Prototype of façade fb720: Report on the life cycle analysis of the materials. Case study

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ABSTRACT: The Façade FB720 project is a study funded by the Spanish Government's "Centre for Industrial Technological Development" (*Centro para el Desarrollo Tecnológico Industrial*, CDTI) (IDI-20090761). The aim of the project is to design and develop a lightweight, modular, unitized façade with low environmental impact and high energy efficiency, mainly for use in the Iberian Peninsula. The design of the façade is based on a proposal by "b720 architects" with the participation of various companies and technology centres acting as consultants. The Universitat Politècnica de Catalunya (UPC) provided advice on the life cycle analysis, in collaboration with the environmental consultancy "Societat Orgànica". The consultancy "JG Ingenieros" was involved in the thermal and light evaluation.

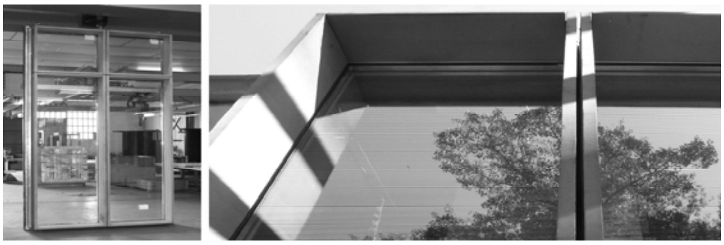


Fig. 1 Photographs, general and detail, of one of the versions of the FB720 prototype

1. OBJECTIVE

From an environmental perspective, the aim of Project FB720 is to attain the greatest reduction in environmental impact. There are several versions of the FB720 façade, depending on the combination of different materials, the types of glass, the proportion of transparent area and the distance between uprights. On the basis of the preliminary design created by the team of architects, the life cycle assessment (LCA) advisory team was asked the following questions:

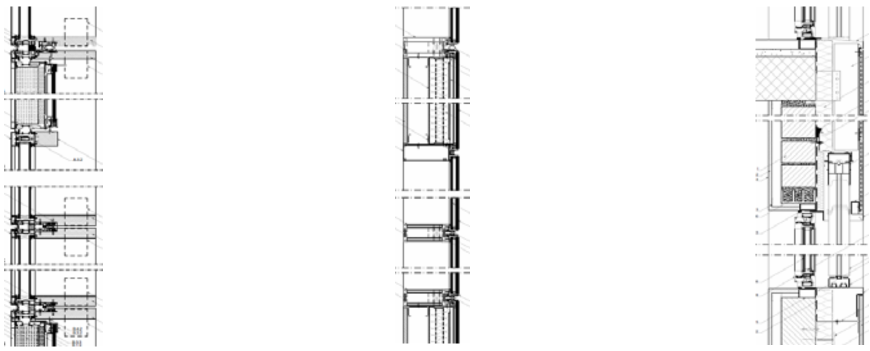
- Is it possible to carry out a LCA of different versions of a new curtain wall called FB720? The versions are based on different combinations of materials (external uprights, thermal insulation, internal walls, etc.), types of glass (clear, seasonal control, low emissivity, etc.), proportions of the transparent part of the wall (75% and 37%) and separation between the axes of the uprights (60 cm and 120 cm), all for a 50 year life cycle.

- Which of all the possible configurations of the façade FB720 leads to the greatest reduction in environmental impact?

- How does the LCA of the new wall FB720 compare with that of a standard modular curtain wall (MCW) and that of a standard traditional facade (TF)?

To answer these questions, a LCA advisory team was formed by the UPC's *Laboratori d'innovació i Tecnología a l'Arquitectura*, (LiTA) and the *Societat Orgànica* consultancy company, which is made up of PhD graduates trained at the UPC.

The environmental assessment that is presented here refers only to the environmental impacts of the cycle of materials during the useful life of the façade. The environmental analysis of the façade's thermal and light behaviour as the skin of the building was carried out by another technical team and is not described in this paper.



