Sustainability assessment of windows and curtain walls

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1 Introduction and scope

Green Building certification schemes are considered by the real estate sector as useful tools for assessing the overall sustainability of buildings. With the related assessment processes, the building's performance can be evaluated comprehensively, depending on the chosen rating tool.

Nevertheless, there is still a lack of in-depth studies and critical assessments of the contribution of windows and curtain walls to the holistic assessment of buildings. Indeed, recently available studies do not analyse how the various indicators related to the façade and window performance are affected by their framing material, i.e. aluminium, timber or PVC.

In the first part of the study, a complete life cycle assessment and a life cycle costing are carried out to evaluate the environmental and economic impacts of similar windows and curtain walls fabricated with different framing materials. Only major framing materials[1] are considered, i.e. aluminium, timber and timber-aluminium for curtain wall system and aluminium, timber, timber-aluminium and PVC for residential windows. In the second part, , the overall sustainability performances of the various window and curtain wall systems have been compared using a quantitative methodology summing up results evaluated on basis of DGNB-GBRS criteria, e.g. criteria covering the environmental footprint, economical quality, social quality (e.g. comfort), technical and process quality.

Following steps are performed in this study:

- Detailed definition of typical curtain wall and window systems,
- Calculation of thermal comfort and energy consumption using numerical advanced thermal simulation software. Two different European climate zones are considered (warm and cold European climate),
- Calculation of life-cycle costs (LCC) according to ISO 15686-5,
- Calculation of life-cycle assessment (LCA) on the basis of ISO 14040 and EN 15804[2],
- Comparing rating tools for green building certification schemes regarding impacts from window and façade solutions.
- Developing in-depth set of indicators to evaluate sustainability for different framing materials in windows and curtain walls

General scope of the study

According to the targets and steps described before, the study focuses on the main and most relevant scenarios for the assessment. Since a holistic assessment identifies a broad set of indicators, a full agreement with ISO 14040 also including sensitivity analysis for each indicator is not part of the scope. Therefore, parameters and boundary conditions corresponding only to the most relevant scenarios have been used to deliver robust results.

[1] See Task 0 report of the preparatory study on the eco-design of windows, www.ecodesign-windows.eu
[2] This study is not an environmental product declaration. Hence, LCA calculations are based on EN15804 but results do not satisfy EN15804 requirements

2 Executive Summary

2.1 General Overview

This study assesses and compares the sustainability aspects of different window and curtain wall framing materials: Aluminium, timber, timber-aluminium and PVC for windows and aluminium, timber and timber-aluminium for curtain walls. The whole life cycle, from manufacturing to use phase and to end of life, is considered. For the modelling of the use phase, standardized room types for residential and office use for two different climate zones (Berlin and Rome) are used as basis for the study. A 3.75 m² double casement window is set as reference for residential buildings. The office curtain wall is defined as a 3-axis mullion-transom construction of about 14 m².

Based on the overall sustainability assessment, this study shows that each framing material presents pros and cons. Indeed, while one material may dominate the economic dimension, it may appear less environment-friendly or may present lower social or technical quality. As a result, no framing material appears as the most sustainable solution for windows or curtain walls.

From an environmental perspective, this study demonstrates that the energy demand during the building operating phase still largely dominates the overall environmental impact of windows or curtain walls on their whole life cycle, as already shown in older studies[1,2,3].

Therefore, from a building sustainability perspective, the optimisation of the contribution of windows and curtain walls to the energy performance of the building appears more essential than selecting a specific framing material.

Influence of windows and curtain walls on Green Building Rating Scheme (GBRS)

The facade assessment is based on sustainability criteria deducted from EN 15643/1 (Sustainability of construction works - Sustainability assessment of buildings) that are broadly used in the European Real Estate sector and which is the most comprehensive scheme in term of indicators and product-level contribution. According to relevant Green Building Rating Schemes, the facade is a crucial part of the building assessment since it contributes up to 10% to the overall sustainability rating of buildings.

Thermal Comfort and Energy Demand during Use Phase

Regarding the thermal comfort and energy demand, the chosen framing systems show very similar characteristics. Only the thermal transmittance differs primarily because of their profile width. As a result, only tiny differences of approximately 1.5% for their energy demands are obtained during the use phase, within the same climate zone.

