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Carbon Conscious! The Impact of Embodied Emissions on Design Decisions for Building Envelopes

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Abstract

A focus on embodied emissions in building materials has been notorious in the last years, mostly due to high improvements in optimisation of operational energy in buildings. The environmental impact of building materials reflected in embodied energy and potential (re) life options that stimulate circular flows has become the focus of discussion. During the design process, designers and engineers are confronted with different decisions that might impact the embodied emissions (EE) of a façade system. This paper focuses on the EE of different curtain wall configurations whilst applying the Kit-of-Parts approach in a case study in California. The study was carried out under the LCA methodology applied from the A1 to A4 stages and limited to five main parameters: façade typology, span and grid size, different LCA phases, material choice, and supply chain. The results are compared against each other to understand the relevance of each parameter and level of impact of each parameter.

Keywords

Kit of parts, embodied emissions, façades, life cycle assessment

1 INTRODUCTION

For many years, due to more stringent building codes, local energy guidelines and regulations a focus on reducing operational energy of buildings and reaching zero energy targets could be observed. More recently, as the efficiency in operational energy use has increased significantly, the focus is moving towards the environmental impact of building materials, primarily reflected in the embodied energy and emissions and the potential (re)life options that allow circular material flows. Façade systems typically represent between 25 and 30% of a building's total embodied energy; however, designers and façade engineers are confronted with several design parameters that affect the environmental impact to a varying extent (Hartwell, R, Overend, M, 2020). The environmental relevance of design decisions is discussed in the literature on an abstract level; how light-weight constructions are favoured over solid assemblies, wood products over metal products, local materials over materials sourced from overseas. In real practice, parameters mix, which leads to higher complexity in answering the questions of design, performance, costs, and environmental concerns into consideration.

This paper addresses embodied emissions (EE) in different curtain wall configurations and presents the results of a case study conducted in the San Francisco Bay Area in California that investigates the application of a Kit-of-Parts approach to curtain wall systems. The goal of this study is to evaluate the relevance and impact of different design parameters on EE that derive from the design process such as façade typology, the span and grid size, the different life cycle phases, material choice, and the supply chain. The study is based on four different typical configurations of curtain wall units with a varying grid based upon standard sizes in the US.

2 METHODOLOGY

The study investigates a façade system that provides different configuration options. For each configuration, the environmental impact is investigated by quantifying the emissions through a life cycle assessment method (LCA) for a façade on an office building located in the San Francisco South Bay, US. The LCA methodology yields information about the embodied energy or embodied greenhouse gases, indicating the environmental impact of materials. The data used originates from German Ökobaudat and Environmental Product Declaration (EPD). Design alternatives are assessed with LCA and compared against each other. Additionally, the different production routes are analysed using the database Ecotransit, which calculates emissions due to transport means. Parallel, a financial calculation was conducted to see the economic dimension of reducing distances. In the end, all alternatives are compared against each other, and their relative share of potential for improvement is evaluated for this case study.

While part of the methodology relies on LCA databases to understand the environmental impact of materials, it also included the collaboration of local partners to assess the supply chain and the typical curtain wall units and configurations (as they are based on typical US sizes). The research aims to go beyond the materials' database standard values and understand a real-life scenario that, besides material impact, also considers logistics and design processes.

3 EXPERIMENT / RESEARCH

The research initiates with a literature review about façade typologies, from which the results direct towards curtain walls. Collaboration with local manufacturers pointed towards typical curtain wall configurations in the Bay Area. Thus, the experiment is limited to four different curtain wall configurations with dissimilar construction, which further derives into four different sizes per configuration.

In addition to the varying sizes, a cradle-to-gate assessment (A1-A3) is conducted to compare each phase and determine the relevance of the production phase. Additionally, the same cradle-to-gate assessment is carried out to understand the environmental impact of curtain walls' typical infill materials. The system boundary is further expanded to A4 to analyse different baselines for transport scenarios. The results are then evaluated and compared to each other to determine each parameter's level of impact.

3.1 FAÇADE TYPOLOGY

In a first analysis of the façade system, the façade typology was considered regarding two aspects; the environmental impact of materials calculated with LCA and the construction typology with its suitability for de-construction.