Wall FB720 (ground plan) Wall MCW (ground plan) Wall TF (section)

Fig. 2 Technical graphic details of the types of façades considered in order to compare results

2. METHOD

Life cycle assessment (LCA), which is established in the ISO 14040/43 standards, is a method used to comprehensively assess the environmental impact of buildings or building solutions. However, the LCA methods and tools that apply to buildings are not well enough known or frequently used by agents in the construction sector, including development companies, construction companies, designers, local authorities and property owners. The LCA method is difficult to implement in this field due to: application difficulties in an industry like construction; the time needed to carry out the method, in view of the tight deadlines for drawing up building plans; and the high financial investment required to apply the method to buildings using the tools and methods that are currently available, which are not adapted to the specific characteristics of the sector in Spain.

As a result, the few LCA studies of buildings that have been carried out in Spain have had to simplify the method considerably and to make various adaptations and approximations of the data that is available in the information sources. This information mainly comes from other countries in Europe or the rest of the world. As stated above, these data cannot be extrapolated directly to the local situation. Such LCA are usually performed on the basis of just a few indicators of environmental impact and only a couple of phases are studied in-depth: extraction and manufacture of materials; and the use and maintenance of the building. The impact of the phases of transport to the building site, construction or renovation of the building, demolition and final waste treatment are either estimated in a general way from statistical information, other evaluations carried out, etc. or are excluded from the study as it is considered that their total contribution to the life cycle is practically negligible.

These simplified studies are known as Life Cycle Assessment Summaries. They do not provide an extremely accurate calculation of the environmental impact of a building, but are particularly useful for assessing trends. The following characteristics, among others, make LCA summaries easy to use in the construction sector: they can be carried out in shorter times; they require less information to represent the life cycle phases and scenarios, and they are less expensive to perform, as much of the assessment can be carried out with readily available, cheap or public tools and sources of information.

If we take into account that the results of this study should be used in the design of a new curtain wall, all of the approaches of the proposed LCA summary are closely related to technologies and information sources that are currently available and feasible.

Therefore, the method used in this case was a LCA with a shortened procedure, considering that the aim was to support the team of architects in their decision making. The following initial considerations were taken into account:

- Functional unit: $1m^2$ of façade, with a useful life of 50 years.

- Phases considered: production of materials [1], transport [2], construction [3], maintenance [4], demolition and final waste management [5].

- Impacts assessed: weight of materials [kg/m^2], energy consumption [MJ/m^2], and CO_2 emissions [$kgCO_2/m^2$]. In some phases, the following parameters were also included: solid waste [kg/m^2], recycled or renewable material at the beginning of the life cycle [kg/kg], recyclable or compostable material at the end of the life cycle [kg/kg] and environmental toxicity [ECA kg/kg].

- Assumptions and limits of the shortened procedure: phase [1] of the LCA summary includes all the operations of extraction and transport of raw materials to the factory where the building materials are manufactured. Transport from these factories to the curtain wall workshops, the manufacture of the walls and assembly of components are also assessed. The material intensity per service unit (MIPS) is excluded. In [2], the use of fuel in the modes of transport is included. The life cycle of vehicles and infrastructures is excluded. In [3], the energy consumption (electricity, diesel, etc.) of machinery is assessed. The energy costs of human activities and the depreciation of production tools are not taken into account. In [4], maintenance operations, partial and total replacement within 50 years are included. Phase [5] includes dismantling of the wall until its component materials have been separated and management of non-recyclable waste.

- Tools and bases: almost all of the calculations were carried out with the help of standard spread sheets, but without the use of expert programs. The materials databases that we consulted were BEDEC PR/PCT of the ITeC, ICE of the University of Bath, EMPA of the Swiss Consortium of Public Universities, ELCD of the European Union and, in some cases, ECOINVENT and IVAM. Calculations were carried out with the SIMAPRO program (obtained from the *Centro de Iniciativas de la Edificación Sostenible* research project) or we used our own calculations to determine the specific weight, volume and density of the materials used in the various building solutions. With respect to the operations of transport and loading, as well as waste generation, we consulted the PR/PCT bank, as well as information provided by manufacturers, other studies, calculations and our own estimations.

To express energy consumption (in electric kWh or litres of diesel) as CO2 emissions, we used the conversion factors established in the Spanish energy certification processes. In the case of recycled or renewable and recyclable or compostable materials, we used our own calculations as well as information provided by manufacturers or others.

3. RESULTS OF THE LCA SUMMARY PROCEDURE

Below, we present a summary of the environmental impact assessment and results for the various phases in the life cycle of the three types of façade under study (FB720, MCW and TF).