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[1] Richter K., Künniger T. and Brunner K. (1996) Ökologische Bewertung von Fensterkonstruktionen verschiedener Rahmenmaterialien (ohne Verglasung). EMPA-SZFF-Forschungsbericht, Schweizerische Zentralstelle für Fenster- und Fassadenbau (SZFF), Dietikon.
[2] Windsperger A., Steinleichner S. (1997), Piringer M., Ökologische Betrachtung von Fensterrahmen aus verschiedenen Werkstoffen, Institüt für industrielle Ökologie, Wien, St Pölten
[3] Kreissig J., Baitz M., Betz M., Straub W (1998)., Ganzheitliche Bilanzierung von Fenstern und Fassaden, Universität Stuttgart-IKP, VFF, Frankfurt

Environmental Assessment over the whole Life-Cycle (LCA)

A life cycle assessment is performed to evaluate the environmental impacts of curtain walls and windows. Combining the manufacturing, end-of-life and use phases, the LCA shows similar global warming potential (GWP) for the four types of windows or for the three types of curtain walls whatever their location, Berlin or Rome. For both locations, the use phase, i.e. the energy demand of the reference room, largely dominates the overall GWP results.

Economical Assessment over the whole Life-Cycle (LCC)

According to the life cycle costing assessment, aluminium appears as the best performing material among the curtain wall systems under comparison. Its investment costs and the overall life cycle costs are lower than with timber or timber-aluminium.

For residential use, PVC windows show the lowest investment cost. For the chosen scenario, PVC windows also appear as having the lowest life cycle cost.

2.2 Sustainability Performance

An in-depth set of indicators are derived from the common Green Building Rating tools and are used to evaluate the sustainability performance of the different profile materials.

Environmental Quality

The energy demand during the use phase determines to a large extent the global warming potential (GWP) of curtain wall and window systems. For curtain walls, this use-phase energy demand contributes to approximately 90% on overall results whatever the façade systems and framing materials. For windows, this use phase contribution reaches approximately 98% for all studied systems

Regarding potential risks to local environment, timber is considered as more problematic than aluminium and PVC due to the use of dangerous substances, such as biocides solvents in timber frames. Aluminium and PVC systems reach high quality level in green building certifications schemes regarding the risks of local environment. The use of tin as stabilizer of PVC frames is not considered due to its low share in the current window market.

End of life collection and recycling rates reported in literature vary quite significantly, especially for PVC and wood framing materials. In this study, these variations have been captured respectively in the respective LCA scenarios used in “Mean Practice End of Life” and in “Good Practice End of Life“. Indeed, the sustainable timber production can be secured through certificates like FSC or PEFC which are already well implemented on the market. However, at the end of life stage, wood frames are still characterised by a low level of reuse or energy recovery and end up mostly as waste in landfill. Hence, the end of life treatment of wood frames still appears as a weak point in the timber life cycle.

Aluminium frames are today systematically recycled into new aluminium products. They have currently a collection rate which is close to 100%[1] due to their high economic value resulting from their ability to be efficiently recycled. Old aluminium frames are sold on the market for a price typically comprised between 50% and 75% of the LME price for primary aluminium.

Recycled PVC still demonstrates some technical limitations. Indeed, when producing new profiles, the recycled PVC must be encapsulated in virgin PVC mainly for aesthetical reasons. As a result, recycled PVC cannot fully substitute virgin PVC.

In terms of sustainable use of resources, aluminium and wood are positively positioned.

Economical Quality

For offices, curtain walls made in aluminium appear as the best option mainly thanks to their durability and low maintenance need. For residential use, the lowest life cycle costs were obtained for PVC profiles since the investment costs compared to the other materials are very low.

All in all, these variations in life cycle costs are limited since a maximum of 20% of overall cost variations are observed between the various solutions.

Social Quality

No significant difference is evaluated between the profile materials regarding thermal comfort.

Concerning indoor air quality, timber curtain walls have negative impacts due to application of paints, biocides and solvents with longer emission decay times.

Best material regarding design possibilities (“architectural innovation”) is aluminium. The mechanical properties and the design freedom of timber curtain walls are limited due to lower specific load resistance, which leads to wider and deeper window frames, mullions and transom profiles.

Technical Quality

Aluminium systems fulfil all fire safety requirements with highest quality level, while timber and PVC show severe disadvantages in terms of fire behaviour and smoke emission.

Process quality

The process quality describes the maintenance efforts, construction processes, assemblage and the ease of product acquisition.

Regarding weather resistance with high exposition to rain, solar radiation and large variation of air humidity, aluminium is the most useful material with the lowest maintenance needs.