According to (Hildebrand, 2014), the façade typology predefines the range of environmental impact; while double skin façades can be lighter compared to solid façades, their embodied energy is significantly higher. Curtain walls fall into the typology with the lowest environmental impact when compared to solid and double skin envelopes. This is due to the low weight that results from a lighter construction required for only one layer (compared to double skin) and the skeleton structure (compared to solid façades). Figure 1 shows the result of different case studies analysed by Hildebrand (2004), where different typologies fall into cluster-like arrangements, indicating the embodied emissions per weight. As Figure 1 depicts, curtain wall envelopes have lower embodied emissions, followed by solid façades/punched windows and, finally, double skin façades.

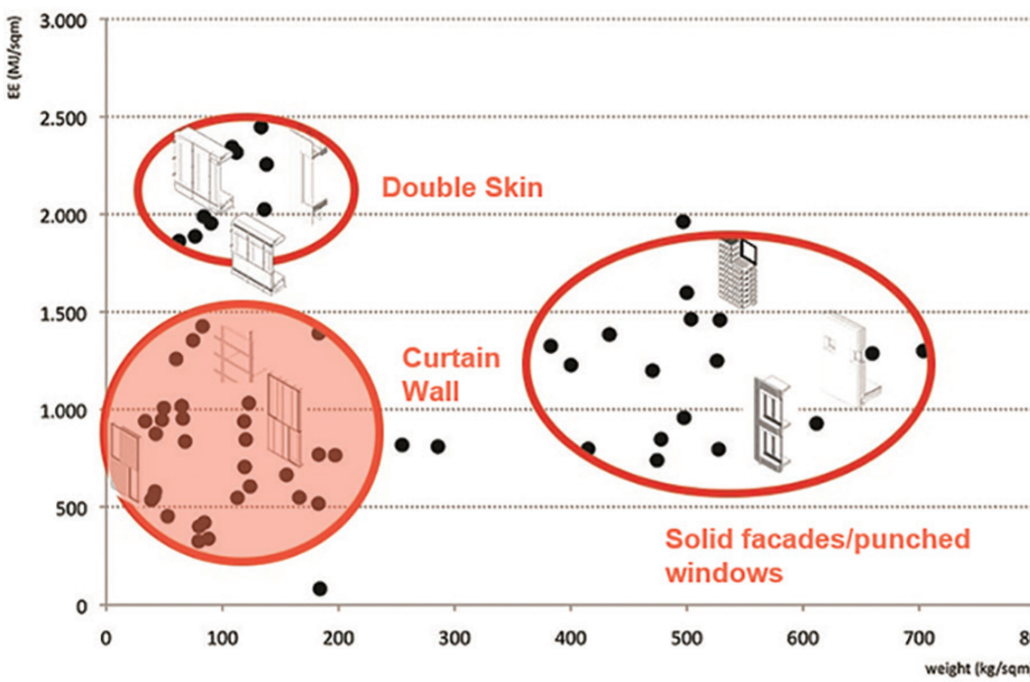

FIG. 1 Curtain walls are relatively low in weight and embodied emissions. Image by Hildebrand (2004)

In addition to their light-weight nature, curtain walls are more suitable for deconstruction compared to solid façades due to their joining technique. In comparison to a traditional brick or block wall, mortar bonds take higher mechanical forces to separate bricks or blocks from one another. Mortar typically remains on the brick, which will lead to a recycling scenario rather than reuse of the material. Curtain wall construction is based on mechanical connections, where components are screwed or clamped with each other, and they can be easily separated. Even where bonded connections are used, surfaces are clean, so silicone bonds can easily be cut off. This helps to deconstruct with little effort, which has proven to be a driver of ease of reuse or recycling, therefore, stimulating a circular flow of materials.

3.2 SPAN/GRID SIZE

To understand the impact of unit sizes and common metrics like window-to-wall ratio on the EE of the components, a variation of unit sizes was assessed. As the size of curtain wall units has a considerable impact on cost as well as transport and installation efficiencies, it was considered important to understand the impact of sizes and framing ratios on the EE, as it would help negotiate performance, cost and environmental impact.

