchi et al. 2024; Khan et al. 2024; Moghayedi et al. 2024) as well as component level (n = 11) (Weng et al. 2020; Yao et al. 2020; Muñoz et al. 2021; Gislason et al. 2022; Ramesh et al. 2024; Genc et al. 2024; Khadka et al. 2024; Jones and Li 2024; Albrecht et al. 2025; Patel and Raphael 2025; Raza et al. 2025) FUs were most common. Closely followed by volume-based units (n = 10) (Sinka et al. 2020; Long et al. 2021; Liu et al. 2022; Mir et al. 2022; Roux et al. 2023, 2024; Sambucci et al. 2023; Khan et al. 2023; Skibicki et al. 2024; Baytak et al. 2024) and building or system-level FU (n = 7) (Long et al. 2019; Han et al. 2021; Pons-Valladares et al. 2023; Jones and Li 2023; Meng et al. 2023; Zhang et al. 2024; Motalebi et al. 2024). Only one study used a mass-based FU (Alonso-Cañon et al. 2024), and three studies employed miscellaneous FUs that employed multiple FUs within their respective study (Abu-Ennab et al. 2022; Fernandez et al. 2023; Ye et al. 2024).

2.3. Methodological gaps and requirements for a unified framework

Existing assessment approaches lack a consistent system boundary, common mathematical structure, and uniform parameter definitions, which limits the comparability of environmental assessment results of concrete AM studies. To address these methodological gaps, a unified framework should adopt a cradle-to-site perspective and consistently account for both production and on-site construction activities. It should distinguish common parameters from technology-specific parameters and be applicable to deposition-based and particle-bed processes. This would facilitate consistent comparisons both within and between concrete AM process families.

3. Methodology

2.1. Identification and classification of parameters for the unified framework for concrete additive manufacturing in construction

The parameters relevant to the environmental assessment of concrete AM were classified according to their respective process stage. The resulting parameter categories are described in the following subsections.

1.1.1. Concrete AM Material

All reviewed studies accounted for the raw materials of the printable concrete mixture (Yao et al. 2020; Abdalla et al. 2021; Ebrahimi et al. 2022; Mir et al. 2022; Salandin et al. 2022; Fernandez et al. 2023; Zhang et al. 2023; Khalili Tari et al. 2023; Khan et al. 2023; Jones and Li 2023, 2024; Ramesh et al. 2024; Genc et al. 2024; Skibicki et al. 2024; Khadka et al. 2024; Motalebi et al. 2024; Ye et al. 2024; Patel and Raphael 2025). Some included already the transport within the raw materials (Kuzmenko et al. 2019; Muñoz et al. 2021; Gislason et al. 2022; Roux et al. 2023, 2024; Alonso-Cañon et al. 2024; Albrecht et al. 2025).

1.1.2. Additional materials

Additional materials comprise all materials required to produce the selected FU beyond the concrete material used in the AM process itself. Some AM construction applications rely on supplementary materials to satisfy structural, functional, or assembly requirements. For example, the incorporation of reinforcement, prestressing tendons, and connecting grout has been reported in AM concrete studies (Zhang et al. 2023; Jones and Li 2023, 2024), while additional materials such as insulation, concrete beams, timber, and concrete masonry were required by Khan et al. (2024) to achieve the specified area-based FU. Accounting for these materials ensures that the environmental assessment reflects the total material demand required to provide the intended functionality of the final product, rather than being limited to the concrete AM material.

1.1.3. Transport

Transportation modelling showed substantial variability across studies (Albrecht 2026) and emerged as an important source of uncertainty. Reported transport distances ranged from as little as 6.5 km to 16,000 km (Jones and Li 2024; Muñoz et al. 2021), reflecting differences in geographical context, supply-chain configurations, and modelling approaches. Different transportation modes were considered, including road freight, rail, and maritime shipping, with transport burdens assigned to various life-cycle stages such as A2 (transport to manufacturing), A4 (transport to the construction site), C2 (transport during the end-of-life phase), and module D (Weng et al. 2020; Khalili Tari et al. 2023; Skibicki et al. 2024; Moghayedi et al. 2024). However, the level of detail provided was often inconsistent. Several studies reported transportation only as aggregated transport work in tonne-kilometres (tkm) (Salandin et al. 2022; Jones and Li 2023; Ramesh et al. 2024; Motalebi et al. 2024), whereas others disclosed material-specific transport distances (Fernandez et al. 2023; Khalili Tari et al. 2023; Skibicki et al. 2024). A third approach was to apply uniform transportation distances across all materials, thereby simplifying the modelling of transport processes (Khadka et al. 2024; Patel and Raphael 2025).

In some cases, transportation impacts were not reported separately but were embedded within broader life-cycle results or background data of materials (Gislason et al. 2022; Roux et al. 2023), thereby reducing inventory transparency and limiting reproducibility. The assumptions underlying transportation modelling also differed considerably. Some studies applied generic transport distances without further justification (Abdalla et al. 2021; Muñoz et al. 2021; Khan et al. 2023), whilst more advanced approaches were less common but did occur. For instance, Fernandez et al. (2023) estimated transport requirements based on the characteristics of Brazil's most densely populated region to better represent transportation conditions in a developing-country social housing context. Overall, the wide range of transport assumptions, and reporting practices contributes significantly to the variability observed in the environmental impacts reported across studies.

