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Comparative Life Cycle Assessment (LCA) of Membrane and Grid Shell Structures: A Case Study Analysis

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Abstract

This study conducts a comparative analysis through Life Cycle Assessment (LCA) of two distinct architectural structures: “M&G Research” (Case Study 1), featuring a membrane structure consisting of a steel primary framework and a PVC-coated polyester fabric skin, and “Walloon Branch of Reproduction Forestry Material” (Case Study 2), characterized by a wooden grid shell structure and glass panels for coverage. The LCA investigates the product stage (A1-A3), the ‘end-of-life’ stage (C1-C4), and the module ‘benefits and loads beyond the system boundaries’ (D), focusing on specific components such as the skin and primary structure. Multiple LCAs are conducted for each case study. In Case Study 1, the assessments evaluate two scenarios for the fabric skin: one without skin replacement and another with a single skin replacement over a 50-year service life. Meanwhile, in Case Study 2, the LCAs assess the environmental impact of two different cover materials: glass versus polyester-PVC fabric.

The findings reveal interesting insights into environmental impacts with a focus on Global Warming Potential (GWP) per covered area. In both case studies, the skin significantly contributes to the overall GWP per covered area (GWP/m²), surpassing the impact of the primary structure. Due to higher quantity of wood material, the GWP/m² of the primary structure in Case Study 2 exceeds that of the steel structure of Case Study 1. The findings underline the complex relation between material selection, structural components and service life duration, providing insights for sustainable architectural design and decision-making processes.

Keywords: Life Cycle Assessment, Comparative Analysis, Membrane Structure, Grid Shell Structure, Environmental Impact, Sustainability, Architectural Design.

1. Introduction

In contemporary architectural designs, sustainability has become an important consideration. As the built environment continues to evolve, understanding the environmental effect of architectural structures is essential to control the impact on the ecosystem. This study explores the relationship between architectural design, material selection, and environmental sustainability through a comparative analysis utilising Life Cycle Assessment (LCA).

The ecological impact of membrane structures plays a role in their design and application. Research explores sustainable innovation in minimal mass structures and lightweight architectures, and suggests for future advancements to align with environmental sustainability goals [1], [2]. These studies collectively emphasize the importance of evaluating the environmental impact of membrane structures and the need for additional research to enhance their sustainability efforts.

The focus of this comparative analysis rests on two distinct architectural structures: "M&G Research" [3] and "Walloon Branch of Reproduction Forestry Material" [4]. Both projects are designed by Philippe SAMYN and PARTNERS architects & engineers. Each structure embodies unique characteristics, with MG Research featuring a lightweight membrane structure with a steel primary framework and a polyvinyl chloride (PVC) coated polyester fabric skin, while Walloon Branch is made of a wooden grid shell structure with glass panels for coverage.

This LCA study examines the environmental implications of these architectural structures. It is essential to clarify that the objective of this comparison is not to rank one structure above the other in terms of environmental impact, or to compare architectural preferences. Instead, the primary focus lies in understanding the influence of material selection and end-of-life (EoL) scenarios on the LCA results.

Figure 1: M&G Research Centrum © Philippe SAMYN and PARTNERS architects & engineers [3].

Figure 2: Walloon Branch of Reproduction Forestry Material © Philippe SAMYN and PARTNERS architects & engineers [4].

2. Research Methodology

The research utilises OneClickLCA [5] to conduct the LCA. OneClickLCA is a Life Cycle Assessment tool designed to evaluate the environmental impact of buildings and infrastructure projects. Developed to facilitate comprehensive sustainability assessments, OneClickLCA enables to analyse various stages of a project's life cycle, including material production, construction, operation, and end-of-life disposal.

To ensure comparability, only the skin and supporting structure are considered. Due to missing data, the foundation is excluded. In the LCA, the transportation module is omitted, and the EoL scenarios are standardised: steel components are recycled, plastics are incinerated, glass undergoes recycling process, and wood is directed to landfill. For the wooden structure, biogenic carbon needs to be taken into account. Biogenic carbon refers to carbon storage in organic materials such as wood through the process of photosynthesis. During the production, wood absorbs carbon dioxide from the atmosphere and stores it in its biomass. When wood reaches the EoL, it undergoes various disposal scenarios, such as landfilling or incineration. Landfilling, as chosen for this study, typically results in slow decomposition, keeping the stored carbon dioxide for longer period. On the other hand, if wood is incinerated, the stored carbon is released back into the atmosphere as carbon dioxide, contributing to greenhouse gas emissions.