Four different unit configurations were assessed to analyse the impact of the curtain wall's span/grid size: glazing panel and shadow box, glazing panel and bottomless shadow box, full-height aluminium panel (opaque), and a full-height shadow box unit (opaque). Each configuration then derives into four different variations to study the impact of span/grid size, where the following sizes are studied: 5' x 14', 5' x 16', 7.5' x 14', 7.5 x 16', summarised as follows:

- Unit A - Curtain wall unit with glazing panel and shadow box
- Unit B - Curtain wall unit with glazing panel and bottomless shadow box
- Unit C - Curtain wall with full-height aluminium panel
- Unit D - Curtain wall with full-height shadow box unit

The number, followed by the letter indicating the configuration, corresponds to the panel's dimensions according to two variations in width (5' or 7.5') and (14' or 16'). This results in four different sizes for each of the four configurations, a total of sixteen variations.

- Size 1 - 5' x 14'
- Size 2 - 5' x 16'
- Size 3 - 7.5' x 14'
- Size 4 - 7.5 x 16'

Additionally, due to the varying dimensions, different glass sizes are required. Depending on the panel size, three different types of glass build-up are used. The built-up glass dimensions are expressed as: outer lite — spacer — inner lite. Laminated lites are expressed as a sum in brackets.

- Glass I: 5/16" — 1/2" — 5/16"
- Glass II: 3/8" — 1/2" — 3/8"
- Glass III: [1/4" + 1/4"] — 1/2" — [1/4" + 1/4"]

Figure. 2 illustrates the different unit configurations, sizes, and glass build-up.

	UNIT A				UNIT B				UNIT C				UNIT D			
	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4
UNIT WIDTH	5	5	7.5	7.5	5	5	7.5	7.5	5	5	7.5	7.5	5	5	7.5	7.5
UNIT HEIGHT	14	16	14	16	14	16	14	16	14	16	14	16	14	16	14	16
SHADOW BOX HEIGHT	3	3	3	3	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	3	3	3	3
GLASS TYPE	I	I	II	III	I	I	III	III	-	-	-	-	I	I	III	III

TABLE 1 Summary of the different unit configurations, panel sizes, and glass build-up. All dimensions in feet.

Each unit and its corresponding variations were assessed according to the established LCA methodology as a cradle-to-gate assessment (A1-A3). Figure 2 shows the results.