[1] Collection of Aluminium from Buildings in Europe, TU Delft study for EAA , 2004 available at http://www.alueurope.eu/publications-building/

In terms of material acquisition for a building construction, wooden curtain walls require in general a longer delivery time in particular for large project developments.

For residential buildings, all window systems are largely available.

Summary - In-depth Assessment

The in-depth assessment results in an overview about sustainable performance of different façade and window materials. Based on a full set of indicators, the systems are evaluated considering a typical solution as well as a best practice solution for each material. The advantages and disadvantages of examined systems are rated by credits 0 (negative), 1 (neutral) and 2 (positive). This rating scheme is taken to show an easy overview about the comprehensive performance regarding sustainable material use for curtain wall and window systems.

Office buildings – façade systems

Based on the quantitative methodology defined for this project, aluminium standard curtain wall reaches an overall sustainability performance summing 92% of total credits, against 80% for timber-aluminium and 76% for timber curtain wall. The aluminium curtain wall appears as the best in terms of life cycle costing and presents advantages on technical, functional and design aspects.

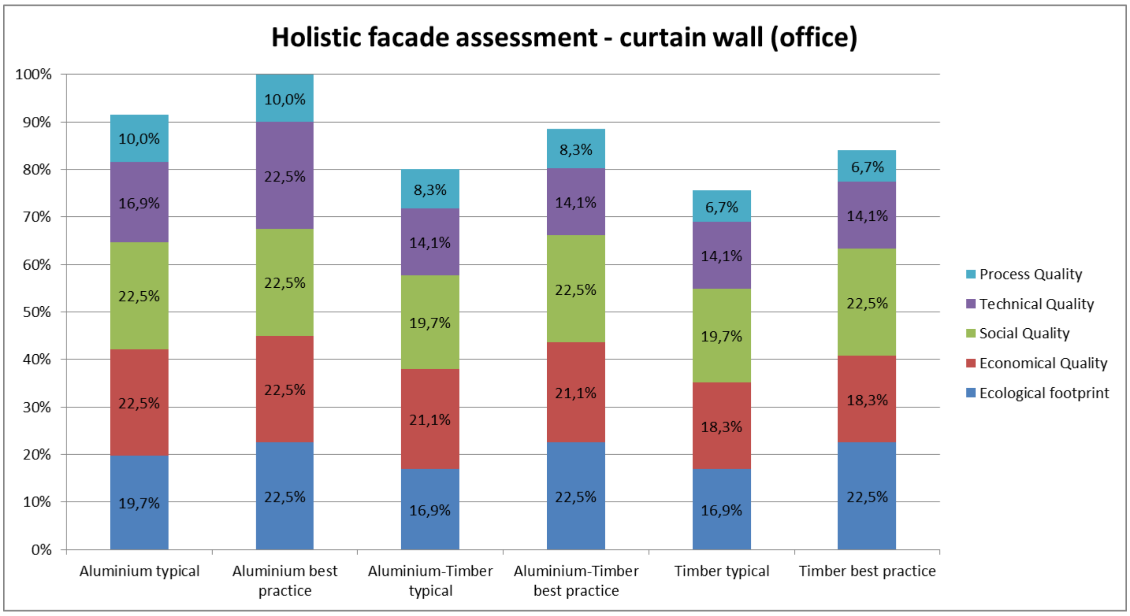


Figure 2-1: Results curtain wall assessment – Office

Residential buildings – window systems

For window systems, this methodology leads to a score of 93% for aluminium standard windows, 83% for Aluminium-Timber, 82% for timber and 84% for PVC. For the best practices, the scores vary from 99% for Al down to 87% for PVC. Considering the fraction of subjectivity associated with the criteria definition, such variation in final results cannot be considered as much significant.

The aluminium standard window appears as the best in terms of technical, functional and design aspects while PVC as the lowest life cycle costing.