The outcomes of the LCA will be evaluated based on the Global Warming Potential (GWP) indicator. The GWP is a measure used to evaluate the impact of greenhouse gases on climate change over a specific timeframe. Using the GWP per covered area will facilitate meaningful comparison. The LCA will focus on the construction materials module (A1-A3). Additionally, the assessment will encompass the construction and installation process module (A5), which addresses material waste management. Further, the replacement and refurbishment module (B4-B5) if applicable, the EoL module (C1-C4), and module D representing benefits and loads beyond the system boundary are taken into account. The module D is not factored into the total GWP.

The first case study involves analysing two scenarios: one with a consistent service life of 50 years for all materials and another with the skin requiring replacement at year 25, which corresponds more closely to a real-life situation, within the project's service life of 50 years. The second case study includes two different simulations, each with a different covering material: glass and PVC-polyester fabric. While glass doesn't require replacement, the PVC-polyester fabric considers a midlife replacement. These simulations will span a service life of 50 years, providing comprehensive insights into the environmental impact of each material choice over a longer period. This study helps to understand how different parts of the building, like the outer skin and main structure, impact the environment.

3. Case Study 1: M&G Research Centrum

The M&G Research project is characterized by its lightweight design, representing steel arches supporting the outer skin. The skin material is a polyester-PVC fabric that is tensioned between the arches and contributes to the stability of the entire structure. The project is located in Venafro, Italy and covers an area of 2.400m². The span of the middle arch is approximately 32 meters, and the length of the structure is 85 meters. The structure exhibits a self-weight of 5,89 kg/m², with the skin accounting for 47% of this weight at 2,76 kg/m², and the remaining 53% attributed to the primary structure, weighing 3,13 kg/m².

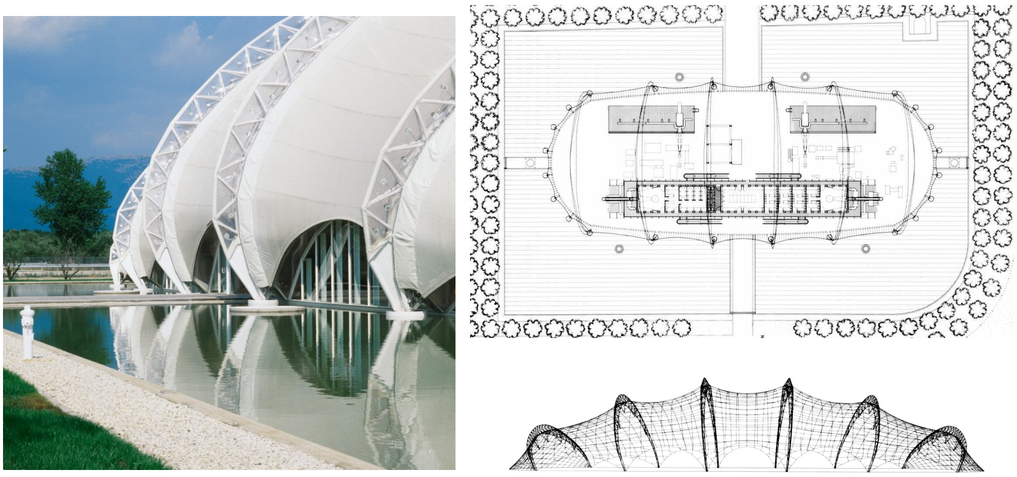


Figure 3: M&G Research Centrum picture and drawings © Philippe SAMYN and PARTNERS architects & engineers [3]

LCA simulations for this project incorporate PVC-coated polyester fabric and transparent PVC foil for the outer skin, alongside steel for the primary structure, edge cables, and corner plates. The polyester-PVC fabric serves as the primary cover material, while the transparent PVC foil is used at the connections with arches. The summarised Life Cycle Inventory (LCI) data for all elements used in the LCA, including weight, default wastage percentage, and material-specific data, are presented in the Table 1 below. The data is retrieved from an Environmental Product Declaration (EPD) representing the most relevant material, or from a Generic Data (GD) sourced from the tool.