3.1 Extraction and manufacture of building materials

We present the four versions of FB720 that had the best environmental results. These were the façades made of normal solar control glass [I], 37% transparent surface [37], 120 cm between the axes of uprights [120] and four combinations of materials: laminated wood, sheep's wool, particle board, Kraft paper [A, renewable natural materials], recycled PVC, recycled textile fibres, plaster fibreboard, EPDM [B, recyclable industrial materials], polymer wood, sheep's wool, particle board, Kraft paper [C, hybrid of natural and industrial materials] and fibre concrete, sheep's wool, particle board, Kraft paper [D, hybrid of natural and industrial materials]. The fig.3 below show the weight, energy and CO_2 emissions results for these four versions. A comparison between them showed that A/I/37/120 had the lowest environmental impacts.

Fig.3 Table of the comparative environmental impact results of the LCA summary procedure applied to four of the best versions of the system

Façade	kg/m^2	MJ/m^2	$kg\ CO_2/m^2$
A/I/37/120	53.99	1348.37	98.96
B/I/37/120	72.17	1387.02	116.93
C/I/37/120	65.22	1656.99	106.27
D/I/37/120	84.49	1516.48	127.86

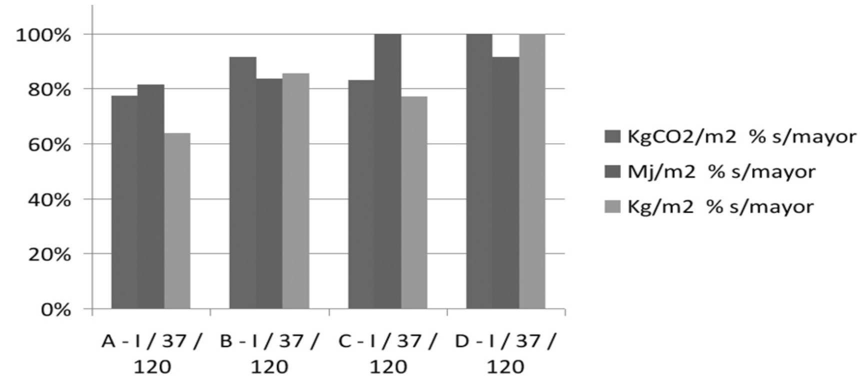


Fig.4 Graph of the comparative environmental impact results of the LCA summary procedure applied to four of the best versions of the system (is expressed as percentage relative to the higher value)

At the other end of the range, the versions of FB720 that had the most environmental impact were C/III/75/60 (polymer wood, sheep's wool, particle board, Kraft paper, low emissivity and seasonal control glass, 75% transparent and uprights every 60 cm) with 89.66 kg/m^2, 2284.01 MJ/m^2 and 149.16 $kgCO_2/m^2$ and D/III/37/60 (fibre concrete, sheep's wool, particle board, Kraft paper, low emissivity and seasonal control glass, 37% transparent and uprights every 60 cm) with 120.81 kg/m^2, 2027.01 MJ/m^2 and 182.39 $kgCO_2/m^2$. Therefore, the difference between the lowest impact and the highest impact versions, which is due to the different combinations of materials, types of glass, transparent area and the distance between uprights, is up to 110% in weight, 70% in energy and 80% in CO_2 emissions.

We also compared the new façade FB720 with the reference façades MCW (modular curtain wall) and TF (traditional façade). We considered identical proportions of glazed area, but differences in the distance between uprights (as in the case of the MCW, only a distance of 120 cm was used). The version of FB720 with the lowest environmental impact (A/I/37/120) consumed 67% less energy and emitted 81% less CO_2 than the MCW. When we compared A/I/37/120 with the TF, these values were 42% and 61% respectively. The version of FB720 façade with the highest environmental impact (C/III/75/60) consumed 45% less energy and emitted 72% less CO_2 than the MCW and 2% less energy and 42% less emissions than the TF.

