Life Cycle Assessment of Masonry Structures: Towards a Systematic, Standardized, and Transparent Calculation Approach

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ABSTRACT

Reducing the environmental impacts of the construction industry is becoming increasingly urgent for Canada to meet its committed climate change mitigation targets. As the masonry industry explores new decarbonization pathways, current life cycle assessment (LCA) efforts remain inconsistent and not standardized. In this respect, the current study evaluates the environmental performance of masonry construction using a comprehensive LCA methodology. The study first appraises the underlying principles behind life cycle-based environmental assessment. Subsequently, focusing on embodied impacts, the study outlines how different calculation tools and data sources can offer a clear, systematic, and transparent approach to assessing masonry products. Rather than solely emphasizing operational efficiency, the analysis highlights the importance of quantifying material-related impacts for energy-efficient buildings. Finally, a case study is presented herein, where the environmental impact of a masonry wall assembly is calculated using different LCA approaches. The analysis results show that black-box LCA calculations showed lower environmental impacts compared to the manual step-by-step calculation alternative. The latter offered a higher level of detail and transparency, allowing for the identification of material hotspots. For example, grout was the dominant contributor across all impact categories, suggesting that optimizing its quantity or using alternative mix designs could enhance the eco-efficiency. Evidently, employing robust calculations strengthens the credibility of the environmental assessment and moves us a step further towards standardizing the assessment of embodied impacts –similar to operational efficiency. This research area is expected to steer the masonry industry toward more sustainable practices and supports the achievement of its decarbonization targets.

KEYWORDS

Life Cycle Assessment (LCA), Environmental Assessment, Decarbonization, Building Sector, Masonry Structures.

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INTRODUCTION

The past decade of construction research never fails to demonstrate the significant energy consumption and greenhouse gas emissions of the building sector, which is responsible for almost 40% of both [1]. In Canada, the building sector's annual emissions peaked at 91 megatons of equivalent CO_2 emissions, with governmental plans to reduce such emissions by 40% from the 2005 benchmark and eventually towards net-zero emissions by 2050 [2]. To achieve such plans, billions of dollars are geared toward decarbonization efforts and incentives in the building sector [3]. Furthermore, mandatory requirements and environmental constraints are continuously developed and adopted on a regional scale [4]. However, most environmental specifications still only consider energy efficiency [5]. Building environmental impacts are mainly divided into two categories: (a) embodied impacts related to building components and their assembly; and (b) operational impacts due to occupancy requirements throughout the building design life. With many advances in operational energy efficiency, embodied impacts are increasingly becoming the hotspot that requires higher eco-efficiency [6]. Embodied impacts are also more critical in energy-efficient buildings, contributing up to 90% of their total impact compared to 25% in conventional buildings [6–8].

Using masonry units for buildings has been prevalent spatially and temporally. Bricks accompanied the first Canadian Settlements [9], and concrete blocks have been manufactured for 120+ years [10]. The conventional method for manufacturing clay bricks is through high-temperature firing, whereas concrete blocks are manufactured using general-use cement, water, and aggregates [9]. The masonry industry went through several rounds of developments to increase efficiency in order to compete with emerging building systems [11]. Now, this renowned industry is developing once more to adapt to the emerging challenges due to climate change by sequestering CO_2 in concrete blocks [12], and by utilizing sustainable fuels for firing clay bricks [13].

An effective evaluation tool is required to quantify the environmental benefits to be gained from such new industry directions. Specifically, this tool should be: (a) systematic, to enable its wide adoption by all masonry industry stakeholders; (b) standardized, to facilitate direct comparisons between different masonry products; and (c) transparent, to equip industry stakeholders with detailed information on the performance of each process making up their masonry products. After its standardization in the 90's, Life Cycle Assessment (LCA) became the standard approach for comparing the environmental impacts of products across industries [14]. LCA is systematic, standardized, and transparent when comprehensively conducted. Nevertheless, assessing the environmental impact of masonry buildings using LCA is still a complex task [15] with significant debates on how it should be performed [7,8]. Significant variability and uncertainty also exist in various masonry-related LCA parameters [16].

In addition to the need for standardizing environmental assessment, the masonry industry needs to invest in building the capacity for its professionals [11] to become adept at performing LCA for the different prototypical masonry wall systems and buildings. In this respect, the current study details the LCA process using different calculation tools, data sources, and levels of detail. Furthermore, we present a case study to transparently showcase the different LCA calculations for a masonry wall. By doing so, we aim to bridge the gap between industry professionals and environmental assessment approaches, enabling informed decision-making and sustainable material choices. A deeper understanding of LCA applications in masonry construction can facilitate the adoption of low-carbon innovations while ensuring compliance with evolving regulatory frameworks.