Table 1: CS1: LCI Input data

Material	Quantity	Wastage	Environmental Product Declaration (EPD) or Generic Data (GD)
Steel Structure	3.747 kg	3,3%	EPD: Steel hot rolled, I, H, U, L, T and wide flats, S235-S960 [6]
PVC-Polyester Fabric	3.540 m² (5.487 kg)	10%	EPD: VALMEX® FR1600 Mehler Texnologies [7]

Transparent PVC foil	930 m^2	7,5%	GD: Transparent board PVC, 1220 kg/m^3
Edge cables ø20mm (incl. thread terminals)	740 kg	4,85%	EPD: Prestressed steel [8]
System cables ø30mm (incl. fork terminals)	2.400 kg	4,85%	EPD: Prestressed steel [8]
10% extra steel connections (corner plates, bolts…)	615 kg	3,3%	EPD: Steel hot rolled, I, H, U, L, T and wide flats, S235-S960 [6]

The results of the LCA are presented in the following Table 2, describing the GWP per module of the LCA. LCA1 represents a scenario where no fabric replacement is considered throughout the structure's entire service life, while LCA2 accounts for a single fabric replacement within the same timeframe. LCA2 shows a higher total GWP compared to LCA1, mainly due to the fabric replacement (module B4-B5), which increases the total GWP by 68,21%. Module B4-B5 accounting for 46.540,63 $kgCO_2eq$, reflects the impact of newly made PVC-polyester and transparent PVC foil, as well as the EoL treatment of the old skin materials. The benefit of the EoL treatment of the initially installed skin materials is accounted in module D.

The construction materials module (A1-A3) is the most impactful module, with an impact of 49.040,54 $kgCO_2eq$ for both LCAs. Module A5 is related to waste management considerations for each material, contributing 5.183,59 $kgCO_2eq$ to the total GWP for both LCAs. Meanwhile, module C1-C4 is related to the EoL treatments, involving incineration for the fabrics and recycling for steel elements, with an impact of 14.004,98 $kgCO_2eq$ for both LCAs. Module D demonstrates a higher benefit of -2.984,22 for LCA2 compared to LCA1, primarily attributed to the impact of the replaced fabric due to the incineration at End-of-Life.

Table 2: CS1: LCA GWP results

	Result category GWP ($kgCO_2eq$)	LCA 1	LCA 2
	Service life	50 years	50 years
	Fabric replacement	0	1
	EoL Fabric	Incineration	Incineration
A1-A3	Construction Materials	49 040,54	49 040,54
A5	Construction/installation process	5 183,59	5 183,59
B4-B5	Material replacement and refurbishment	0,00	46 540,63
C1-C4	End of life	14 004,98	14 004,98
D	External impacts (not included in Total)	-15 603,23	-18 587,45
	Total GWP	**68 229,11**	**114 769,74**
	Total GWP/m^2	**28,43**	**47,82**

Figure 4 below shows the impact of the structural elements on the total GWP, revealing that in this case study, the fabric and foil exert a more significant influence compared to the primary structure.

With the inclusion of fabric replacement, the total GWP increases from 68.229,11 kgCO_2eq to 114.769,74 kgCO_2eq.

In LCA1, the fabric accounts for approximately 75% (51.045,25 kgCO_2eq) of the total GWP. The primary structure, including the steel structure and system cables, contributes to approximately 20% (13.900,95 kgCO_2eq) of the total GWP. The remaining 5% is attributed to the impact of edge cables, corner plates, and accessories. Conversely, in LCA2, the fabric, including the replacement of the fabrics, represents approximately 85% (97.585,88 kgCO_2eq) of the total GWP. The primary structure along with the system cables, accounts for 12% (13.900 kgOC_2eq) of the total GWP, with the remaining 3% attributed the impact of edge cables, corner plates, and accessories.

While the GWP for the primary structure (including the system cables), edge cables, corner plates remain constant across both simulations, the impact of the skin increases with the fabric replacement, totalling 46.540,63 kgCO_2eq.