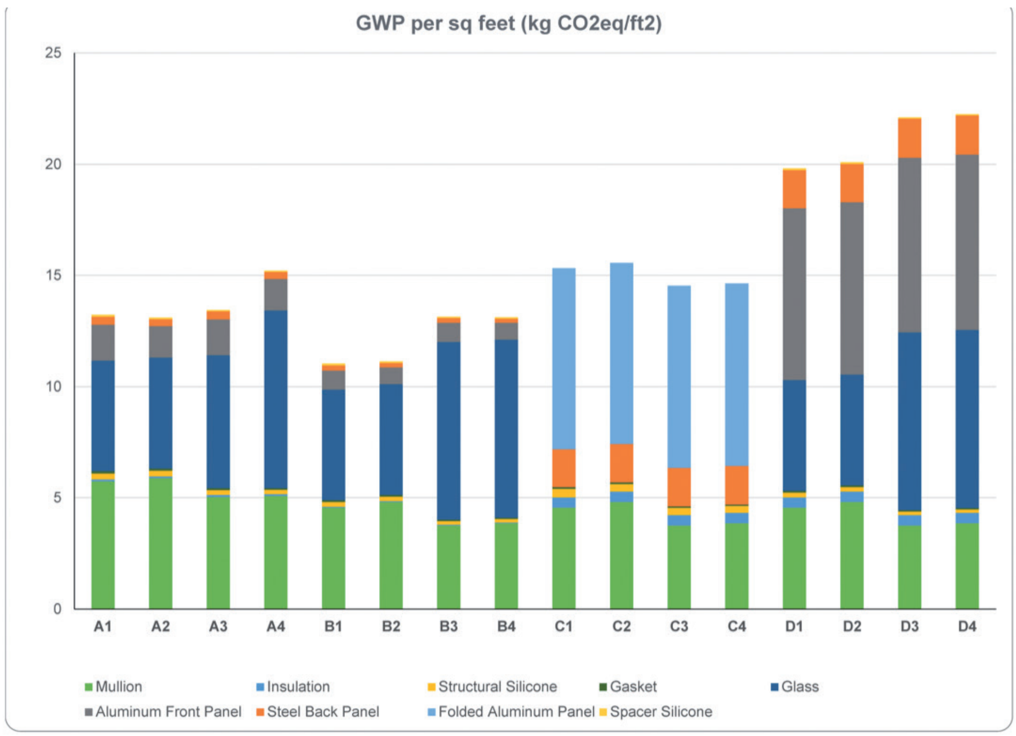

FIG. 2 Results of A1-A3 assessment for the different unit configurations described in Table 1.