Fig.5 Table of the comparative environmental impact results of the LCA summary procedure applied to the different types of façades and their best and worst versions

Façade	kg/m^2	%	MJ/m^2	%	$kg\ CO_2/m^2$	%
FB720 A/I/37/120	53.99	100%	1348.37	100%	98.96	100%
MCW I/37/120	59.20	110%	4111.32	305%	525.93	591%
TF 37/120/C	121.81	226%	2327.17	173%	255.49	258%
FB720 C/III/75/60	89.66	166%	2284.01	169%	149.16	151%

3.2 Transport

For this assessment, we considered a building site located in Madrid as this city is in the centre of Spain. We took into account the fact that the workshop for manufacturing façades is in Olot (Catalunya, Girona). It was difficult to determine the rest of the locations (factories, warehouses, distributors) for each and every one of the materials involved (the selection of one supplier or another tends to depend on issues such as price, payment conditions, availability, transport logistics, etc., rather than on optimizing the movement of materials). Consequently, we considered the normal distances for the transport of construction materials, according to the literature (Wege zum Gesunden Bauen, Holger König, 1985, Ökobuch, Freiburg). Depending on the specific materials used in each version of façade FB720, we also altered the distances, weights, packaging, transport density, etc. With a few exceptions, the mode of transport that was considered was 16-ton lorries with an estimated load for each journey (factory-warehouse, warehouse-building site, factory-façade workshop, façade workshop-building site, etc.), in accordance with the experience of the sector and consultations. The results are shown in the following table in Fig. 6.

Fig.6 Table of the results of fuel consumption calculations, the conversion to primary energy and CO_2 emissions for the different types of façades and versions considered

FAÇADE	DIESEL, liters / m^2	ENERGY, Mj / m^2	EMISSIONS, kg CO_2 / m^2
FB720 - A	2,44	102,71	8,19
FB720 - B	3,74	134,97	11,18
FB720 - C	2,50	105,50	8,41
FB720 - D	2,58	108,56	8,65
MCW	2,76	116,19	9,26
TF	2,19	92,44	7,37

In the previous phase, the variation in values for the different façades was considerable. In contrast, the results for the transport phase showed less variation in the energy consumption and CO2 emissions associated with each façade. Nevertheless, the Type A versions of FB720, which were based on natural, light, local materials, had the lowest environmental impact of the prefabricated systems. The least impact of all was recorded for the TF system (assembled “in situ”), due to the wide geographical dispersion of materials manufacturers, workshops and building sites in the prefabricated systems (FB720 and MCW).

3.3 Construction

To determine the environmental impact of using production tools at the building site to unload, lift up, stockpile, install and remove waste, as well as that of the packaging materials and the management of waste generated on site, we considered that the different façades were constructed in the same imaginary eight-storey building, with a ground plan of 40 x 60 m and a height between floors of 3.50 m. As the FB720 and MCW façades are both modular and prefabricated they have practically identical impacts in this phase. The environmental impact of the TF façade, which is mainly constructed on site, was calculated from the different steps that the work involves.

Fig.7 Table of comparative environmental impact results of the construction phase for the different types of façades and versions considered.

Façade	Location	Concept	MJ/m^2	%	kg CO_2/m^2	%	m3/m^2
FB720 y MCW	Prefabricationn	Façade workshop	2,94		0,53		
	Building site	Electrical machinery	2,41		0,43		
		Diesel machinery	4,10		0,33		
		Packaging materials	4,41		0,53		
		Waste management	0,28		0,02		
		Total	14,14	100%	1,84	100%	0,00

Façade	Location	Concept	MJ/m^2	%	kg CO_2/m^2	%	m3/m^2
TF 37/120/C	Building site	Electrical machinery	33,58		6,05		
		Diesel machinery	40,08		3,20		
		Packaging materials	14,00		1,68		
		Waste management	0,11		0,01		0,14
		Total	87,77	621%	10,94	594%	0,14

The results in the fig.7 show considerable differences in both energy consumption and CO_2 emissions between the prefabricated façades with the lowest environmental impact and the façades constructed in situ with the greatest impact. In the first group, the values were up to six times lower than in the second group. The on-site solid waste generation for prefabricated systems is so much lower than that of systems constructed in situ that the values of this group are not reflected in the table.

3.4 Maintenance

This is the longest phase in the established life cycle (50 years). Fifty-year cycles are predominantly used in this type of study. Consequently, we selected this value so that comparisons could be made with the literature. However, the useful life of a standard curtain wall is around 35 years. This difference between the theoretical and real useful life means that, for the purposes of this study, we considered a first phase from construction up to 35 years, in which maintenance work is carried out such as resealing the gaskets (at 20 years) in all façades. In a second stage from 35 to 50 years, the modular prefabricated FB720 (A/I/37/120) and MCW (I/37/120) façades are finally dismantled, some of the materials are recovered (when possible), and replaced by others. In the case of the TF façade that is constructed in situ, at 35 years the exterior cladding is replaced as well as the openings and the part of the interior wall that is indirectly affected by these operations. The table in Figure 8 sums up these calculations.