While transportation impacts were generally lower than those associated with material production, they remained a non-negligible contributor in several studies. For in-situ printing, transportation requirements included not only the delivery of materials but also the mobilisation of printing equipment. Reported transport distances for the printer itself varied substantially, ranging from 80 km in Zhang et al. (2024) to as much as 6,500 km in Abdalla et al. (2021). In contrast, Bianchi et al. (2024) assumed a transport distance of 500 km for an off-site printing scenario. Despite the comparatively short transport distances in general (8–80 km) considered by Zhang et al. (2024), transportation contributed more to the environmental impacts than energy consumption in the comparative assessment. Similarly, Alhumayani et al. (2020) identified transportation as the second-largest contributor to environmental impacts after material production, whereas Meng et al. (2023) ranked transportation as the third most significant contributor, following material production and construction machinery operation.

The relative importance of transportation was also found to depend on the selected production and construction configuration. While Jones and Li (2023, 2024) reported only negligible transportation impacts for in-situ 3DCP scenarios, transportation contributed approximately 3% of total GWP impacts in a hybrid system combining prefabricated 3D-printed formwork with on-site concrete casting. This increase can be attributed to the additional logistics associated with transporting the prefabricated printed elements from the production facility to the construction site. The findings suggest that transportation

becomes more relevant when off-site manufacturing and prefabricated components are integrated into the construction process. Consequently, cradle-to-site transportation should be included in a unified E-LCA framework for both in-situ and off-site concrete AM systems to ensure consistent representation of logistical impacts across different production configurations.

1.1.4. Production information

The availability of production-related inventory data varied considerably across studies. With regard to operational energy consumption, 13 studies did not provide any production-related data (Long et al. 2019, 2021; Sinka et al. 2020; Abu-Ennab et al. 2022; Ebrahimi et al. 2022; Salandin et al. 2022; Khalili Tari et al. 2023; Ramesh et al. 2024; Genc et al. 2024; Khan et al. 2024; Skibicki et al. 2024; Khadka et al. 2024; Albrecht et al. 2025). In contrast, 22 studies reported electricity consumption associated with concrete production and/or printing operations (Alhumayani et al. 2020; Mohammad et al. 2020; Weng et al. 2020; Yao et al. 2020; Abdalla et al. 2021; Han et al. 2021; Liu et al. 2022; Mir et al. 2022; Fernandez et al. 2023; Zhang et al. 2023, 2024; Sambucci et al. 2023; Pons-Valladares et al. 2023; Khan et al. 2023; Meng et al. 2023; Bianchi et al. 2024; Moghayedi et al. 2024; Alonso-Cañon et al. 2024; Motalebi et al. 2024; Ye et al. 2024; Patel and Raphael 2025; Raza et al. 2025).

However, electricity consumption alone does not capture the full environmental burden of the printing process. To quantify impacts associated with the manufacturing, inventory data for the printing system must also be available. Only seven studies (Kuzmenko et al. 2019; Muñoz et al. 2021; Gislason et al. 2022; Roux et al. 2023; Jones and Li 2023, 2024; Baytak et al. 2024) included both operational electricity consumption data and environmental inventory data for the robotic printing system. Consequently, these studies were the only ones that allowed the process-related impacts of the robotic setup to be linked to printing duration and allocated to the FU. This observation provides the methodological basis for including both electricity consumption and robotic-system inventory data as parameters in the proposed calculation framework.

Notably, five of the seven studies relied on the robotic inventory dataset originally developed by Kuzmenko (2021), indicating a strong dependence on a single secondary data source for modelling printer-related impacts. Furthermore, the environmental contribution of the robotic system is highly sensitive to assumptions regarding equipment service life, which directly affects the allocation of manufacturing impacts per operating hour. Reported values varied substantially across studies. Kuzmenko et al. (2020) assumed a service life between 52,008 and 105,120 operating hours for the complete robotic printing cell. Roux et al. (2023), whose modelling approach was largely based on Kuzmenko (2021), explored a range of approximately 12,000–47,000 operating hours. Gislason et al. (2022) assumed a service life of 35,000 h for both the robot and concrete pump and additionally evaluated a wider range of 10,000–100,000 h for 3DCP equipment in sensitivity analyses. The wide variation in these assumptions highlights a major source of uncertainty when quantifying equipment-related impacts and further justifies the inclusion of service life as an explicit parameter in the equation.

Despite these differences, studies consistently reported that process-related impacts were small compared with material-related impacts. Roux et al. (2023) found that the contribution of the 3D-printing equipment and the electricity consumption combined remained below 5% of total GWP, while the material dominated the results. Similarly, Jones and Li (2023, 2024) found that construction-stage processes associated with in-situ 3D concrete printing, including the operation, contributed only 0.5–2.1% of total environmental impacts, whereas material production accounted for 97.9–99.1% depending on the printing scenario and concrete mix design. For the hybrid scenario combining prefabricated 3D-printed concrete formwork with conventional cast-in-place concrete, the combined contribution of production and construction processes was even lower, representing only 0.3% of total cradle-to-gate GWP, while material production remained the dominant impact contributor. (Muñoz et al. 2021) likewise found that printing and polishing operations, including the complete life cycle of the printing equipment, contributed less than 1% of total greenhouse-gas emissions. (Baytak et al. 2024) reached a similar conclusion, stating that the GWP attributable to the printing process were negligible because the actual usage time of the printer was small relative to its assumed service life.