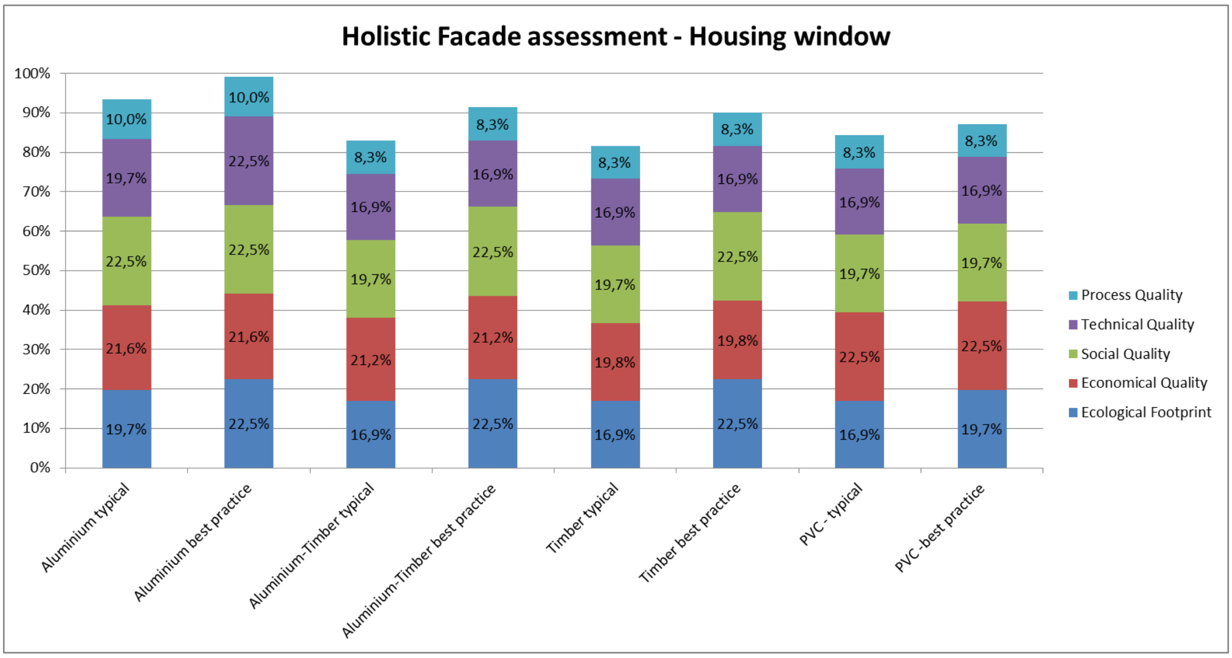


Figure 2-2: **Results window assessment – Housing**

3 Description of curtain wall and window systems

This study analyses the overall performance of various curtain walls and windows for two typical climate conditions: Berlin and Rome. For each location, the same energy performances characteristics have been used for the various windows and curtain wall systems analysed. This allows for a fair comparison of the systems over their life-cycle, since their design is energy performance-driven. These reference energy performance characteristics are representative of typical systems used in each climatic zone.

3.1 Window system of residential buildings/housing

3.1.1 General properties of window systems

As it is widely spread in the residential sector across Europe, a double tilt & turn window is defined as reference window for the purpose of this study. One sash of the window can either tilt inwards at the top, or can open inwards hinged at the side. The second sash of the window can only open inwards hinged at the side.

We distinguish four framing materials or materials combination: Aluminium, Timber, Timber-Aluminium and PVC.

The general specifications of the window system are defined for Berlin and Rome as follows:

Dimension:

Window Width: 2.500 mm

Window Height: 1.500 mm

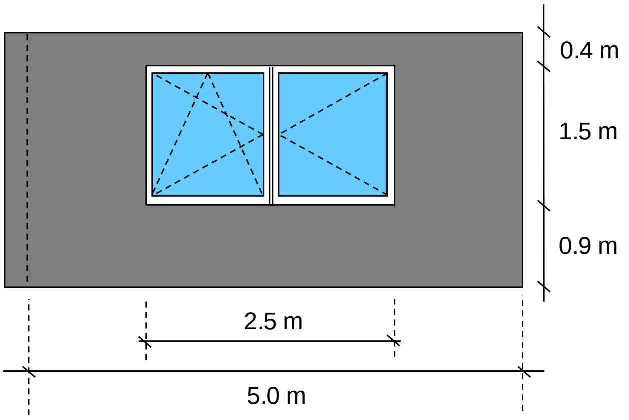


Figure 3-1: Reference window dimension - Housing

This reference window presents the following characteristics:

– Building Physics:	Berlin	Rome
– Glazing:	triple-glazing	double-glazing
– U_w-Value:	1.0 W/m²K	2.0 W/m²K
– U_g-Value guidance value:	0.7 W/m²K	1.8 W/m²K
– U_f-Value guidance value:	1.3 W/m²K	2.0 W/m²K
– g_{gl}-Value:	60%	60%

– Light transmission:	> 65%	> 65%
– Acoustic requirement R_w:	34 dB	34 dB
– Air permeability EN 12207:	Category 4	Category 4

The choice of the above values for the thermal transmittance of windows complies with the maximum requirements in force for U_w-value in Germany and Italy[1].