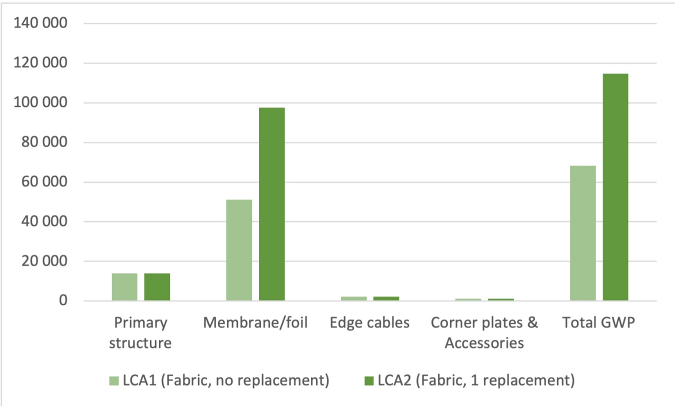
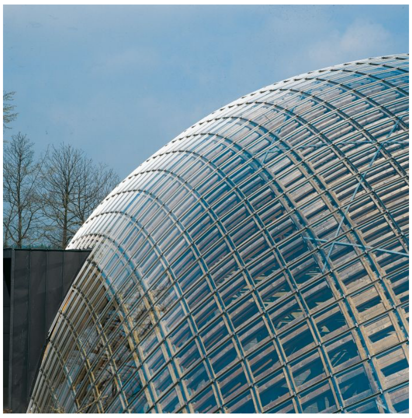


Figure 4: CS1-LCA1 & LCA2: GWP results per building element

4. Case Study 2: Walloon Branch of Reproduction Forestry Material

The ‘Walloon Branch of Reproduction Forestry Material’, also called ‘The Forestry Branch’, is located in Belgium. The project presents a structure characterized by a wooden grid shell supporting a glass outer skin. The structure has an oval shape with dimensions of approximately 43 meters by 27 meters. Encompassing a covered area of 1.144m², the structure has a self-weight per covered area of 88,09 kg/m². Notably, 39,5% of this weight, equivalent to 34,79 kg/m², concerns the outer skin, while 60,5% or 53,30 kg/m², is attributed to the structure itself. The wood used in this project is spruce wood, specifically sourced from the ‘Grand Bois Forest’ in Vielsalm, Belgium, supplied by the Department of Nature and Forests. The grid shell structure is covered with laminated glass, which is fixed through special anodised aluminium profiles positioned along the central axis of each arc on the outer side.



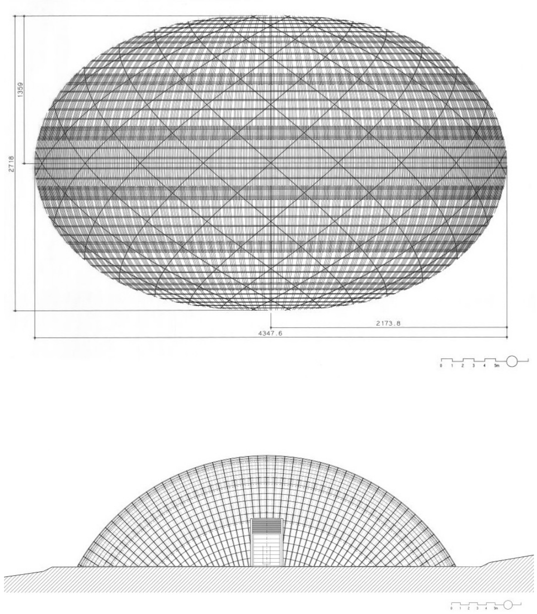


Figure 5: Walloon Branch of Reproduction Forestry Material picture and drawings © Philippe SAMYN and PARTNERS architects & engineers [4].

