CANOPY WOLKE MARIENFELD

Comparing the environmental performance of a short use, a reusable and a permanent membrane structure

Figure 1. Canopy Wolke Marienfeld. 1a/d ©Tom Bilsen, Stageco; 1b/c © form TL

Research context

The following research has been done in the context of the PhD of Zehra Eryuruk, under the supervision of Marijke Mollaert and Lars De Laet. The PhD research concerns the environmental impact of membrane structures.

Membrane structures are made of tensioned membranes with the major advantages of being lightweight and structurally optimized, but the End of Life (EOL) scenario and Life Cycle Assessment (LCA) are currently not fully resolved. There are many tools, studies and reference cases for LCA, but the context for tensile structures is very specific. In particular, the lifespan can vary from a few days to 40 years or more.

In more conventional construction sectors the considered life span for LCA simulations is 50- to 70-years. For short use or reusable membrane structures, the approach should be verified. Generating an LCA for these temporary lightweight structures requires more simulations with different input and EOL options. In this paper, we evaluate the environmental performance of a temporary membrane structure considering different simulations.

General description

The canopy Wolke Marienfeld (Fig. 1) is a pneumatic structure that served as the Pope's stage roof for the world youth day in 2005 (Cologne). The design represents a big white cloud placed on 4 steel columns (trusses).

Form TL provided the conceptual design along with the tender documents. The support structure was designed and built by Stageco, the Belgian company known for its worldwide temporary event structures. IF did the detailed design of the additional steelwork and the membrane, and Canobbio fabricated the membrane.

The dimensions of the roof are 30m x 32m. The grid, a standard structure, consists of trusses (1.8m or 1.3m high). These trusses are taken from Stageco's warehouse and returned after use (Fig. 3). The rectangular perimeter of the truss grid is extended with an elliptical ring to attach the top and side cushions to create the Cloud (Fig. 2). The five individual cushions are made of PVC-coated polyester. The top cushion (39m by 32m) is attached on top of the grid, and four smaller cushions (22m or 27m by 6m or 6.5m) form the border, which is attached to the perimeter of the grid. The total weight is about 120kg/m^2, and the covered area is 960m^2. Compared to more regular membrane constructions, this is a

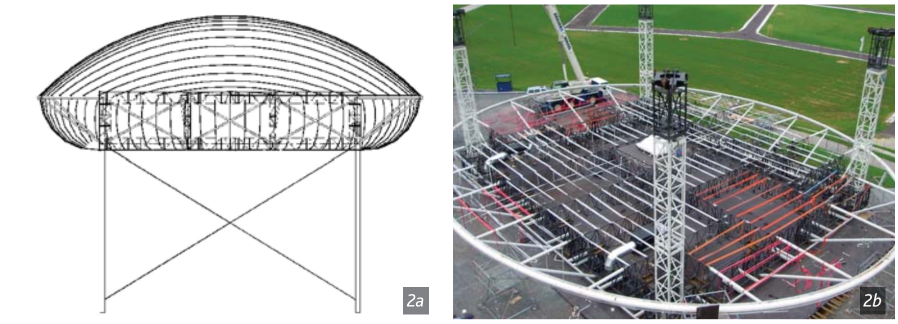

Figure 2. Structural system supporting the Cloud, 1a © form TL, 1b ©Tom Bilsen, Stageco
Figure 3. Stageco warehouse with standard steel columns and beams,
www.hln.be/economie/interview-podiumbouwer-hedwig-de-meyer-van-stageco-na-2-verloren-jaren-opnieuw-volop-aan-de-slag-in-de-vs-de-echte-test-komt-er-pas-volgend-jaar~a58c4dea/

fairly heavy construction. For example, the Dancing Tent designed by Frei Otto, has a weight of about 5kg/m².

Input data for the LCA

The simplified LCA simulations, based on rough quantity estimates, are performed using the OneClickLCA tool. The LCA process starts from raw material extraction, through production, transport, consumer use, and finally disposal and recycling. For this assessment, the following stages of the LCA are considered: the impact of construction materials (A1-A3), the construction and installation process (A5), the energy consumption for inflation (B6), the end of life (C1-C4) and the benefits and loads beyond the system boundaries (D). The Global Warming Potential (GWP) results are evaluated.

Three structural entities are considered in the LCA simulations: the standard steel trusses, the special steel components, and the membrane. For transport and other parameters, default settings are kept.