LIFE CYCLE ASSESSMENT

Definition and Methodology

LCA presents a standardized methodological framework to systematically compare the environmental impact of different products with similar functional output across various impact categories [14]. LCA methodology has witnessed many developments, starting with its precursor environmental profile studies in the 1960s, leading to the creation of impact assessment methods and standards. The ISO 14000 environmental standards have been globally adopted to homogenize LCA applications, where ISO 14040 defines the underlying framework and ISO 14044 details the requirements for LCA studies. Other specifications have also emerged to guide the development of environmental declaration programs (ISO 14025) and environmental product declaration (EPD) for different product categories (e.g., EN 15804 for construction products). Guidance for the environmental performance of buildings throughout their life cycle has also been established through different specifications such as EN 15978.

LCA is becoming increasingly relevant for many sectors, including construction, as it is continually utilized within policy frameworks to regulate environmental performance. For example, in 2025, Denmark mandated all new buildings to have a maximum cradle-to-grave global warming impact of 6.7 kg-CO_2e/m^2/year for single-family houses [17]. Since most contemporary LCA applications rest on the ISO 14040 framework, a brief description is provided herein. However, the ISO 14040 specification does not provide detailed methodological details on the LCA process but rather defines only the underlying principles. A more detailed specification is provided via the ILCD (International Life Cycle Data) system, which is built on the ISO framework, but it has not yet gained the same degree of adoption. The ISO LCA framework is broken down into four main stages, as shown in Figure 1: (1) Goal and scope definition; (2) Inventory analysis; (3) Impact assessment; and (4) Interpretation.

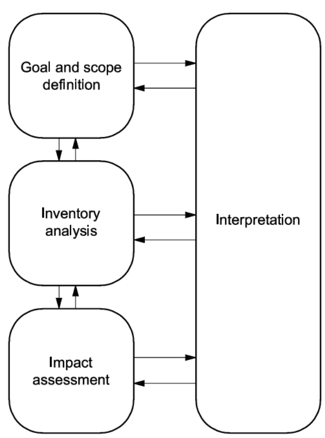

Figure 1: Life Cycle Assessment Framework [18]

LCA is defined as an iterative process, where different stages would warrant changes in previous ones. First, the goal defines the intended application, guiding the rest of the LCA process and defining the required level of detail to achieve a predetermined goal. The scope defines the spatiotemporal setting of the study, and which parts are included in the product system (i.e., the model defining the lifecycle of the studied product). It also defines the impact categories, and method of impact assessment, among other requirements in line with the study goal. For buildings, LCA studies can cover the life cycle fully (i.e., whole building considering cradle-to-gate/site/handover, or operation). The scope also defines the functional unit (i.e., quantitative description of the function), to which all inputs/outputs are related. The second step in the ISO LCA framework is the inventory analysis, where data is collected and calculated for all relevant processes and flows (i.e., inputs and outputs). Then, in the third stage, inventory flows are classified under different impact categories (classification), and the total impact for each category is calculated (characterization). Finally, the last step builds on the inventory and impact analyses to evaluate whether the study goal has been satisfied and provide conclusions/limitations for the study to enhance its robustness and credibility.

The advantages and limitations of LCA are acknowledged in the ISO specifications and the literature [19]. Specifically, LCA is a comprehensive method that evaluates impacts within the chosen categories and study boundaries. It can thus qualitatively determine the trade-offs and burden shifting when comparing different products. However, it cannot benchmark the performance of a certain product (i.e., LCA cannot define whether the eco-efficiency of a product is good enough). Moreover, LCA is limited by the generalizations on which its calculations are built, which is essential due to the complexity of LCA modelling. Other concerns may stem from the LCA application itself. For example, LCA can be seen as a "black box" with the increasing complexity of its application [20], despite requiring transparency to be comparatively effective. Other concerns of comparative LCA application include proper functional equivalence and unit conversions.