[1] Atanasiu B., Maio J., Staniaszek D., Koulompi I., Kenkmann T. (2013), Overview of the EU-27 building policies and programs and cross-analysis on Member States nZEB-plans, Buildings Performance Institute Europe (BPIE) & Öko-Institut e.V., www.entranze.eu

3.1.2 Specific properties of window systems

Based on the reference window characteristics, typical window systems have been selected as described in the 4 next sections and used then in the LCA calculation. The small variation which may exist between the declared product specification and the above list of characteristic of the reference window were not considered in the thermal modelling.

Aluminium window systems

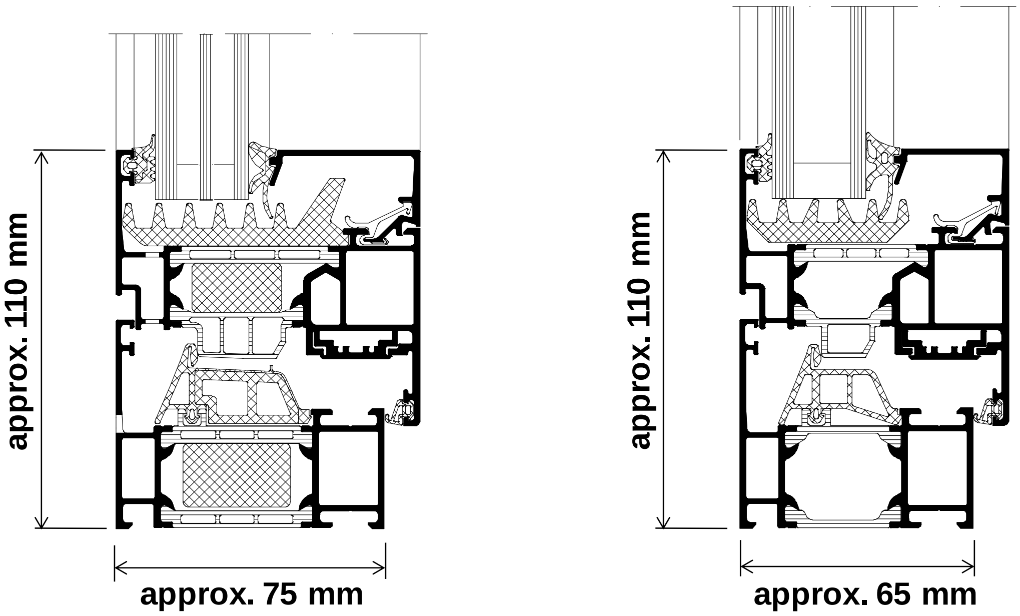


Figure 3-2: Vertical sections of Aluminium window systems (left: Berlin, right: Rome)

Aluminium double tilt & turn window system

- Thermally-broken aluminium profile systems with a depth of approx. 75 mm for Berlin system and approx. 65 mm for Rome, according to glazing depth.
- Manually openable aluminium tilt-turn sash, flush-mounted to the outside window frame.
- Rebate gaskets and polyamide webs with foam core for Berlin-system and without foam core for Rome-system.
- Profile surface: powder-coating.