The total weight of the steel structure is about 105.000kg. 80% corresponds to reusable standard steel components. The towers and beams are reusable components from Stageco's warehouse, and the 'reused material' option is used in OneClickLCA. At the End of Life (EOL), the components are disassembled, stored and ready to be used for the next erection. For this purpose, the 'reuse as material' option is selected in the tool. The remaining 20% corresponds to recyclable special steel components and will be recycled at the EOL; for this process, the 'steel recycling' option was selected in the tool. The service life of steel is set at 70 years. Since no information is available, a steel with low recovered content was selected in the LCA tool: 'structural hollow steel sections (HSS), cold rolled, generic, 10 % recycled content, circular, square and rectangular profiles, S235, S275 and S355'.

The total amount of used PVC-coated polyester membrane is about 10.000m² with a wastage range of 20%. Two scenarios of EOL are possible for the membrane. The first is incineration and the second is, if reuse is applicable, 'reuse as material'. The service life of PVC-coated polyester is set at 25 years. For the inflation of the cushions, the operational energy is estimated to be 0,25kWh per year and per m².

The LCA parameter 'End of Life calculation method' is set to 'market scenario, user adjustable'. This means the EOL scenario is based on standard market practices. For example, if the considered country has highly regulated taxes and recycling rates (e.g., most of Europe), recyclable materials are recycled by default. In markets that lack regulations and landfill taxes (e.g., the Middle East), most materials are landfilled by default.

The service life of the structure must be specified in an LCA. For Wolke Marienfeld, which was dismantled after 2 weeks of use, the calculation period is set at 0.04 years.

LCA simulations

Different simulations are needed to understand the LCA of a short use canopy, a reusable structure and a permanent structure. Each simulation reflects a scenario.

Canopy Wolke Marienfeld (simulation 0) is considered as the reference. Newly made special steel components and a new membrane are installed, while standard steel trusses are reused from the warehouse. At the EOL, the standard steel components will be stored for reuse, the special steel components will be recycled and the membrane skin will be incinerated. The canopy is installed for 2 weeks.

As alternative, 3 scenarios of a reusable structure are analysed: a scenario where the structure is installed for the first time (simulation 1 - first), a scenario where the stored structure is reused and stored again (simulation 2 - intermediate), and a scenario where the structure is installed for a last time (simulation 3 - last). A duration of 2 weeks is considered for each set-up. The first installation is the scenario where new components are made to create the structure and where all materials are reused for another installation at the EOL. An intermediate installation is the situation where existing components are reused to build the structure and where at the EOL all materials are stored for a future installation. The last installation corresponds to the scenario where the materials are worn out and where all existing components and materials are used for the last time to build the structure. At the EOL, the standard steel trusses and special steel components are recycled, while the membrane is incinerated.

A final alternative design (simulation 4) considers a permanent membrane canopy where the canopy is used for 25 years. The installation is done with new standard steel elements, new special steel components and a new membrane. At the EOL, the standard steel trusses and special steel components are recycled, while the membrane is incinerated. The disadvantage of short use can be verified by comparing simulation 1 with simulation 4.

TABLE 1. GWP RESULTS FOR SIMULATIONS 0, 1, 2, 3 AND 4

Simulation	0	1	2	3	4
	Wolke Marienfeld		Reusable structure		Permanent
Installation	Once	First	Inter-mediate	Last	Once
Standard steel structure	Reused	Newly made	Reused	Reused	Newly made
Special steel components	Newly made	Newly made	Reused	Reused	Newly made
Coated fabric	Newly made	Newly made	Reused	Reused	Newly made
EOL: Steel	Recycling	Reuse as material	Reuse as material	Recycling	Recycling
EOL: Coated fabric	Incineration	Reuse as material	Reuse as material	Incineration	Incineration
Service life	2 weeks	2 weeks	2 weeks	2 weeks	25 years
Units	$kgCO_2e$	$kgCO_2e$	$kgCO_2e$	$kgCO_2e$	$kgCO_2e$
A1-A3 Construction Materials	131.000	443.000	0	0	443.000
A5 Construction and installation process	17.700	23.600	0	0	28.100
B6 Energy consumption for inflation	57	57	57	57	35.900
C1-C4 End of life	22.600	0	0	26.000	26.000
D External impacts	-356.000	-461.000	-438.000	-213.000	-221.000
Total	**173.000**	**469.000**	**1.720**	**27.700**	**535.000**
Per floor area m2 per year	4.510	12.200	44,7	721	22,3

A1-A3 Construction Materials and D External impacts

Global Warming Potential (GWP) results

The 5 simulations are evaluated based on the GWP indicator.