Methods and Tools

LCA studies vary in their level of detail, where various methodologies exist for performing inventory and impact analyses. Nevertheless, LCA needs "good" research that is "well-communicated" [14], no matter the chosen methods and level of detail. Different software packages are used in literature and industry to quantify the environmental impact via whole-building LCA. Each package differs in its inventory, level of detail, complexity, and transparency/control over the impact assessment process. Significant discrepancy in their impact assessment results is also found [21], owing to differences in LCI (life cycle inventories). Common LCA calculation methods are presented and compared in Table 1.

Table 1: Comparison between LCA Calculation Methods

Method	Assembly-based	EPD-based	Process-based
Software	Athena IE4B[22]	OneClick LCA[23]/Manual	OpenLCA[24]/SimaPro[25]
Building-Specific?	Yes	Yes	No
Complexity	Simple	Simple	Complex
Control	Low	Moderate or High	High
Inventory	Athena's Life Cycle Inventory	Various EPDs	Various LCI including Ecoinvent, USLCI, etc.
Transparency	undisclosed	Undisclosed or Transparent	Transparent

The three common methods of LCA are represented by different software packages. First, Athena's IE4B (impact estimator for buildings) presents a user-friendly whole-building LCA application, requiring the least input (both in quantity and complexity). However, the user is limited to the predefined materials in Athena's inventory, and a breakdown of emissions is not fully provided. Moreover, variations in environmental assessment can also be seen when material takeoff is automatically calculated [26]. OneClick LCA uses different construction products' EPDs for its inventory and thus has higher spatial accuracy albeit with constrained material input. Both IE4B and OneClick are specifically designed for whole-building LCA applications. Finally, OpenLCA and SimaPro represent the most comprehensive and generalized approach, where the product system is assembled using different unit processes, each defined by their respective flows. In addition to whole buildings, LCA studies may focus on subassemblies such as structural walls. In this case, control over the LCA process is critical to generating robust processes. In theory, although practitioners could manually conduct inventory calculations, managing the extensive number of flows across the various processes comprising the product system would be highly complex and challenging. However, this process is manageable if the product system is discretized using EPDs, where EN 15804 [27] specifies that EPDs should allow for aggregation to represent the environmental impacts of a building assembly or subassembly.

CASE STUDY

A case study is presented to demonstrate the LCA calculations for a sample wall assembly, shown in Figure 2, using different methods, namely assembly-based using Athena's IE4B and EPD-based using manual calculations. A typical wall arrangement consists of: (1) A fully-grouted Concrete Masonry Unit (CMU) wall; (2) vapor barrier and insulation; and (3) brick veneer.

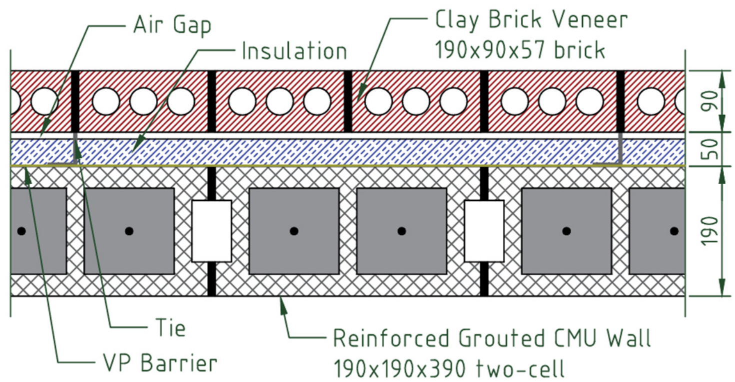

Figure 2: Case Study Wall

The goal of this LCA is to quantify the environmental impacts of constructing the presented wall assembly. A functional unit of 1m^2 of wall area is chosen for this study. The reason is to showcase the LCA calculations and highlight potential differences in environmental impact calculations. The study has a cradle-to-gate scope—covering A1-A3 modules as per the EN 15978 definition of life cycle stages. The system boundary includes the CMU wall, the brick veneer, and its reinforcement (1M10 per cell and truss mesh at 400mm spacing). Insulation and vapor barriers are excluded from the system boundary due to their higher variability in both assembly and material choices. Ties are also not included in the system boundary. The LCI differs for each LCA method used, as discussed earlier.

The LCA study is located in Ontario, Canada, and thus LCI data will spatially reflect the study area as much as possible by using inventory data specific to Ontario, Canada, or North America based on availability. Impact assessment is performed as per TRACI LCIA methodology [28], which is widely used for North American building LCA studies. Specifically, five environmental impact categories will be investigated: (1) GWP (Global Warming Potential); (2) AP (Acidification Potential); (3) EP (Eutrophication Potential); (4) Smog (Photochemical Ozone Creation Potential); and (5) ODP (Ozone Depletion Potential).