Originally designed with a membrane covering, the project underwent revisions and was finally executed with glass. As a result, two LCA simulations were conducted for this case study: one incorporating glass, and one considering PVC-coated polyester fabric with fabric replacement, all within a total service life of 50 years. The primary structure is made of wooden arches and diagonal metal strip elements. While the primary structure of a membrane structure is typically lighter, due to a lack of specific information, this study assumes an equal amount of primary structure for both scenarios. The skin is either glass or fabric, and the accessories represents the connections elements, bolts, and aluminium profiles for the glass option. The aluminium frame profiles are excluded from the fabric covering option. At the end of their service life, wood components are destinated for landfill disposal, glass and all metals undergo recycling processes, while fabric is intended for incineration. The detailed LCI data is provided in Table 3, offering information about the quantities of used materials, waste percentages, and whether EPD or Generic Data were used for each material.

Table 3: CS2: LCI Input data

Material	Quantity	Wastage	Environmental Product Declaration (EPD) or Generic Data (GD)
Wood Structure	106,64m^3 (46.921,6 kg)	17,9%	GD: Softwood beam, kiln dried, planed, 440 kg/m3, 10% moisture content, coniferous wood (One Click LCA)
Diagonal Metal Strips	1.668kg	3,3%	GD: Structural steel profiles, generic, 0% recycled content (only virgin materials), I, H, U, L, and T sections, S235, S275 and S355
Glass 7mm thickness	1.895m^2 (39.795 kg)	1%	EPD : Coated laminated glass, Saint-Gobain Glass, France [9]
Polyester-PVC fabric	1.895m^2	10%	EPD: VALMEX® FR1400 Mehler Texnologies [10]
Connection pieces	5.404kg	3,3%	GD: Structural steel profiles, generic, 0% recycled content (only virgin materials), I, H, U, L, and T sections, S235, S275 and S355

Aluminium profiles	3.070kg	7,5%	GD: Extruded aluminium profiles for window and door frames, generic, 0% recycled content, average world aluminium manufacturing technology (One Click LCA)
Bolts	3.913 kg	2,5%	GD: Stainless steel screws

The results of the GWP per module of the LCA are shown in Table 4. LCA3 presents the actual structure with glass covering, while LCA4 serve as illustrative simulation to demonstrate the LCA outcomes if the original design with polyester-PVC fabric was maintained. LCA4 represents the structure with polyester-PVC fabric, considering a replacement of the fabric during the 50-year service life.

In LCA3, the total GWP is calculated at 143.712,44 kgCO_2eq, with the most significant impact attributed to the construction materials module A1-A3, amounting to 135.693,43 kgCO_2eq. The EoL module registers a relatively low impact of 2.198,13 kgCO_2eq. Module D, representing benefits and loads beyond the system boundary, shows an impact of -64.124,59 kgCO_2eq.

Transitioning to the polyester-PVC fabric option with one fabric replacement reduces the total GWP by 48,5%, resulting in a total GWP of 74.027,77 kgCO_2eq for LCA4. The GWP for module A1-A3 is 47.008,77 kgCO_2eq, which is almost 3 times lower compared to the A1-A3 module of the glass option. This decrease within the A1-A3 module is attributed to the lower environmental impact of the polyester-PVC and the removal of the aluminium glass frames. Material replacement module (B4-B5) accounts for a GWP of 17.077,22 kgCO_2eq. Module C1-C4 accounts for 6.025,38 kgCO_2eq and is 2,7 times bigger compared to the C1-C4 of LCA3, with the incineration process of the fabric significantly influencing this difference. The impact on module D is approximately 2 times lower for the fabric covering option compared to the glass covering option. Recycling all glass and metal elements generates a greater benefit for D compared to incinerating fabric and recycling only the metal elements.

For the wooden structure, it is essential to account for biogenic carbon storage. For this study, the biogenic carbon amount to 86.022,93 kgCO_2eq and this impact is not accounted into the A1-A3 module of LCA3 and LCA4.

Table 4: CS2: LCA results

	Result category GWP (kgCO_2eq)	LCA 3	LCA 4
	Service life	50 years	50 years
	Skin	Glass	Fabric
	Skin replacement	0	1
	EoL Skin	Recycling	Incineration
A1-A3	Construction Materials	135 693,43	47 008,77
A5	Construction/installation process	5 820,88	3 916,40
B4-B5	Material replacement and refurbishment		17 077,22
C1-C4	End of life	2 198,13	6 025,38
D	External impacts (not included in Total)	-64 124,59	-32 549,70
	Total GWP	**143 712,44**	**74 027,77**
	Total GWP/m^2	**125,62**	**64,71**

Figure 6 illustrates the impact of structural elements on the total GWP for both simulations. In LCA3, with a total GWP 143.712,44 kgCO_2eq, about 51% of the total GWP is attributed to the accessories, including connection pieces, aluminium profiles, and bolts, accounting for 73.035,20 kgCO_2eq. Glass represents 39% of the total GWP, with an impact of 55.879,84 kgCO_2eq, while only 10% of the total GWP, 14.797,58 kgCO_2eq, is attributed to the primary structure.