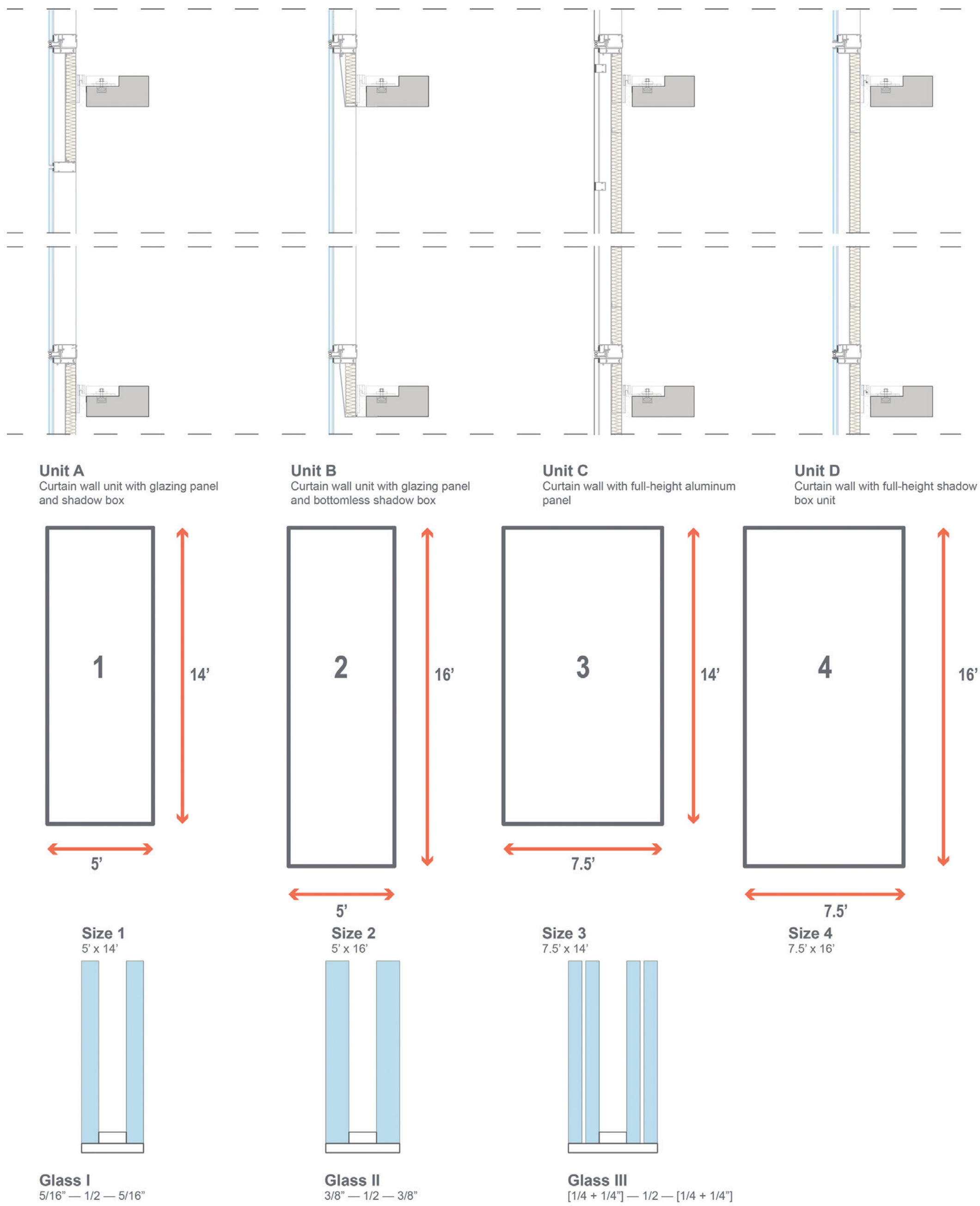

FIG. 3 Diagram showing the different unit configurations described in Table 1.

The results' overall trend shows similar GWP output in Units A and B, along with its corresponding variations. Unit C has slightly higher results, where the highest contribution is from aluminium panels. A significant increase in GWP is shown in unit D, mostly due to its construction nature. Since this is a shadow box unit, it uses both glass and aluminium panels, meaning that it uses all the materials from the previous configurations, making it the most material-intensive unit of all four. The increment in GWP for A4, B3, B4, D3, and D4 is because they require a thicker glass build-up, due to the larger panel size.

3.3 LIFE CYCLE PHASES

The system boundary was established as cradle-to-gate, referring to the A1 – A3 production phases. Four different glass types were compared: clear float glass, clear laminated glass, clear coated glass, and tinted coated glass. Figure 4 shows the percentage of energy corresponding to each production phase (A1 to A3). While the effort to supply raw materials and transport them is comparably low, production emissions are the most significant. Such is the case for other building materials, especially if intensive treatment is involved. It shows the relevance of the energy source. Operating a production plant with renewable energy helps essentially to reduce the overall environmental impact.

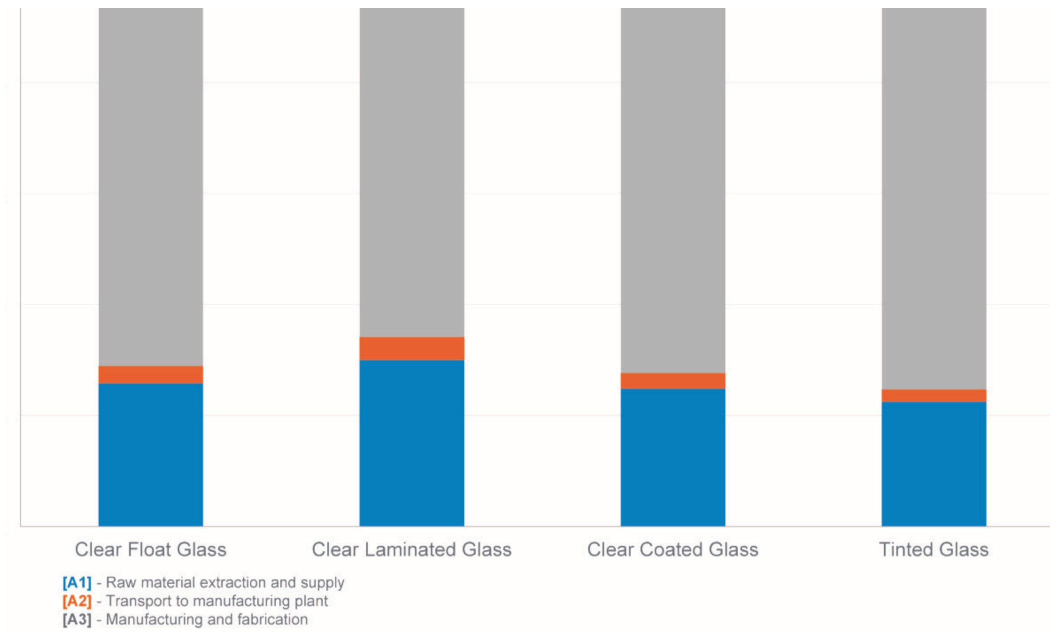

FIG. 4 Results of cradle-to-gate assessment showing a breakdown of embodied emissions for the A1 - A3 phases.