As shown in fig. 8 the above table, there is a great difference in the energy consumption, CO_2 emissions and solid waste impacts caused by maintenance operations between the prefabricated façades FB720 and MCW, particularly in the sub-phase between 35 and 50 years. This is due to the fact that the envelope needs to be dismantled and replaced in this period. As a result, many of the materials that could be reused or recycled become waste, particularly in the case of MCW. The MCW façade has an environmental impact that is around 1.9 to 3.5 times higher than that of the FB720 prefabricated façade, depending on which aspect is analysed. The values for the TF façade constructed in situ are in an intermediate position. However, they are still between 1.8 and 2.6 times higher than the values for FB720, depending on which indicator is considered.

Fig.8 Table of comparative environmental impact results of the maintenance phase for the different types of façades and versions considered

Façade	Concept	MJ/m^2	%	Kg CO_2/m^2	%	Kg/m^2	%
FB720	Maintenance from 1 to 35 years	25,20		1,28		0,00	
(A/I/37/120)	Replacement at 35 to 50 years	677,62		60,36		22,36	
	Total	702,82	100%	61,64	100%	22,36	100%
MCW	Maintenance from 1 to 35 years	25,20		1,28		0,00	
(I/37/120)	Replacement at 35 to 50 years	2.399,90		289,01		41,75	
	Total	2.425,10	345%	290,29	471%	41,75	187%
TF	Maintenance from 1 to 35 years	51,31		7,57		0,00	
(37/120/C)	Replacement at 35 to 50 years	1.410,00		154,81		39,76	
	Total	1.461,31	208%	162,38	263%	39,76	178%

3.5 Demolition / Dismantling

This phase of the life cycle includes all of the dismantling operations in the case of the modular prefabricated façades FB720 and MCW, and demolition in the case of the TF façade constructed in situ. The values, which include waste management, are summarized in the following table.

Fig.9 Table of comparative environmental impact results of the demolition/dismantling phase for the different types of façades and versions considered

Façade	Concept	MJ/m²	%	kg CO_2/m²	%	kg/m²	%
FB720	Dismantling and removal	9,27		0,67			
(A/I/37/120)	To a recycling centre	2,94		0,53			
	Waste management	0,15		0,39		9,38	
	Total	12,36	100%	1,59	100%	9,38	100%
MCW	Dismantling and removal	9,27		0,67			
(I/37/120)	To a recycling centre	2,94		0,53			
	Waste management	4,48		1,60		31,24	
	Total	16,69	135%	2,80	176%	31,24	333%
TF	Dismantling and removal	33,95		6,59			
(37/120/C)	To a recycling centre	0,00		0,00			
	Waste management	1,72		4,61		109,80	
	Total	35,67	289%	11,20	705%	109,80	1171%

In this phase, as in the previous one, there is a considerable difference in the energy consumption, CO_2 emissions and solid waste impacts between the prefabricated façades FB720 and MCW, particularly in the sub-phase of waste management. Particularly in the case of MCW, this is due to the fact that many materials that could be recycled or reused become waste. Therefore, their environmental impact extends beyond the initial dismantling to the operations of final management of these materials. This final waste management phase has a strongly negative effect as, in the case of FB720, the impact of reusable or recyclable materials is no longer counted when they are dismantled and their components enter a new life cycle. Thus, from a LCA perspective, their impact does not have an effect on the cycle that has already been completed. The difference between the prefabricated façades FB720 and MCW is considerable: MCW has an environmental impact between 1.3 and 3.3 times higher than that of FB720, depending on the specific indicator that is analysed. The TF façade that is constructed in situ has the greatest impact of all the façades in this phase, particularly because the energy cost its demolition is much higher than that of dismantling the prefabricated façades, and because it generates larger quantities of waste that is neither reusable nor recyclable. The façade FB720 façade is between 2.9 and 11 times lower, depending on which indicator is considered.