Assembly-based using Athena IE4B

Athena's IE4B only requires the input of material types, dimensions, and metadata. No additional input is required from the user as the characterization factors are built-in IE4B. A 1m^2 wall assembly, consisting of Concrete block wall and brick cladding, is defined by choosing from the predetermined list of wall assembly options. IE4B also assigns additional materials as an allowance for construction waste. Based on that definition, the bill of material is automatically generated, as presented in Table 2.

Table 2: Athena IE4B's Material List for 1m^2 Wall Assembly (i.e., Reference Flows)

Item	Unit	Quantity	LCI source*	Temporality
8" Normal Weight Concrete Block	Blocks	13.125	CCMPA's CMU EPD	2022
Cold Rolled Sheet	t	2.02E-04	AISI LCI North America	2020
Grout-Coarse	m^3	0.055	Internal Calculations**	2023
Metric Modular (Modular) Brick	m^2	1.050	Athena's LCA study***	2009
Mortar	m^3	0.050	Internal Calculations**	2023
Rebar, Rod, Light Sections	t	1.98E-03	CRSI's reinforcement EPD	2022

*LCI sources as per IE4B's manual [29]

**originally developed in 2005 and uses recent Canadian cement profiles from CAC's EPD

***published LCA report in 1998 with data updated in 2009

EPD-based using Manual Calculations

The second LCA method manually calculates the bill of materials and uses EPDs (i.e., presented in Table 3) to estimate the environmental impacts. The characterization factors extracted from the respective EPDs are shown in Table 4. Finally, reference flows are manually calculated for each material, as shown in Table 5. They represent the amount of input material required per functional output.

Table 3: Material Environmental Product Declaration (EPD) Sources

Item	EPD Source	Product Description
Concrete Block	CCMPA	Normal Weight CMU GUL SCM
Clay Brick	Brick Industry Association	General Clay Brick Product
Grout	Sika	CellFiller C-30 Grout
Mortar	Sika	1-1-6 Mortar
RFT	Arcelor Metal	Fabricated Rebar

Table 4: Characterization Factors for Each Material per the Pre-defined Unit

Impact Category	Factor	Concrete Block *(per m^3)*	Clay Brick *(per m^3)*	Grout *(per ton)*	Mortar *(per ton)*	RFT *(per ton)*
GWP	kg CO2 eq	190.58	503	250	259	1290
AP	kg SO2 eq	1.12	1.52	1.39	1.04	9.58
EP	kg N eq	0.16	0.888	0.312	0.233	1.28
Smog	kg O3 eq	14.34	15.6	18.9	15.2	61.7
ODP	kg CFC-11 eq	6.26E-06	6.29E-05	1.97E-05	3.18E-05	3.03E-05

Table 5: Manually Calculated Material List for 1m^2 Wall Assembly (i.e., Reference Flows)

Item	Unit	Quantity
Concrete Block	m^3	1.03E-01
Clay Brick	m^3	1.51E-02
Grout	t	1.87E-01
Mortar	t	3.60E-02
RFT	t	4.27E-03

Manual calculations are detailed in Figure 3. Calculations are broken down by material, where either mass or volume is calculated depending on the reference flow type present in their respective EPDs. First, actual brick and block volumes are geometrically calculated within the $1m^2$ wall using the profiles of standard metric bricks and size 20 CMU. The remaining wall volume is assigned to mortar, and CMU inner cell volumes are assigned to grout. Since mortar and grout are defined by weight in their EPDs, volumes were converted using material density from the product material sheet. An alternative calculation for grout and mortar would be specifying the mass of each component based on the established mix design. In that case, however, characterization factors shall be provided for each component. Finally, steel weights are calculated based on the length and diameter of the reinforcement bars.