In contrast, in LCA4, with a total GWP of 74.027,77 kgCO_2eq, about 42% (35.862,16 kgCO_2eq) is associated with the fabric, 40% (34.139,66 kgCO_2eq) with the accessories (including connection pieces and bolts), and 18% (14.807,26 kgCO_2eq) with the structure. The primary structure impact, including the wooden grid shell and the diagonal metal strips remains consistent for both options. However, the biogenic carbon storage of the wooden grid shell, totalling 86.022,93 kgCO_2eq, is not accounted in this value.

The impact of the accessories decreases from 73.035,20 kgCO_2eq for LCA3 to 34.139,66 kgCO_2eq for LCA4. This reduction is attributed to the exclusion of aluminium glass frames in the PVC-polyester option. Additionally, the impact for the skin decreases from 55.879,84 kgCO_2eq for LCA3, which includes laminated glass, to 35.862,16 kgCO_2eq for LCA4, representing a PVC-polyester skin. While the weight of the primary structure of this case study is relatively high, the impact of the wood structure (excluding biogenic carbon storage impact) and the diagonal metal strips stays relatively low compared to the skin and all remaining metal accessories.

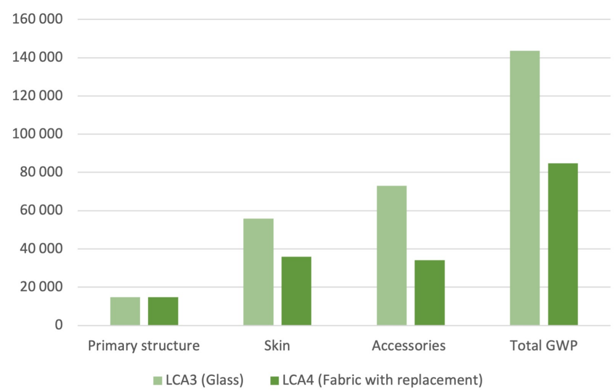


Figure 6: CS2-LCA3 & LCA4: GWP results per building element

5. Comparison

The comparison between the two case studies, each representing distinct architectural types with different self-weight, material choices, and end-of-life scenarios, highlights the varying of environmental impacts. Although the same LCA methodology was used with the evaluation of the GWP indicator, the results differ significantly.

In Case Study 1, the M&G Research Centrum, a lightweight design featuring steel arches supporting the outer skin is showcased. The structure's self-weight per covered area is relatively light at 5,89 kg/m^2, with the 'self-weight to skin-structure' proportion approximately 1:1. LCA simulations consider scenarios with and without fabric replacement over a 50-year service life, emphasizing the significance of construction materials and the impact of fabric replacement on GWP.

Contrarily, Case Study 2, the Walloon Branch of Reproduction Forestry Material, highlights a wooden grid shell supporting a glass outer skin. The structure's self-weight per square meter covered area is 88,09 kg/m^2, notably higher compared to Case Study 1. The primary structure represents 60,5% of the total self-weight per covered area, or 53,30 kg/m^2, while glass contributes 39,5%, or 34,79 kg/m^2 of the total self-weight per covered area. LCA evaluations compare scenarios with glass and PVC-polyester fabric coverings, considering fabric replacement within a similar service life. The results highlight the varying contributions of structural elements to the total GWP, depending on the material choices and EoL considerations.