Nevertheless, these findings should be interpreted with caution because the environmental impacts of the assessed systems were largely governed by the use of cement-intensive mixtures. (Kuzmenko 2021) and (Roux et al. 2023), for example, employed mixtures containing approximately 540 kg/m³ OPC, while Gislason et al. (2022) considered a mixture with 578 kg/m³ Portland cement. Baytak et al. (2024) reported cement contents of 806–861 kg/m³ for Portland cement-based mixtures and about 515 kg/m³ for Portland limestone cement mixtures. By comparison, Girskas and Kligys (2025) reported Portland cement contents for 3D printable concretes ranging from approximately 330–620 kg/m³. Since cement production typically dominates the life cycle impacts of concrete, such elevated cement contents can overshadow the environmental contribution of printing equipment, electricity consumption, and other process-related activities, thereby reducing their apparent relative importance. As the cement content decreases, the relative contribution of the robot operation and electricity consumption to the overall environmental impacts may become more significant than reported in the reviewed studies.

Moreover, (Kuzmenko 2021) further noted that the contribution of process-related impacts may increase in regions with more carbon-intensive electricity grids, such as those relying heavily on coal-based electricity generation. These observations suggest that although equipment-related impacts are often secondary to material production, their relative importance depends on both the electricity mix and the assumptions adopted for equipment lifetime and utilisation.

Overall, the literature reveals substantial gaps and inconsistencies in the reporting of foreground production data. While electricity consumption is increasingly reported, detailed environmental inventory data for robotic printing systems remain scarce, and assumptions regarding equipment service life vary widely.

1.1.5. Waste materials

The relevance of waste-related impacts is reflected in several studies that explicitly incorporated waste flows into their environmental inventories. Muñoz et al. (2021) accounted for the disposal of manufacturing waste, particularly waste concrete generated during production, as part of the life cycle of the printed component. Similarly, Ramesh et al. (2024) included waste streams within their life-cycle inventory to represent the specific production practices and technologies employed in the assessed system. Albrecht et al. (2025) quantified waste concrete generated during production and additionally considered the

wastewater required for equipment cleaning, illustrating that environmental burdens associated with waste management can persist even when overall material consumption is reduced.

1.1.6. Auxiliary processes

Auxiliary processes were identified as a relevant parameter encompassing additional operations performed during or after printing that are required to achieve the intended surface quality, geometry, or functionality of the final product. These processes may include surface finishing, polishing, drilling, milling, or engraving. For example, Muñoz et al. (2021) included a polishing post-processing step and noted that the same equipment could also be used for other finishing operations such as drilling, milling, and engraving.

1.1.7. Construction installation

Construction installation activities commonly involve the use of lifting equipment for the handling and erection of prefabricated components. Jones and Li (2023) and Bianchi et al. (2024) included crane operations as part of the installation and assembly phase of prefabricated AM elements. Although Bianchi et al. (2024) reported the associated environmental impacts to be negligible, such activities still consume resources and generate emissions.

2.2. Case study application and added-value assessment compared to the Kuzmenko approach

The unified E-LCA framework was applied to a Selective-Paste-Intrusion (SPI) Particle-bed case study to demonstrate its practical application and assess its added value compared with the approach proposed by Kuzmenko (2021). First, the environmental impacts of the case study were calculated using the parameters identified within the unified framework. The same case study was then evaluated using the Kuzmenko approach. The results of both approaches were compared to determine how the extended system boundary and the inclusion of additional parameters affect the calculated environmental impacts. Finally, a sensitivity analysis was conducted for one of the parameters introduced in the unified framework to examine its influence on the overall results.

1.1.1. Case study application

For the E-LCA the framework developed in ISO 14040 and ISO 14044 was applied (Organization for standardization 2021a, b). The software openLCA 2.6.2 and the database ecoinvent 3.11 cut-off were used. The life cycle phases A1 - A5, extraction of raw materials, transport to manufacturing, manufacturing, transport to construction site and the construction installation were analysed (Deutsches Institut für Normung (DIN) e.V. 2022). For the FU, a bridge spanning 5.0 m × 2.5 m was chosen (Schneider et al. 2024). The assessed bridge was manufactured with SPI, a particle bed process. It was printed in 21 segments connected by dry joints and two-post-tensioning cables, enabling future disassembly and reconstruction.

The LCI comprises the production of all constituent materials, including their transportation to the manufacturing facility in South Tyrol (see Table 1). Manufacturing was performed using the SPI printing system, consisting of a printer, mixer, and pump. Following production, the 21 printed SPI segments and the required assembly materials were transported to the construction site at the Technical University of Munich. On-site assembly involved a timber support structure and a forklift for handling and erection activities. Detailed inventory data, modelling assumptions, and the datasets used for the E-LCA are provided in Albrecht and Schneider (2026).