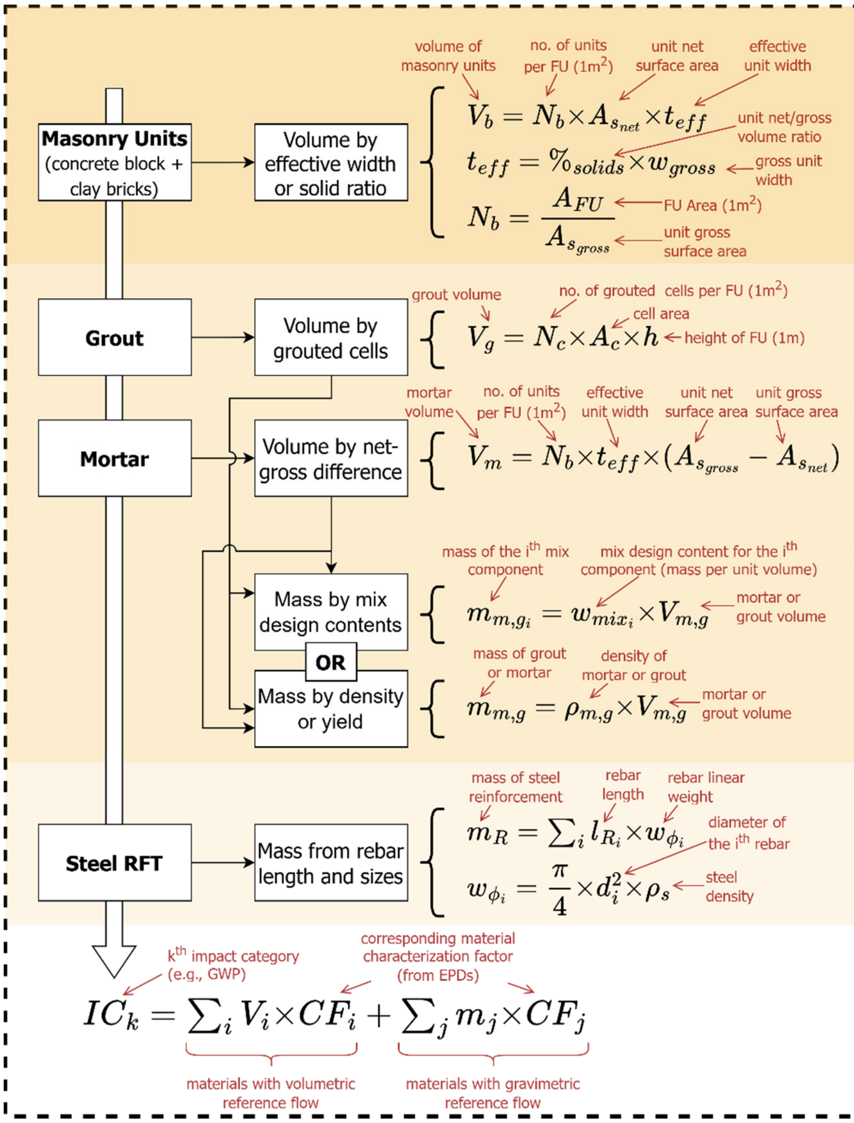

Figure 3 Manual Calculation Steps for Environmental Impact

Figure 4 shows all required inputs for the manual calculations. An additional 5% is added to the CMU, brick, mortar, and grout quantities as an allowance for waste to facilitate direct comparisons to IE4B's calculations. Care should be taken in the calculation of reference flows, especially where unit conversions are required to match those used in the EPDs.