Table 5: Properties comparison of the 2 case studies

	M&G Research	Walloon Branch
Service life	50 years	50 years
Skin	Fabric	Glass
EoL Skin	Incineration	Recycling
Structure	Steel	Wood
EoL Structure	Recycling	Landfill
Covered area m^2	2 400	1 144
Type	Enclosed	Enclosed
Structure	Arches	Grid shell
Self-weight kg/m^2	5,89	88,09
Self-weight skin kg/m^2	2,76 (47%)	34,79 (39,5%)
Self-weight structure kg/m^2	**3,13 (53%)**	**53,30 (60,5%)**

To facilitate a meaningful comparison, the results of LCA modules in GWP are divided by the covered area. Figure 7 illustrates the GWP/m^2 for the modules of the LCA across the assessed LCAs. The wooden grid shell structure (LCA3) with glass cover exhibits the greatest impact on total GWP and the A1-A3 GWP module. Opting for the same structure with polyester-PVC fabric and considering fabric replacement (LCA4) reduces the total GWP almost by half, with the GWP for the A1-A3 module decreasing nearly three times. However, fabric replacement at midterm significantly contributes to the total GWP, highlighting the need for careful consideration.

Transitioning to a structural design where fabric acts as a load-bearing element, as in Case Study 1, results in an almost factor of ten reduction in self-weight, which has a considerable impact on the overall results. The total GWP/m^2 is 2,7 times lower than in Case Study 2, with the GWP/m^2 of the A1-A3 module being almost six times lower.

For this case study analysis, opting for fabric rather than glass results in better total GWP and lower GWP for the A1-A3 module. However, this choice presents disadvantages, notably the need for fabric replacement halfway through the service life. This replacement accounts for a significant proportion of the total GWP, representing 40,6% in Case Study 1 and 23,1% in Case Study 2. In addition, the absence of recycling practices for polyester-PVC fabrics means that the majority are landfilled or incinerated, worsening environmental impacts. The absence of material reuse means that all new polyester-PVC materials are produced from virgin sources.

The EoL options for fabrics, incineration, or landfill, are evident in LCA modules C1-C4 and D. Module C1-C4 demonstrates a GWP/m^2 almost three times higher for fabric skin options than for glass. Figure 7 shows that recycling glass and metal materials offers greater benefits than incinerating fabric and recycling metal materials. This is reflected in module D of the LCA.

Figure 8 shows the LCA results categorized by building elements: primary structure, skin (glass or fabric), and accessories. Although the self-weight per covered area of the primary structure of Case Study 2 being nearly 17 times heavier than that of Case Study 1, the GWP/m^2 for the primary structure is only approximately 2 times larger for Case Study 2. Similarly, although the skin weight per covered area in Case Study 2 is almost 13 times higher than the self-weight of the skin in Case Study 1, the difference in GWP/m^2 between LCA3 and LCA1 is almost twofold. Additionally, the difference between LCA2 and LCA4, showing the fabric replacement (B4-B5) for both case studies, is of the same order of magnitude. From this analysis, it can be inferred that the accessories, encompassing components such as aluminium glass frames, steel connection elements, and bolts, exert a significant impact on the total GWP/m^2 of LCA3.