The comparison of the three different stages, Raw material extraction and supply (A1), Transport to manufacturing plant (A2), and Manufacturing and fabrication (A3), shows that from these three, the highest impact comes from the manufacturing process. This is highly related to the nature of the process itself, as mining and transporting material is less energy-intensive.

3.4 INFILL MATERIALS

To further understand the environmental impact of different materials, several infill materials commonly used in curtain walls are assessed in a cradle-to-gate system boundary for Unit C, the opaque façade element. The objective is to compare the results of units with the same configuration, but with different infill materials and varying thickness. The assessed materials are natural stone, aluminium panel, meshed metal baffle, fibre cement, wood fibreboard, and gypsum board. Figure 5 shows the results of the assessments applied to Unit C and its corresponding four variations.

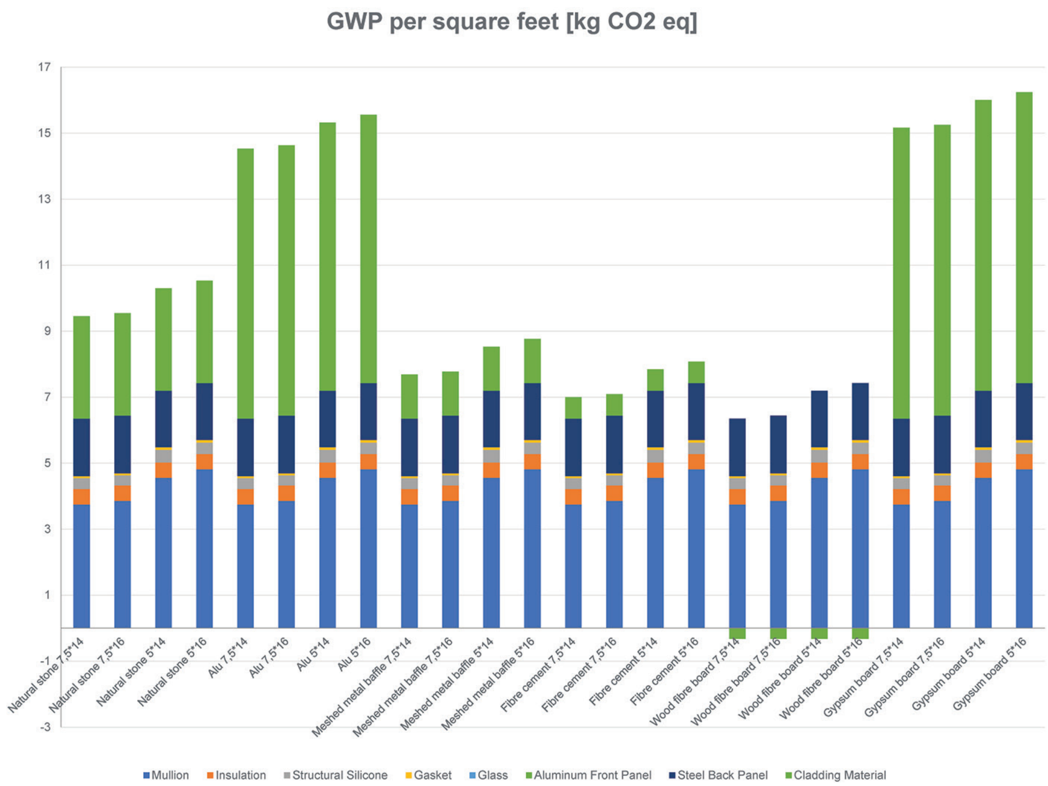

FIG. 5 Results of cradle-to-gate assessment comparing different infill materials and varying thickness

The results for different infill panels show that each material's production process has a significant impact on the embodied emissions. The results show that the wood fibreboard cladding has the lowest GWP per square feet, followed by fibre cement, meshed metal baffle, and natural stone. Both the aluminium and gypsum board panels have the highest embodied emissions.

3.5 SUPPLY CHAIN

The supply chain cost analysis focuses on understanding how much percentage accounts for transportation. Therefore, the system boundary was expanded by adding the A4 transport stage. Three scenarios with different international baselines were analysed: Italy, Vietnam, and Thailand. Table 2 summarises the baselines for each international scenario.