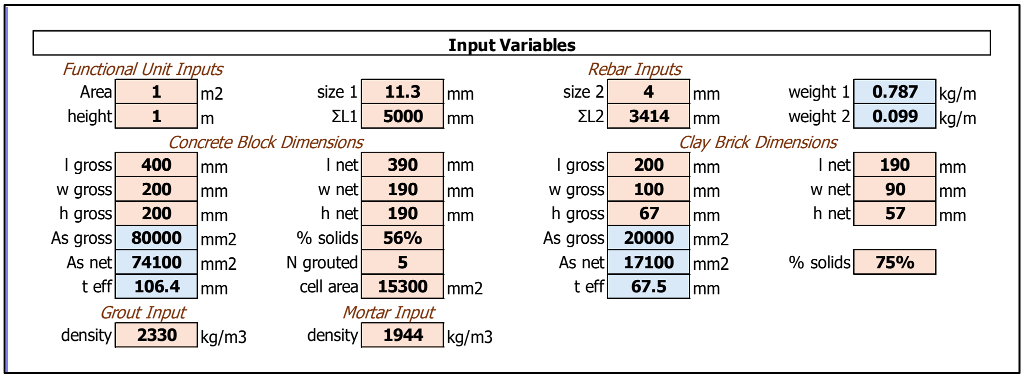

Figure 4 Inputs Required for Manual Calculation

RESULTS AND DISCUSSION

The estimated environmental impacts using Athena's IE4B and manual EPD-based calculations are compared in Table 6. Overall, IE4B calculates lower impacts across all categories except ODP, where IE4B estimates a significantly higher impact. However, its automatic estimation for materials varies from manual calculations. For example, manual calculations show 46% more grout than that of IE4B calculations. Only ODP has a significant difference between IE4B and manual calculations. That is attributed to that manual calculations use GUL concrete masonry units instead of GU in the Eastern region—yielding significantly different emissions (6.26E-06 and 7.78E-04 kg CFC-11 eq per m^3, respectively, as per CCMPA's EPD). This order of magnitude difference is present in the results even though they use the same inventory reference for masonry. It can neither be modified nor detected using a black-box calculation.

Table 6: Impact Assessment Results

Impact Category	IE4B	Manual	Unit	IE4B / Manual
GWP	68.70	89.08	kg CO2 eq	77%
AP	0.47	0.48	kg SO2 eq	98%
EP	0.06	0.10	kg N eq	60%
Smog	4.82	6.07	kg O3 eq	79%
ODP	7.77E-05	6.56E-06	kg CFC-11 eq	1184%

Significant variation in the bill of quantities exists between IE4B's estimation and manual calculations. IE4B relies on sizing curves for automatic quantity estimation [26]. So, certain customizations in the material flows cannot be directly accounted for, including the void ratio of clay bricks, wall grouting condition, different CMU sizes, and mortar thickness. Such modifications would require manual quantity calculations, estimating the difference between manual and automatic quantities, and then adding the difference manually to the wall assembly inside IE4B. Another limitation of the black-box calculations is the limited level of detail for the results, where the environmental impact for each material flow cannot be separately quantified. This may limit the interpretability of some results, including the significantly higher ODP estimated using IE4B compared to EPD-based calculations, as discussed earlier.

Unlike IE4B's automatic calculations, the contribution of each input flow to each impact category can be calculated and visualized. As shown in Figure 5, grout has the highest contribution across all impact categories, followed by clay bricks, CMU, or mortar depending on the impact category. As the highest contributors to environmental impacts are identified, the total environmental impact associated with the wall assembly can be optimized for eco-efficiency. For example, equivalent partially-grouted wall designs may be utilized. Low-carbon mixes for grout and mortar may also be explored.

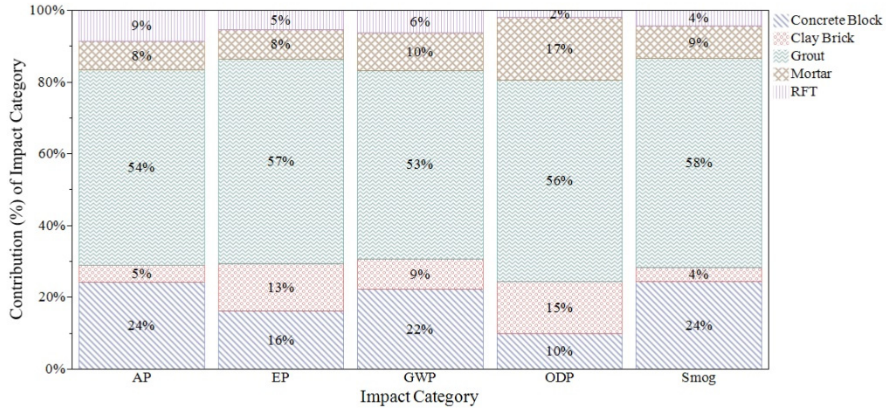

Figure 5: Contribution Analysis of Input Flows across all Impact Categories

CONCLUSIONS

The masonry industry, with its long history and widespread use, is adapting to environmental challenges by exploring pathways for reducing its environmental footprint. To support this transition, industry professionals need standardized and transparent methods that enable meaningful comparisons and informed decision-making. Thus, LCA has become an essential tool for the construction industry. Nevertheless, LCA remains a complex process with variations in methodology, inventory data, and software tools. Our study highlights these challenges and demonstrates different LCA methods through a case study.

To accelerate progress towards decarbonization, the industry must prioritize capacity building, equipping professionals with the skills to navigate LCA complexities and interpret results effectively. Standardizing assessments and fostering collaboration between policymakers, manufacturers, and researchers will further enhance the reliability of environmental claims. Bridging the gap between environmental assessment and industry practice is crucial. As such, the masonry sector can adopt low-carbon innovations more effectively while meeting evolving regulatory requirements.

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