Table 1
Life Cycle Inventory of the analysed Selective Paste Intrusion 3D printed bridge

Parameter/Material	Amount	Unit
A01_V_M		
cement, CEM II/A (EN 197-1 (Deutsches Institut für Normung (DIN) e.V. 2011))	1,233.65	kg
expanded clay	813.50	kg
plasticiser, for concrete, based on sulfonated melamine formaldehyde	11.02	kg
silica sand	270.94	kg
tap water	468.95	kg
A01_M_A		
steel, chromium steel 18/8	20.59	kg
steel, low-alloyed	0. 58	kg
tube insulation, elastomere	1.43	kg
A02_T_M		
transport, freight, lorry, > 32 metric ton, diesel, EURO 6	553.22	t*km
A03_P_I		
air compressor, screw-type compressor, 4kW	6.69E-03	Item(s)
building, hall, steel construction	0.04	m²
operation, computer, desktop, with liquid crystal display, active mode	6.00	h
ventilation system, decentralized, 6 x 120 m3/h, steel ducts	1.76E-02	Item(s)
water pump, 22kW	2.09E-04	Item(s)
Pressure tank	4.0E-03	Item(s)
Mixer	0.01	Item(s)
3D printer	5.83E-02	Item(s)
A03_E_I		
electricity, high voltage	1,188.00	kWh
A03_W_I		
cement, CEM II/A	12.34	kg
expanded clay	8.14	kg
plasticiser, for concrete, based on sulfonated melamine formaldehyde	0.11	kg
silica sand	2.71	kg
tap water	4.69	kg
A03_A_I		
electricity, high voltage	1834.76	kWh
A04_T_C		
transport, freight, lorry, > 32 metric ton, diesel, EURO 6	917.57	t*km
transport, freight, lorry, diesel, unspecified	4.06	t*km
transport, freight, train, fleet average	0.49	t*km
A05_C_I		
building machine	1.09E-04	Item(s)
cleft timber, measured as dry mass	31.28	kg
plywood	2.38E-02	m³

The impact categories climate change - total (GWP-t); climate change – fossil (GWP-f); climate change – biogenic (GWP-b); climate change – land use and land use change (GWP-l); Ozone Depletion Potential (ODP); Acidification Potential (AP); eutrophication potential - aquatic freshwater (EP-freshwater); eutrophication potential - aquatic marine (EP-marine); eutrophication potential - terrestrial (EP-terrestrial); photochemical ozone creation potential (POCP); abiotic depletion potential for non-fossil resources (ADPE); abiotic potential for fossil resources (ADPF); water use (WDP); total use of renewable primary energy resources (PERT); and total use of non-renewable primary energy resources (PENRT) were determined according to DIN EN 15804 (Deutsches Institut für Normung (DIN) e.V. 2022). The results of ADPE, ADPF, and WDP should be used with care as the uncertainties of the results are high and as there is limited experience with the indicator.

1.1.2. Comparison with the Kuzmenko approach

The results obtained using the unified E-LCA framework for concrete AM in construction were compared with those calculated using the Kuzmenko (2021) approach. The Kuzmenko (2021) framework applies a cradle-to-gate system boundary and primarily considers material- and extrusion-process-related environmental impacts, thereby excluding transportation to the construction site (A4) and construction and installation activities (A5). In contrast, the proposed framework extends the system boundary to cradle-to-site and incorporates additional parameters required to represent particle-bed AM processes. The comparison separately examines the effects of the extended system boundary and the newly included parameters on the overall environmental impacts of the case study to determine whether these methodological extensions provide a more comprehensive representation of the production and construction process.

1.1.3. Sensitivity analysis

A sensitivity analysis was conducted for the excavation of the SPI printed parts. This parameter was selected because auxiliary processes is one of the newly introduced parameters within the proposed unified E-LCA framework, allowing the influence of process-specific activities to be explicitly quantified. As such, it provides a clear example of the additional insights enabled by the expanded framework and highlights the relevance of including the new parameters in the environmental assessment.

In the baseline scenario, the electricity demand associated with excavation was calculated as 1,834.76 kWh based on the mass of material removed. Depending on site-specific conditions, excavation could potentially be performed manually, resulting in no machine-related environmental burden. For the upper-bound scenario the maximum assumed bulk density resulted in an electricity demand of 3,627 kWh. This range reflects potential variations in material composition, excavation methods, and site conditions.

4. Results

1.1. Mathematical Integration of the parameters for the unified framework for concrete additive manufacturing in construction

The proposed framework quantifies the total environmental impact I_{Env} of an AM concrete FU by integrating all relevant materials and processes from material production to the installation on the construction site. The total environmental impact I_{Env} is calculated as followed:

$$I_{Env} = V_M \times M_I + \sum M_A + \sum T_M + \Delta t \times (P_I + E_I) + \sum W_I + \sum A_I + \sum T_C + \sum C_I$$

1

Based on the distribution of system boundaries identified in Section 2.2, with most studies adopting either a cradle-to-gate or cradle-to-site perspective, a cradle-to-site system boundary was selected for the unified framework to include relevant construction-site activities. The individual terms represent the environmental impacts assigned to raw material supply (A1), material transportation (A2), manufacturing (A3), transportation to the construction site (A4), and construction and installation (A5).

Following their identification and classification in Section 3.1 the parameters were integrated into a unified framework for concrete AM in construction equation according to their function within the production and construction process and their allocation of the life-cycle modules A1 - A5. The allocation of individual parameters depends partly on whether the process is conducted off- or on-site.