3.6 Complete life cycle

If we add up the values obtained for each of the life cycle phases, we can obtain some total values that give us an overview of the behaviour of each façade system and its versions. This also enables us to detect in which phases of the cycle the main differences are found. Below are the total results for the four versions of façade FB720: [A], [B], [C] and [D] with type II glass (normal solar control), 37% of transparent area and a 120 cm separation between uprights.

Fig.10 Table of the aggregated environmental impact results for the versions of façade FB720 in all the LCA phases considered

Fb720 (II/37/120	Extraction + Manufacture		Transport		Construction		Maintenance		Dismantling		Total	
	(*)	(**)	(*)	(**)	(*)	(**)	(*)	(**)	(*)	(**)	(*)	(**)
Version A	1.447,5	107,41	102,71	8,19	11,99	0,75	699,89	61,11	10,99	1,18	2.273,08	178,64
Version B	1.486,1	125,38	134,97	11,18	11,99	0,75	699,89	61,11	10,99	1,18	2.343,99	199,60
Version C	1.756,1	114,71	105,50	8,41	11,99	0,75	699,89	61,11	10,99	1,18	2.584,49	186,16
Version D	1.615,6	136,31	108,56	8,65	11,99	0,75	699,89	61,11	10,99	1,18	2.447,04	208,00

(*) Mj / m²
(**) Kg CO_2 /m²

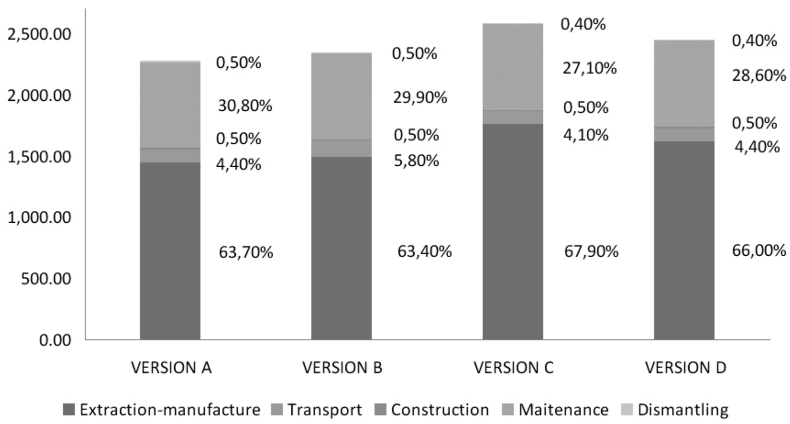


Fig.11 Graph of the aggregated environmental impact results, in terms of energy (Mj/m2) only, for the versions of façade FB720 in all the LCA phases considered

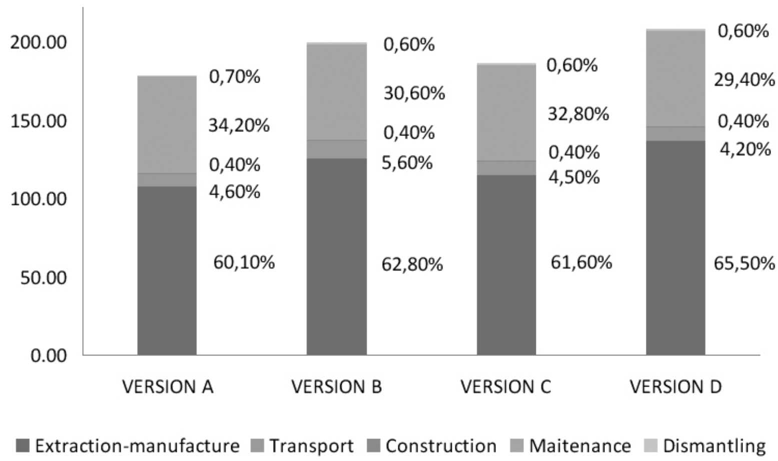


Fig.12 Graph of aggregated results, in terms of greenhouse gas emissions represented by carbon dioxide ($kgCO_2/m^2$) only, for the versions of façade FB720 in all the LCA phases considered

Version A/I/37/120, which is comprised mainly of renewable natural materials, has the best environmental behaviour throughout its life cycle (as indicated in the extraction and manufacture phase). In addition, most of the environmental impact is concentrated in the extraction and manufacture phase (range between 60% and 66%) and maintenance phase (range between 27% and 34%).