A1-A3 Construction Materials and D External impacts

The reference simulation (simulation 0, Table 1) assumes reused standard steel components, which will be stored after dismantling, newly made special steel components which will be recycled, and a newly made membrane, which will be incinerated after use.

The GWP of the modules A1-A3 (partly reused materials) is low (131.000$kgCO_2e$), and the GWP of module D is high (-356.000$kgCO_2e$). The GWP of module D contains firstly the benefit of the material (-354.000$kgCO_2e$), which is the sum of the following contributions: the reuse of the standard steel structure (-84.000 * 3,66 = -308.000$kgCO_2e$), the recycling of the specially designed steel components (-21.000 * 2,2 = -41.700$kgCO_2e$) and the incineration of the technical textile (-10.000 * 0,4927 = -4.930$kgCO_2e$) and secondly the benefit of the material wastage on the construction site (module A5), which is -2.360$kgCO_2e$. In these calculations, the coefficient for the reusing steel is 3,66$kgCO_2e$/kg, for recycling steel is 2,2$kgCO_2e$/kg, which is lower, while the coefficient for the burning technical textile is 0,4927$kgCO_2e/m^2$.

The first simulation (simulation 1, Table 1) corresponds to the scenario where the canopy is constructed with newly made materials and all materials are reused at EOL. The GWP of the modules A1-A3 is high (443.000$kgCO_2e$). The higher value, compared to simulation 0, is because the steel components and the membrane are newly fabricated. The GWP of module D (-461.000$kgCO_2e$) is of the same order of magnitude as modules A1-A3, which means that the GWP of the benefits beyond the system boundaries balance the GWP of production and manufacturing of the construction materials. The higher value of module D, compared to simulation 0, is because the reuse of all materials gives a higher result for the GWP of this module. Module D in this case, contains the reuse of the standard steel structure (-84.000 * 3,66 = -308.000$kgCO_2e$), the reuse of the specially designed steel components (-21.000 * 3,66 = -76.900$kgCO_2e$), the reuse of the technical textile (-10.000 * 5,34 = -53.400$kgCO_2e$) and the benefit of the material wastage on the construction site, which is -23.400$kgCO_2e$.

The intermediate installation (simulation 2, Table 1) corresponds to the scenario where the canopy is constructed with existing materials, and where all materials are reused at EOL. The GWP of modules A1-A3 is 0 because all materials of simulation 1 were reused in this simulation. The GWP of module D is high (-438.000$kgCO_2e$) due to reuse at EOL, and there is no material wastage considered at the construction site.

The third simulation (simulation 3, Table 1) reflects the situation where all steel components are made of reused materials and are recycled at the EOL. The membrane is also reused and will be incinerated at the EOL. The GWP of modules A1-A3 is 0 because all components are reused components. The GWP of module D (-213.000$kgCO_2e$) contains benefits and loads beyond the system boun-daries for recycled steel and incinerated membrane. This result is lower compared to simulation 2 or 3, where all materials were reused at the EOL.

The final alternative assumes a newly fabricated steel structure and membrane, with steel recycling and membrane incineration at the EOL (simulation 4, Table 1). The GWP of modules A1-A3 is high (443.000$kgCO_2e$) as for simulation 1, and the GWP of module D is comparable to the value for simulation 3 (-221.000$kgCO_2e$).

The total GWP

The total GWP for the canopy Wolke Marienfeld is low (173.000kgCO_2e) thanks to the reuse of standard steel components (80%).

For the alternative case of a reusable similar structure, the total GWP for the 3 simulations is very different:
first installation (469.000kgCO_2e), intermediate installation (1.720kgCO_2e) and last installation (27.700kgCO_2e).
One way to take into account the first and the last set-up for reusable structures could be to add a part of it to the GWP of the intermediate installation. For instance, consider n intermediate installations, which means n+2 total installations, the average GWP for each installation becomes:

$$\frac{(GWP\ simulation\ 1) + (GWP\ simulation\ 2)\ x\ n + (GWP\ simulation\ 3)}{n+2} \quad [1]$$

Using this formula, the total GWP for an intermediate installation varies, for example, between 166.140kgCO_2e for n=1 and 19.989 kgCO_2e for n=25.

The total GWP for the permanent canopy installed for 25 years is 535.000kgCO_2e. The total GWP increases by only 12% for a much longer service life of the structure, 25 years instead of 2 weeks (comparison of simulations 1 and 4).