V_M represents the volume of AM material required for the FU and M_I the environmental impact associated with the AM material. The product of these two terms yields the material-related environmental impact and is equivalent to the formulation used in the (Kuzmenko 2021) equation. The parameter $\sum M_A$ accounts for any additional materials required to achieve the specified FU that are beyond the concrete AM material itself. The term $V_M \times M_I + \sum M_A$ represents the environmental impacts associated with the raw material supply (A1) life cycle phase.

The transportation impacts (A2) of these materials are captured by $\sum T_M$ which is calculated individually for each material based on the transported quantity, transport distance, and the specific type of transportation vehicle.

The term $\Delta t \times (P_I + E_I)$ represents the manufacturing stage of additive concrete production, where Δt is the printing duration, P_I is the process-related environmental impact of the printing setup, and E_I is the impact associated with electricity consumption to produce the declared FU. The term is equivalent to the formulation used in the (Kuzmenko 2021) equation. The proposed equation explicitly includes parameters describing operational electricity demand, robotic-system inventory impacts, printing time, and equipment service life, thereby enabling a more transparent and reproducible estimation of production-stage impacts and facilitating sensitivity analyses for key sources of uncertainty.

Waste generated during manufacturing is represented by $\sum W_I$, which is calculated as $V_W \times M_I$, where V_W is the volume of waste material. As waste quantities and treatment routes can vary across materials, technologies, and production configurations, waste is included as an explicit parameter in the proposed equation. This enables the transparent assessment of environmental impacts associated with material losses, wastewater, recycling, transportation, and disposal. The term $\sum A_I$ captures additional auxiliary processes required during or after production.

For off-site production, these contributions $(\Delta t \times (P_I + E_I) + \sum W_I + \sum A_I)$ are allocated to module A3 (manufacturing).

For in-situ concrete AM, life cycle phase A3 includes only concrete mixing and the associated mixer electricity consumption. All other impacts associated with $\Delta t \times (P_I + E_I) + \sum W_I + \sum A_I$ related to the printing process are allocated to Module A5, reflecting the fact that manufacturing takes place directly on the construction site. A cradle-to-site system boundary is therefore essential for consistently capturing and comparing the environmental impacts of off-site and in-situ concrete AM configurations, including differences in material supply chains logistics, and printer deployment.

The parameter $\sum T_C$ captures transportation impacts related to the construction stage (A4). For off-site production, it accounts for transporting the prefabricated element to the construction site, whereas for in-situ production it accounts for transporting the printing equipment and setup. This distinction ensures that scenario-specific logistics are assessed consistently without double-counting material transport impacts already included in $\sum T_M$.

The parameter $\sum C_I$ is introduced to account for the environmental impacts associated with the assembly, installation, and on-site construction activities required to deliver the FU. As explained for life cycle phase A3 for in-situ AM, the environmental burdens of the printing process itself are calculated by $\sum C_I = \Delta t \times (P_I + E_I) + \sum W_I + \sum A_I$ excluding the concrete mixing process. Additional auxiliary on-site processes required for in-situ production can also be incorporated within $\sum A_I$.

The structure of the equation enables a transparent assessment of the relative contributions of materials, transportation, manufacturing operations, waste generation, auxiliary activities, and construction processes while maintaining compatibility with the modular life-cycle framework defined by EN 15804 (Deutsches Institut für Normung (DIN) e.V. 2022).

1.2. E-LCA impacts of the SPI bridge

The environmental performance of the SPI case study was assessed using the unified E-LCA framework for concrete AM in construction. Table 2 presents the results by impact category and framework parameter. Within the defined system boundary, the excavation ($\sum A_I$) of the printed components emerged as a major contributor to several

environmental impact categories (GWP-t, GWP-f, GWP-b, GWP-l, ODP, AP, EP-freshwater, EP-terrestrial, ADPF, WDP, PERT, and PENRT). Across these impact categories, excavation accounted for at least 20% of the total environmental burden, reaching contributions of up to 47%. These results identify excavation as one of the dominant environmental hotspots of the SPI process for this product and demonstrate that manufacturing-related activities can contribute environmental burdens comparable to those of material production. In contrast, the transport to construction site (A4) and construction installation (A5) stages, had a comparatively minor influence on the overall environmental profile. Their contribution remained below 6% of the total impact in almost all categories, except for PERT, where they accounted for approximately 17% of the total impact.

E-LCA results of the analysed Selective Paste Intrusion printed bridge separated int

Impact category	Unit	$\varvec{V}_{\varvec{M}} \times \varvec{M}_{\varvec{I}}$	$\sum \varvec{M}_{\varvec{A}}$	$\sum \varvec{T}_{\varvec{M}}$	$\varvec{\Delta t} \times$
GWP-t	kg CO_2-eq	1,210.29	102.09	56.33	228.55
GWP-f	kg CO_2-eq	1,209.70	101.83	56.30	227.16
GWP-b	kg CO_2-eq	0.31	0.15	0.01	1.07
GWP-l	kg CO_2-eq	0.28	0.11	0.02	0.32
ODP	kg CFC-11-eq	1.03E-04	2.79E-05	2.58E-05	6.49E-05
AP	molc H + eq	3.78	0.60	0.14	4.55
EP-freshwater	kg P-eq	0.21	0.11	0.00	0.13
EP-marine	kg N-eq	1.64E-02	4.67E-03	8.63E-04	1.69E-02
EP-terrestrial	molc N eq	9.47	1.07	0.39	16.52
POCP	kg NMVOC-eq	2.72	0.35	0.23	0.92
ADPE	kg Sb-eq	1.77E-03	2.91E-03	1.64E-04	1.89E-02
ADPF	MJ	5,795.80	1,126.79	838.56	2,535.10
WDP	m3 world eq	146.36	43.31	5.11	102.77
PERT	MJ-eq	626.70	324.27	13.17	296.96
PENRT	MJ-eq	6,833.41	1,365.00	908.29	2,995.14