Fig.13 Comparative table of the aggregated environmental impact results for each type of façade considered: FB720 (the optimum version) compared to the reference façades MCW (modular conventional) and TF (traditional façade)

	Extraction + Manufacture		Transport		Construction		Maintenance		Dismantling		Total	
	(*)	(**)	(*)	(**)	(*)	(**)	(*)	(**)	(*)	(**)	(*)	(**)
Fb720 (II/37/120)	1.447,50	107,41	102,71	8,19	11,99	0,75	699,89	61,11	10,99	1,18	2.273,08	178,64
MCW (1/37/120)	1.486,15	125,38	134,97	11,18	11,99	0,75	699,89	61,11	10,99	1,18	2.343,99	199,60
TF (37/120/c)	1.756,12	114,71	105,50	8,41	11,99	0,75	699,89	61,11	10,99	1,18	2.584,49	186,16

(*) Mj / m^2

(**) $Kg\ CO_2/m^2$

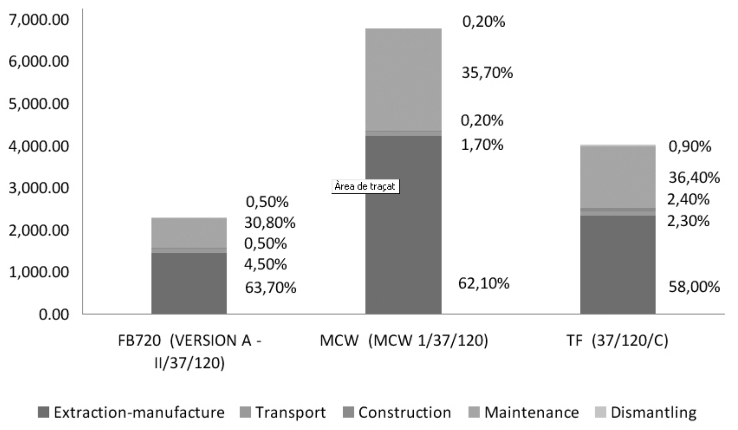


Fig.14 Graph of aggregated environmental impact results, in terms of energy only, for each type of façade considered: FB720 (the optimum version) compared to the reference façades MCW (modular conventional) and TF (traditional façade)

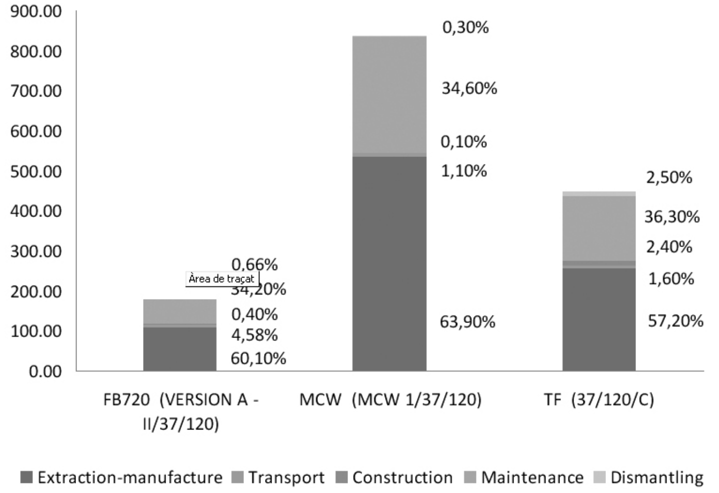


Fig.15 Graph of aggregated environmental impact results, in terms of greenhouse gas emissions represented by carbon dioxide only (kg CO_2/m^2), for each of the types of façade considered: FB720 (the optimum version) compared to the reference façades MCW (modular conventional) and TF (traditional façade)

As in all the life cycle phases studied, there were notable differences in the environmental impacts (in terms of energy and CO_2 emissions) of façade FB270 compared to the reference façades MCW and TF. The best version of façade FB720 reduced energy consumption and CO_2 emissions values in the order of 2 to 1 in comparison with the TF, and 3 to 1 in comparison with the MCW. The major effects of the material extraction and manufacturing phase, in the first place, and the maintenance phase, in the second, were also observed in comparisons of the different façade systems, including both those that were prefabricated and those constructed in situ. Regarding the impact of solid waste (those materials that cannot be recycled or composted that therefore end up at the dump), a comparison was made between the four versions of façade FB720 and the reference façades MCW and TF. All of the life cycle phases were considered, except for the transport phase as this mainly produces emissions to the atmosphere rather than solid waste (at least, no solid waste is directly formed by the use of fuel in the lorries considered here). When there was a lack of available public data on waste generation in all of the phases and systems under consideration, the values were calculated using information from databases (IVAM, BEDEC, etc.), manufacturers, the literature, assimilable materials and our own estimations. Therefore, the results should be considered representative of trends rather than exact.