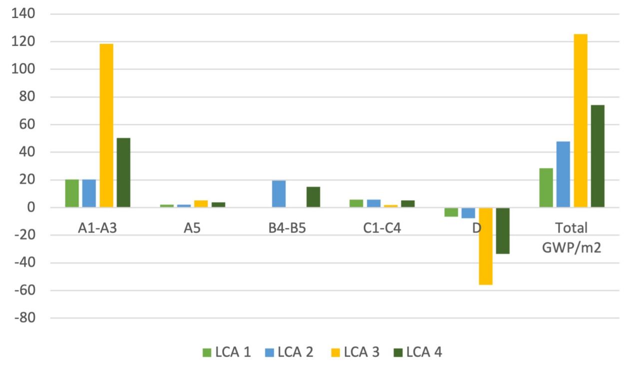


Figure 7: Comparison of LCA results per module in GWP/m^2

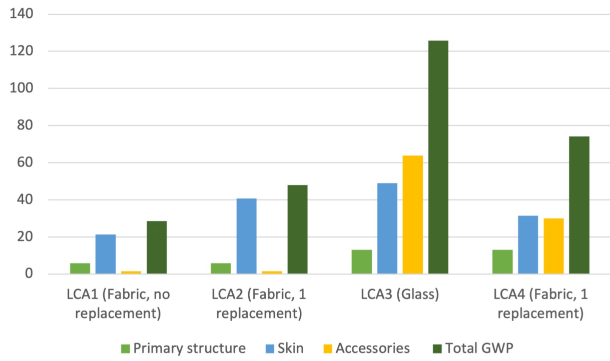


Figure 8: Comparison of LCA results per building component in GWP/m^2

6. Conclusion

In conclusion, the comparison of the Global Warming Potential from Case Study 1 and Case Study 2 highlights the different results of assessing the environmental impact of architectural structures with very different self-weights. They differ significantly in structural design, material choices, end-of-life scenarios.

Case Study 1, the M&G Research Centrum, features a lightweight design with steel arches supporting a fabric skin. In contrast, Case Study 2, the Walloon Branch of Reproduction Forestry Material, features a wooden grid shell supporting a glass skin. The comparison shows that switching to a fabric-based load-bearing structure significantly reduces the self-weight and total GWP/m^2, even though the fabric has to be replaced halfway through its service life.

In addition, the choice between fabric and glass skin has implications for end-of-life scenarios, with fabric options facing challenges in recycling and contributing to higher GWP/m^2 in modules related to end-of-life treatments. Recycling glass and metal materials offer greater benefits compared to incinerating fabric.

Overall, this comparison underscores the importance of considering structural design, material choices, and end-of-life scenarios in assessing the environmental impact of architectural structures. It highlights the need for global approaches that combine environmental sustainability with structural and functional integrity.

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The data utilised for this paper was sources from the State Archives of Belgium.

References

[1] C. Monticelli and A. Zanelli, 'Life Cycle Design and Efficiency Principles for Membrane Architecture: Towards a New Set of Eco-design Strategies', *Procedia Eng.*, vol. 155, pp. 416–425, Jan. 2016.

[2] A. Zanelli, C. Monticelli, and M. Mollaert, 'Sustainable innovation in minimal mass structures and lightweight architectures', *Archit. Eng. Des. Manag.*, vol. 17, no. 3–4, pp. 167–168, Jul. 2021, doi: 10.1080/17452007.2021.1938458.

[3] 'M&G Ricerche | Philippe SAMYN and PARTNERS, architects & engineers', SAMYN AND PARTNERS. Accessed: Feb. 27, 2024. [Online]. Available: https://samynandpartners.com/portfolio/222-mg-ricerche/

[4] 'Walloon Branch of Reproduction Forestry Material | SAMYN & PARTNERS', SAMYN AND PARTNERS. Accessed: Feb. 27, 2024. [Online]. Available: https://samynandpartners.com/portfolio/walloon-branch-of-reproduction-forestry-material/

[5] 'One Click LCA', One Click LCA. Accessed: Feb. 15, 2024. [Online]. Available: https://www.oneclicklca.com/

[6] 'Environmental Product Declaration Structural Steel: Sections and Plates, Bauforumstahl e.V., EPD-BFS-20130094-IBG1-EN, IBU'. 2013.

[7] 'Environmental Product Declaration VALMEX FR1600, Mehler Texnologies GmbH, EPD-MTX-20130168-IBA1-EN, IBU'. 2013.

[8] 'Environmental Product Declaration PC Strands, Siderurgica Latina Martin S.p.A., EEPD-SLM-081-EN, KIWA.' 2020.

[9] 'Environmental Product Declaration Verre à couche assemblé en verre feuilleté de sécurité STADIP PROTECT® et STADIP® PROTECT SP ou STADIP® PROTECT SILENCE et STADIP® PROTECT SP SILENCE pour l'isolation acoustique renforcée (sans accessoire de pose) Composition 44.4, 44.5, SP 510 (44.6), 53.4, 53.5, 53.6 PLANITHERM, ECLAZ, PLANISTAR SUN, COOL-LITE, BIOCLEAN, MIRASTAR, TIMELESS, VISION-LITE , SAINT-GOBAIN GLASS FRANCE, 1-29:2021, INIES'.

[10] 'Environmental Product Declaration VALMEX FR1400, Mehler Texnologies GmbH, EPD-MTX-20130167-IBA1-EN, IBU'. 2013.