BASELINE - ITALY	BASELINE - VIETNAM	BASELINE - THAILAND
Glass is sourced from Germany and taken to Italy.	Glass is sourced from Germany.	Glass is sourced from Germany.
Components are assembled in the factory in Italy.	Aluminium is extruded in Vietnam.	Aluminium is extruded in Thailand.
Components are transported by ship to Oakland, and then to the SF Bay Area by truck	Components are shipped to Bangkok to be assembled in the factory, transported by ship to Oakland, and then to the SF Bay Area by truck.	Components are assembled in Thailand, transported by ship to Oakland, and then to the SF Bay Area by truck.

TABLE 2 — Comparison of international scenarios

To have a domestic comparison, three different North America baselines are analysed, where production took place on the East coast of the US and then transported to the West coast. The following table summarises each domestic scenario.

DOMESTIC (1)	DOMESTIC (2)	DOMESTIC (3)
Glass is sourced from Minnesota, US. Aluminium is extruded in New York, US. Components are shipped to Quebec, CA, where they are assembled. Assembled units are distributed from Quebec, CA to the SF Bay Area by truck.	Glass is sourced from Minnesota, US. Aluminium is extruded in New York, US. Components are shipped to Connecticut US, Where they are assembled. Assembled units are distributed from Connecticut US to the SF Bay Area by truck.	Glass is sourced from Massachusetts, US. Aluminium is extruded in New York, US. Components are sent to California by truck to be assembled close to the construction site in the SF Bay Area.

TABLE 3 — Comparison of domestic baseline scenarios

The results indicate that several parameters within the baselines play a role, such as the country of origin, the source of primary energy in each country, and the shipping method. When comparing the results between the international baseline and the domestic scenarios, it can be observed that shipping from Europe to Asia can be in the same range or lower compared to trucking from the East to the West coast of the US. Electrically operated transportation, such as train or even shipping, but mostly by avoiding trucking. As trains within the US are primarily diesel operated however, the use of trains has limited effect on the improvement of shipping impact within the US. Additionally, a financial assessment was carried out to determine if the domestic scenarios are cost-competitive compared to international baselines. The results indicated that both domestic and international baselines yield very similar costs.

4 DISCUSSION OF RESULTS

According to the results, the highest impact parameters are façade typology, life cycle phases, infill materials, and supply chain. For the first parameter, Façade typology, literature results show that curtain wall façades average 50% less embodied emissions than double-skin façades, and roughly 20% - 25% compared to solid façades. Therefore, it is determined that the overall impact of façade typology is high.

The second parameter, different spans/grid sizes, shows only a small deviation when comparing one configuration to the other. The increase in GWP for the panels that require a larger built-up is no more than 15%. Overall, it is concluded that varying the width and height of façade panels does not have a significant impact.

The third studied parameter, life cycle phases, shows the relevance of the energy source used in the factory, as, on average, 75% of the embodied emissions are produced by the manufacturing stage. If the energy used for manufacturing relied on a renewable source, a significant GWP reduction would be possible. Therefore, it is concluded that the impact of the life cycle phases, particularly concerning the A3 stage, is high.

The fourth parameter of the research, infill materials, shows that aluminium and gypsum board panels have the highest emissions. If we compare an aluminium panel of 5" x 16" against a wood fibreboard panel of the same size, the aluminium panel has roughly 50% more embodied emissions. The result shows the importance the selected material has not only due to the required energy for mining but also for production, as previously discussed. Hence, it is concluded that the impact of infill materials is high.

The last studied parameter, supply chain, indicates that transportation accounts for 3% to 10% of the total embodied emissions in an A1 – A4 system boundary, as shown in Table 4.

	BASELINE - ITALY	BASELINE - VIETNAM	BASELINE - THAILAND
Account for transport	6%	3%	3%

	Domestic (1)	Domestic (2)	Domestic (3)
Account for transport	6%	10%	3%

TABLE 4 — Results of the international and domestic scenarios

The supply chain results indicate that transportation accounts between 3% to 10% of the total embodied emissions in an A1-A4 system boundary. Potentially, if the procurement and fabrication occur close to the construction site and its neighbouring states, the reduction in embodied emissions is also significant, as shown in Domestic (3). Therefore, it is concluded that the impact of the supply chain is high.