1.1.1. Comparison with the Kuzmenko approach

The environmental impacts calculated using the Kuzmenko (2021) approach corresponded to approximately 73% of those obtained using the proposed cradle-to-site framework. When the proposed framework was restricted to a cradle-to-gate system boundary, the Kuzmenko (2021) results corresponded to approximately 76% of the calculated impacts. In the Kuzmenko (2021) approach, material transportation is already included in the material impact factor M_I and is therefore incorporated into the term $V_M \times M_I$. Consequently, this term is higher than the corresponding AM-material term in the proposed framework, whereas the separately reported material-transportation term $\sum T_M$ is zero. In the proposed framework, material production and material transportation are reported separately to improve transparency and avoid double counting. The remaining differences are primarily attributable to the additional process-specific parameters included in the proposed framework. The excavation process substantially affected the environmental profile of the SPI process, as shown in Table 3.

Table 3
GWP-t results comparison of the Kuzmenko calculation framework and the E-LCA unified framework proposed in this study

Impact category	Unit	$V_M \times M_I$	$\sum M_A$	$\sum T_M$	$\Delta t \times P_I$	$\Delta t \times E_I$	$\sum W_I$	$\sum A_I$	$\sum T_C$	$\sum C_I$	TOTAL
GWP-t - Albrecht	kg CO_2-eq	1,210.29	102.09	56.33	228.55	392.99	12.10	606.95	94.07	13.99	2,717.37
GWP-t - Kuzmenko	kg CO_2-eq	1,266.62	102.09		228.55	392.99					1,990.25

1.1.2. Sensitivity analysis

For the purpose of this paper, the sensitivity analysis focuses on GWP-t. The detailed sensitivity results for all impact categories are reported in Albrecht and Schneider (2026). The sensitivity analysis revealed a considerable influence of the auxiliary processes' parameter ($\sum A_I$) on the GWP-t. In the minimum-impact scenario, which assumed manual excavation, the GWP-t was 2,110.42 kg CO2-eq, while the maximum-impact scenario increased the GWP-t to 3,310.24 kg CO2-eq. Thus, the minimum scenario was 606.95 kg CO2-eq, or approximately 22%, lower than the baseline, whereas the maximum scenario was 592.87 kg CO2-eq, or approximately 21.8%, higher. The overall difference between the minimum- and maximum-impact scenarios was 1,199.82 kg CO2-

eq. Under the maximum-impact excavation scenario, the excavation stage contributed approximately 36% of the total GWP-t, making it one of the most influential analysis parameters approaching the GWP-t contribution of the AM concrete mixture ($V_M \times M_I$) (see Fig. 2).

Figure 2 Sensitivity results of GWP-t impact of the minimum (left) and maximum (right) scenario for $\sum \mathrm{A_I}$

5. Discussion

The proposed framework should be viewed within the broader digital transformation of the construction sector, characterised by the trend towards increasing digitisation and automation of the production environment (Oesterreich and Teuteberg 2016). Within this context, the framework provides a methodological basis for evaluating different concrete AM process families and production configurations. Although further application and validation are required, it represents an initial step towards more transparent and environmentally informed decision-making in construction.

5.1 Practical Implications

The cradle-to-site system boundary provides practitioners with a comprehensive basis for assessing concrete AM processes from material production through construction and installation. This is particularly relevant when comparing off-site and in-situ production configurations, as it captures differences in material transportation, equipment deployment, on-site production, and installation activities. Although modules A4 and A5 contributed only marginally to the overall environmental impacts of the investigated case study, their inclusion ensures that potentially relevant project- and site-specific activities are not omitted. The selected boundary is also broadly consistent with current E-LCA practice, as approximately 75% of the reviewed case studies applied either a cradle-to-gate or cradle-to-site perspective.

Compared with existing assessment approaches, the unified framework provides a more integrated representation of the production and construction processes associated with concrete AM. The separate reporting of material production and transportation improves transparency, while the inclusion of process-specific parameters enables activities characteristic of different AM process families to be represented. This is particularly important for particle-bed processes, for which excavation activities are not captured by the original Kuzmenko (2021) approach. The framework can therefore support researchers, technology developers, and construction companies in identifying environmental hotspots and determining which material, process, or logistical parameters should be prioritised for optimisation.

The sensitivity analysis further demonstrates the practical importance of representing process-specific activities explicitly. Excavation had a substantial influence on the total GWP impact of the SPI process and, under the maximum-impact scenario, approached the contribution of the AM concrete mixture. Consequently, the environmental performance can be considerably influenced by the particle-bed composition, the quantity of material removed, the efficient utilisation of the available build volume, and the selected excavation method. The framework therefore supports environmentally informed process development by identifying improvement opportunities that would remain undetected if the assessment were limited to the concrete mixture and the principal printing process.