Fig.16 Comparative table of aggregated results table for the waste generated by each type of façade considered in each phase and in the total life cycle, expressed as kg/m^2: FB720 (the optimum version) compared to the reference façades MCW (modular conventional) and TF (traditional façade)

Façade	Manufacture [1]	Construction [2]	Maintenance [3]	Dismantling [4]	Total	%
FB720 A/I/37/120	9,2	3,11	22,36	9,38	44,05	100%
FB720 B/I/37/120	11,29	3,11	22,36	9,38	46,14	105%
FB720 C/I/37/120	26,19	3,11	22,36	9,38	61,04	139%
FB720 D/I/37/120	12,68	3,11	22,36	9,38	47,53	108%
MCW I/37/120	48,74	3,11	41,75	31,24	124,84	283%
TF/37/120	33,04	9,68	39,76	109,8	192,28	437%

Kg/m2 of (1) Waste from the manufacture of basic materials, (2) Waste from packaging (FB270, MCW and TF) and surplus construction material (TF), (3) Non-recyclable waste due to the partial replacement of the wall at 35 years, and (4) Non-recyclable waste due to the dismantling or demolition of the wall at 50 years.

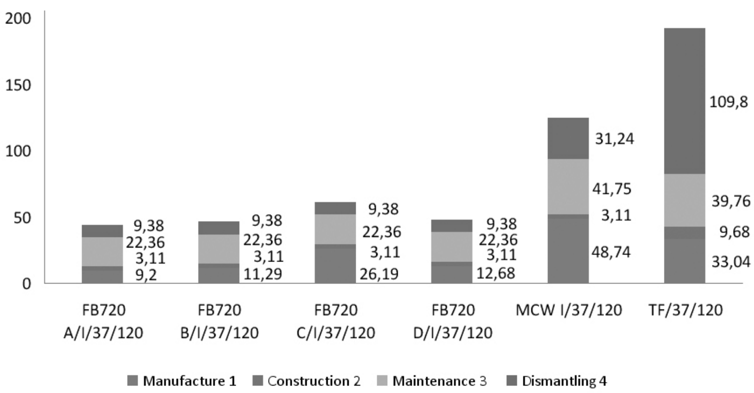


Fig.17 Comparative graph of aggregated results for the waste generated by each type of façade considered in each phase and in the total life cycle, expressed as kg/m^2: FB720 (the optimum version) compared to the reference façades MCW (modular conventional) and TF (traditional façade)

The same information displayed as a graph provides a clearer idea of the impact of each phase on the total waste in each case, as well as a relative comparison between the various façade systems. The lowest values, with a variation of up to 40% due mainly to the manufacture phase, correspond to the different versions of the FB720 façade. The MCW type of envelope is in an intermediate position, with double the impact of the FB720 façade that generates most waste. The highest level of impact was caused by the TF façade, with four times the average impact of FB720 and a 50% greater impact than MCW.

4. CONCLUSIONS

- The application of the environmental strategies defined in project FB720 for designing a façade led to a considerable reduction in environmental impacts throughout the life cycle.

- In the phase prior to taking design decisions, technical factors have been identified that are crucial to the control of environmental impacts and do not depend directly on the materials that are used: on the one hand, the geometric definition of the system, such as the distance between uprights (the further apart the better) and the full/empty ratio (the higher the better). In addition, it is important to define joining systems that could facilitate the dismantling process.

- This overview of the life cycle shows that industrialization in itself does not lead directly to environmental benefits. However, the issue changes considerably when the design of a construction solution (the materials selection, the geometric definition and the determination of joints) implicitly involves appropriate management of the material resources up to the end their cycle. Industrialization can make the impact considerably lower than in conventional construction if it is linked to an environmentally responsible design.

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