While the parameters were studied independently, they are also related to each other, such as the case of the life cycle phases and the infill materials. Some infill materials have a higher GWP closely related to the manufacturing phase. Several infill materials that are opaque have lower embodied emissions, and thus selecting them might reduce the GWP per square feet in a façade system. This is also cross-referenced to the results in the varying span/grid size. As observed in the results from Span/Grid size, Unit D had the highest embodied emissions from all configurations. This is because it uses both glass and aluminium panels, meaning that it is more material-intensive by design. Using spandrel panels (as observed in Unit C) instead of shadow boxes can significantly decrease roughly 35%, where such reduction is strongly related to the infill materials. To achieve additional reduction, an important recommendation would be to carefully select the adequate window to wall ratio, as results also showed that glass has higher embodied emissions. However, while glass is a material that is not easily replaced, opaque infill materials have the potential of offering a wider variety of options, where lower GWP is preferred. Therefore, having a correct window to wall ratio, where opaque materials have low embodied emissions, can also be a strategy that can lower the embodied emissions of a façade system.

Additionally, it was proven that while transportation does not account for more than 10%, a significant reduction is possible when trucking is avoided. This was mainly observed in the domestic baseline scenarios, where trucking from the East to the West coast of the US was comparable to shipping from Europe to Asia. Container shipping does not only show lower embodied emissions, but it also allows us to ship more components at once. Table 5 summarises the results of each parameter while highlighting its impact level.

PARAMETER	LEVEL OF IMPACT	EXPLANATION
Façade typology	High	Assessment documented in academia shows that façade typology influences environmental impact; double-skin façades with high glass share the highest contribution, followed by solid façades with punched windows. Curtain wall systems belong to the group with the lowest environmental impact.
Span/grid size	Low	Assuming a fully glazed system, the ratio of glass and aluminium per square feet varies, which leads to a small deviation.

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Life cycle phases (A1-A4)	High	Comparing A1, A2 and A3, the production (A3) indicates the highest impact with 66-75%. This suggests that the location of production should be assessed carefully for every project.
Infill material	High	The choice of the infill material impacts the environmental performance significantly. Many opaque materials perform better environmentally than glass, depending on the chosen fabrication.
Supply chain	High	By using aluminium with recycled content, the GWP of the entire façade can be reduced by approximately 25%. Using locally sourced materials and optimising transport can contribute up to 15%.

TABLE 5 — Summary of the studied parameters and their impact level.

5 CONCLUSIONS

The research conducted presents results that apply to curtain walls, with five different parameters assessed and compared to determine their level of impact, respectively. The study shows that the parameters with the highest level of impact are façade typology, life cycle phases, infill material and supply chain. The only parameter that did not show a significant level of impact was the span/grid size, as only a small deviation is observed. The different parameters aimed to study an approach that changes while looking not only at design decisions but also at logistics and processes that involve manufacturers and local supply chains. It is also important to consider that the level of impact of these parameters is limited to curtain walls, and it would need to be reassessed for other typologies. Most likely, it would need to be incorporated into a specific LCA separately to determine the level of impact of each parameter when applied to a new typology. The same applies to the supply chain, as each part would need to be incorporated with a specific LCA separately.

In addition, the results of the research show that there are several design decisions that can be taken into consideration to lower embodied emissions, such as selecting an adequate window-to-wall ratio, infill materials with low GWP, and selecting to assemble components close to the construction site whilst avoiding trucking. Additionally, regarding the different life cycle phases, the results showed the relevance of the production phase, where it was observed that the source of energy used in the factory had a significant impact. If materials are manufactured with renewable energy, the embodied emissions are significantly lower. Overall, it is concluded that the embodied emissions in curtain wall envelopes can be significantly reduced when these parameters are considered. However, it is still to be determined how these parameters relate to financial feasibility, which is also a main driver in construction and design decisions.

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