5.2 Limitations and future research

A key limitation of this study is the limited availability of detailed inventory data for several process steps. Data on mixing operations, pumping and printing equipment, dust extraction systems, and waste generation are often unavailable or reported only in aggregated form. Consequently, assumptions and proxy datasets are required to establish a consistent life-cycle inventory. Additional uncertainty arises from the limited availability of representative industrial-scale equipment data. For example, the compressor dataset used in this study is based on a 5.5 kW industrial unit with an air flow rate exceeding 600 L min^{-1}, which is likely oversized for laboratory-scale applications. Therefore, the results should be interpreted considering these data limitations. Future studies should prioritise direct measurements of electricity consumption, equipment utilisation, process duration, material losses, and waste flows under representative operating conditions.

The increased methodological completeness of the framework also results in greater data requirements. The explicit consideration of additional materials, transportation, waste, auxiliary processes, and construction activities improves the transparency of the assessment but requires information that may not be available during early technology development. Access to operational data may also be restricted in commercial applications because of confidentiality concerns. This creates a potential trade-off between assessment completeness and practical data availability. Future research should therefore develop technology-specific data collection protocols and reporting templates for concrete AM. The development of representative default values and uncertainty ranges for different process families and production scales could further facilitate preliminary assessments when primary data are unavailable.

The comparison with the Kuzmenko (2021) approach should be interpreted cautiously. While the Kuzmenko approach primarily represents material- and process-related impacts of extrusion-based AM within a cradle-to-gate system boundary, the proposed framework adopts a cradle-to-site perspective and includes additional materials, transportation, waste, auxiliary processes, and construction-related activities. It is designed to support comparisons between different concrete AM technologies and between AM and conventional construction technologies, while enabling the identification of technology-specific environmental hotspots across different AM production processes. Differences between the calculated results therefore reflect differences in purpose, system boundaries, parameter definitions, process representation, and impact allocation rather than necessarily indicating that one approach is more accurate than the other. The higher environmental impacts obtained with the proposed framework should not, by themselves, be interpreted as evidence of superior model performance. Adding processes to the system boundary will generally increase the calculated impacts, particularly when these activities are not represented in the reference approach. The main contribution of the comparison is therefore not the numerical difference between the two results but the demonstration that a process-specific environmental hotspot, namely excavation, remains invisible when an equation developed for extrusion-based AM is transferred to a particle-bed process without modification. This finding supports the need for technology-specific parameters within a common assessment structure. However, it does not constitute an independent validation of the proposed framework. A more robust comparative assessment would require

equivalent functional units, harmonised system boundaries, consistent background datasets, identical allocation rules, and primary inventory data for both extrusion-based and particle-bed systems.

The sensitivity analysis also represents only a partial examination of uncertainty. Excavation was selected because it was the most environmentally significant of the newly incorporated parameters in the SPI case study. However, other parameters, including the electricity mix, printing duration, equipment service life, material composition, transportation distances, waste rates, and utilisation of the available build volume, may also substantially affect the results. Future research should extend the sensitivity analysis to these parameters and investigate their combined effects through scenario-based or probabilistic uncertainty analysis.

Finally, the framework is limited to environmental life cycle assessment and does not incorporate economic costs, occupational safety, labour requirements, social impacts, construction time, or technical performance. Environmental results alone may therefore be insufficient to support production technology selection in practical construction projects. Future research could integrate the framework into a broader life-cycle sustainability assessment or multi-criteria decision-making approach. This extension would support more comprehensive evaluation and optimisation of concrete AM technologies across environmental, economic, and social dimensions.

6. Conclusion

This study developed a unified E-LCA framework for concrete AM in construction. The framework is intended to provide a common methodological structure for evaluating both deposition-based and particle-bed concrete AM processes. Based on a systematic literature review, the parameters relevant to the environmental assessment of concrete AM were identified, classified, and integrated into a cradle-to-site framework covering raw material supply, transportation, production, construction, and installation.

The application of the framework to the SPI particle-bed case study demonstrated the relevance of including process-specific parameters that are not represented in existing assessment approaches developed primarily for extrusion-based processes. The comparison with the Kuzmenko (2021) approach showed that these additional parameters provide a more comprehensive representation of the production and construction processes. In particular, the sensitivity analysis revealed that excavation can substantially affect the overall environmental impact, highlighting the importance of considering auxiliary and technology-specific activities in the environmental assessment of concrete AM production processes.

The separate reporting of raw material transportation within module A2 further improved the transparency of transportation-related contributions, although its influence on the overall results was limited in the investigated case study.

Overall, the proposed framework provides a consistent methodological basis for identifying environmental hotspots, comparing concrete AM processes and production configurations, and reducing the methodological fragmentation of existing environmental assessments. Its applicability to both particle-bed and deposition-based processes supports future assessments across different concrete AM technologies and enables technology-specific environmental trade-offs to be identified without assuming that material savings automatically result in lower life-cycle impacts. However, further applications to both process families are required to evaluate the framework's transferability and support more comparable and environmentally informed decision-making in construction.