An important note is that for short-use structures the total GWP should be given per floor area and per year of use. The comparison of simulations 1, with a lifetime of 2 weeks, and 4, with a lifetime of 25 years, shows that the total GWP value decreases from 12.200 to 22,3kgCO_2e/m²/year.

The total GWP per element

The GWP results for the primary structure (Fig. 4) show that the canopy Wolke Marienfeld (simulation 0) benefits from the reuse of standard steel components.
The GWP of the primary structure for the first simulation of a reusable structure is as high as for a permanent similar structure (simulation 4). Considering the GWP results for the membrane, the GWP results for Wolke Marienfeld and a permanent similar structure are comparable, as they both use a new membrane which will be incinerated at the EOL. Moreover, the sum of the GWP of the membrane for simulation 1 and 3 has the same order of magnitude as the result for simulation 0 and 4, as one can expect.

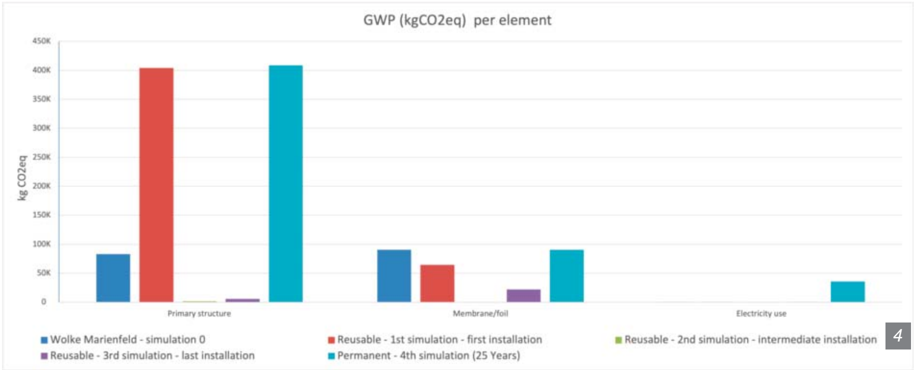

Figure 4. Life-cycle assessment - Global warming results per element (primary structure, membrane and electricity use) for simulations 0, 1, 2, 3 and 4

The GWP for the energy consumption for inflation (module B6) increases from 57kgCO_2e (simulations 0, 1, 2 and 3) to 35.900kgCO_2e (simulation 4) and becomes of the same order of magnitude as the GWP for the construction and installation process (module A5).

Circularity score

OneClickLCA allows to estimate a circularity score for a scenario. It takes in account and averages both the input material and the end-of-life processes. The material used as input for the LCA can contain a certain percentage of reused content or be an existing component. The options for the EOL are recycling, downcycling, reusing as same material. The circularity score is the average of the fraction of recovered and recycled material.
Downcycling is considered for only 50%.

Comparing simulation 1, 2 and 3 shows well that the circularity score is higher if the components and material are reused. The highest values (83%, 100% and 97%) are obtained if the set-up reuses at least part of the materials. Note that the circularity score of simulation 3 is still reasonable high, while the complete steel structure will be recycled and the membrane incinerated. This is because in the circularity tool reuse and recycling are accounted for 100%. It must be mentioned again that components need to be made, need to be maintained and at a certain time, their use comes to an end. As proposed in the formula [1] above, making and maintenance could be divided among the subsequent installations.

Conclusions

The canopy Wolke Marienfeld was designed to be used for a short time. Environmental indicators must be calculated per year to reflect the impact of the period of use. In this case, the GWP (simulation 0) is 12.200kgCO_2e/year/m², while the GWP of simulation 4 is 22,3kgCO_2e/year/m².
For shorter periods of use, reuse and recycling are utmost important.
The considered case study is mainly a steel structure. For lighter constructions with less steel components and for which the coated fabric thus contributes more, recycling of coated fabrics will be needed to obtain an overall good environmental performance.

Department of Mechanics of Materials and Constructions, VUB
Zehra Eyruruk
Zehra.Eyruruk@vub.be
Danny Van Hemelrijck
Danny.Van.Hemelrijck@vub.be
Department of Architectural Engineering, VUB
Lars De Laet
Lars.De.Laet@vub.be
Marijke Mollaert
Marijke.Mollaert@vub.be

TABLE 2. CIRCULARITY SCORE FOR THE 5 SIMULATIONS

Simulation	0	1	2	3	4
Service life	2 weeks	2 weeks	2 weeks	2 weeks	25 years
Circularity score	83%	50%	100%	97%	47%