Declarations

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by S.V.A. The first draft of the manuscript was written by S.V.A. and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated and analysed during the current study are available in the zenodo repository, (https://zenodo.org/doi/10.5281/zenodo.22212754 and https://zenodo.org/doi/10.5281/zenodo.22234315).

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Figures

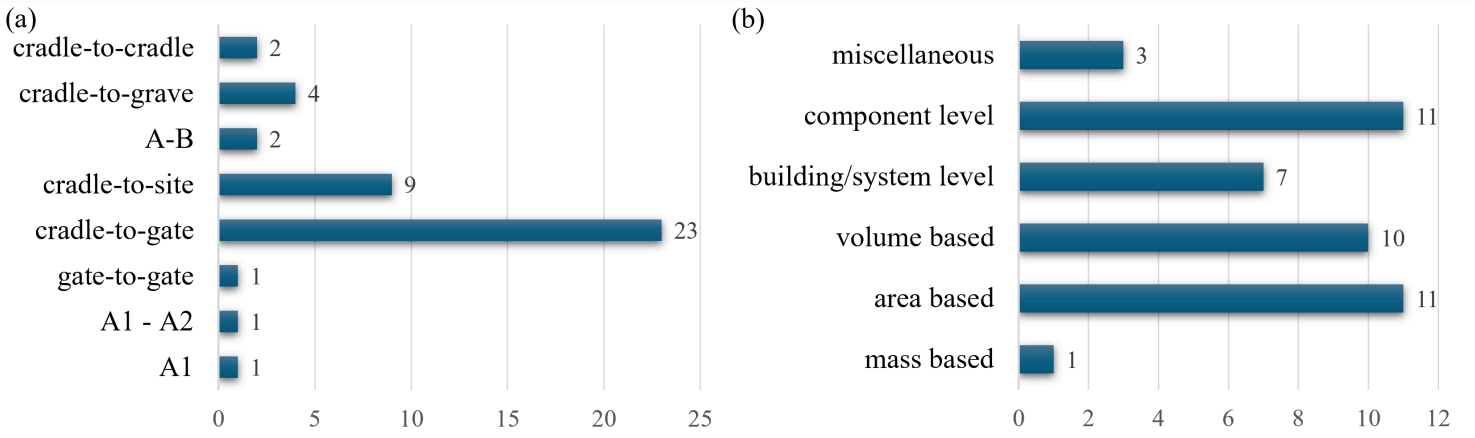


Figure 1

Distribution of (a) System boundaries and (b) Functional units in the reviewed literature

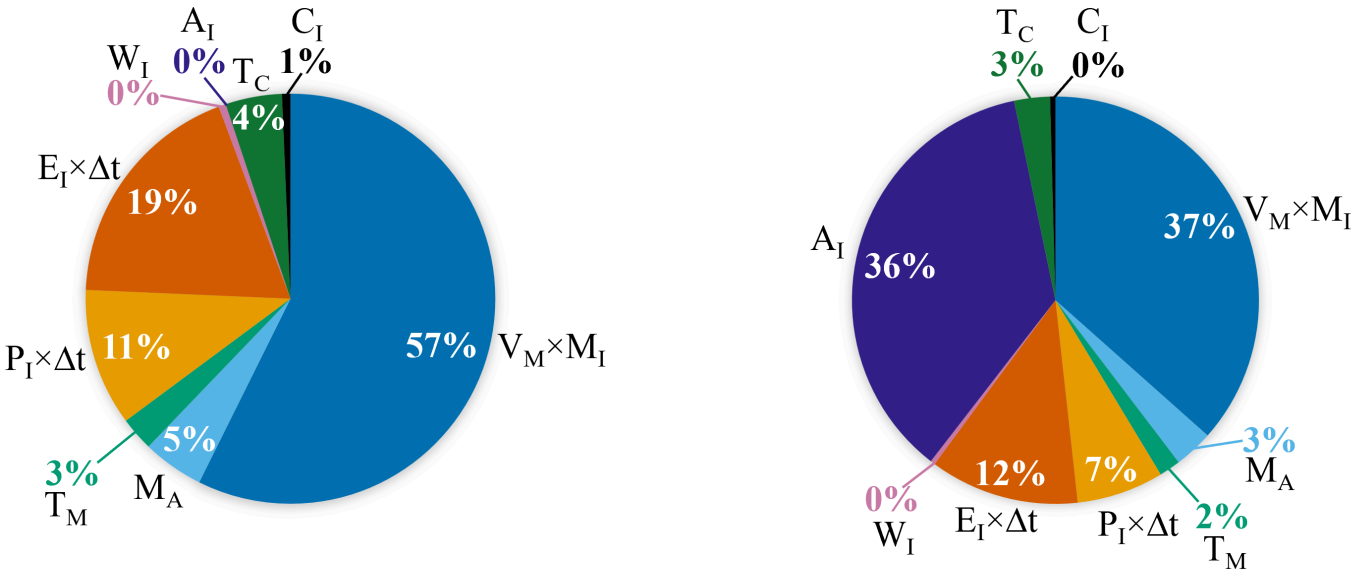


Figure 2

Sensitivity results of GWP-t impact of the minimum (left) and maximum (right) scenario for $\sum A_I$

Supplementary Files

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- Table2.docx
- Table3.docx
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