Timber-Aluminium window system

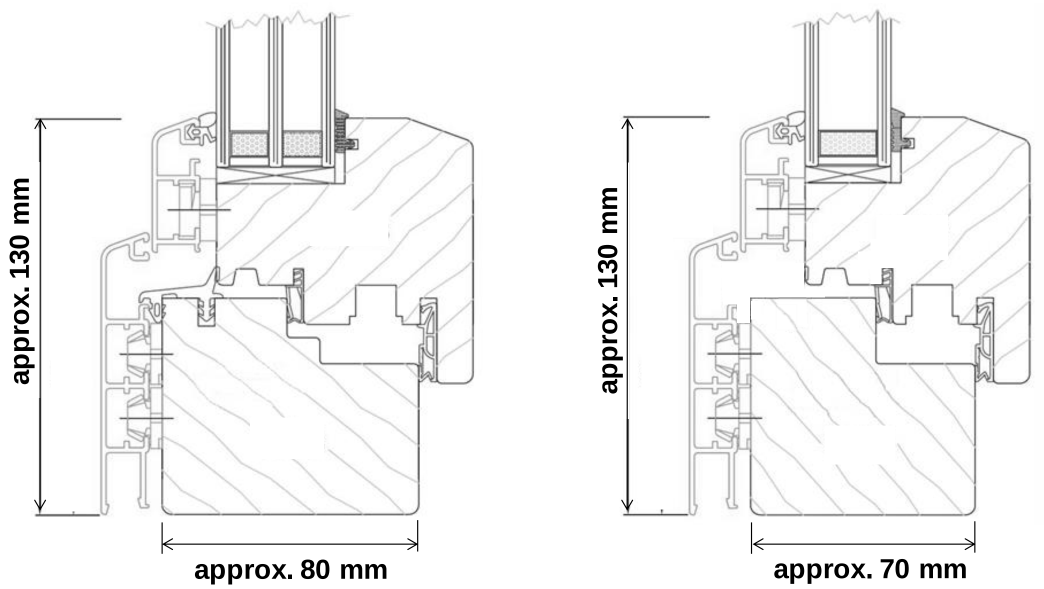


Figure 3-3: Timber-Aluminium window system (Berlin und Rome)

Timber-aluminium double sash window covered by an aluminium shell, back ventilated, fixed to the outside of the timber profiles.

- Timber frame consisting of min. three laminated timber layers of pinewood, approx. 80 mm depth for Berlin and approx. 70 mm depth for Rome according to glazing depth.
- Frame width approx. 130 mm.
- Timber frame corner connection executed with pressed and glued spigot or stud connections.
- Centre profile with glued spigot or stud joint connection.
- Outer aluminium cover shell consisting of mitred aluminium extrusion profiles, back-ventilated fixed via glass-fibre-reinforced polyamide spacer profiles.
- Inner continuous vapour tight membrane connection to sub-structure.
- Outer continuous breather membrane and water tight connection to sub-structure.
- Manually openable timber-aluminium turn-tilt open vent, flush-mounted to the outside window frame.
- Aluminium profile surface: aluminium powder-coating.
- Timber profile surface: breathable transparent timber stain.

Timber window system

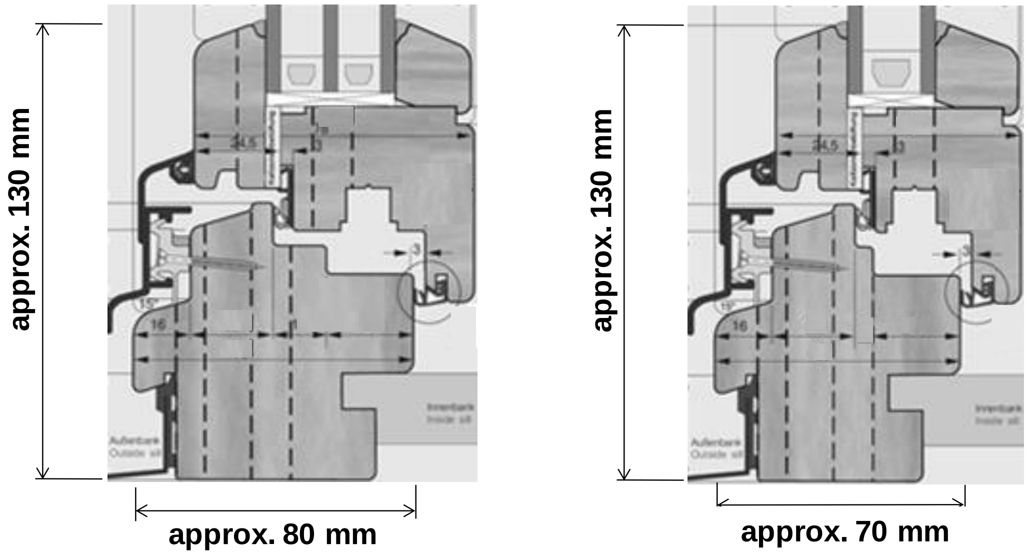


Figure 3-4: Timber window system (Berlin und Rome).

Timber double sash window in frame construction.

- Timber frame consisting of min. three laminated timber layers of pine wood profiles approx. 80 mm depth for Berlin and approx. 70 mm depth for Rome, according to glazing depth.
- Frame width approx. 130 mm.
- Timber frame corner connection executed with pressed and glued spigot or stud connections.
- Centre profile with glued spigot or stud joint connection.
- Inner continuous vapour tight membrane connection to sub-structure.
- Outer continuous breather membrane and water tight connection to sub-structure.
- Manually operable timber turn-tilt open vent, flush-mounted to the outside window frame.
- Timber profile surface: breathable transparent timber stain.
- Rain protection profile.

PVC window systems

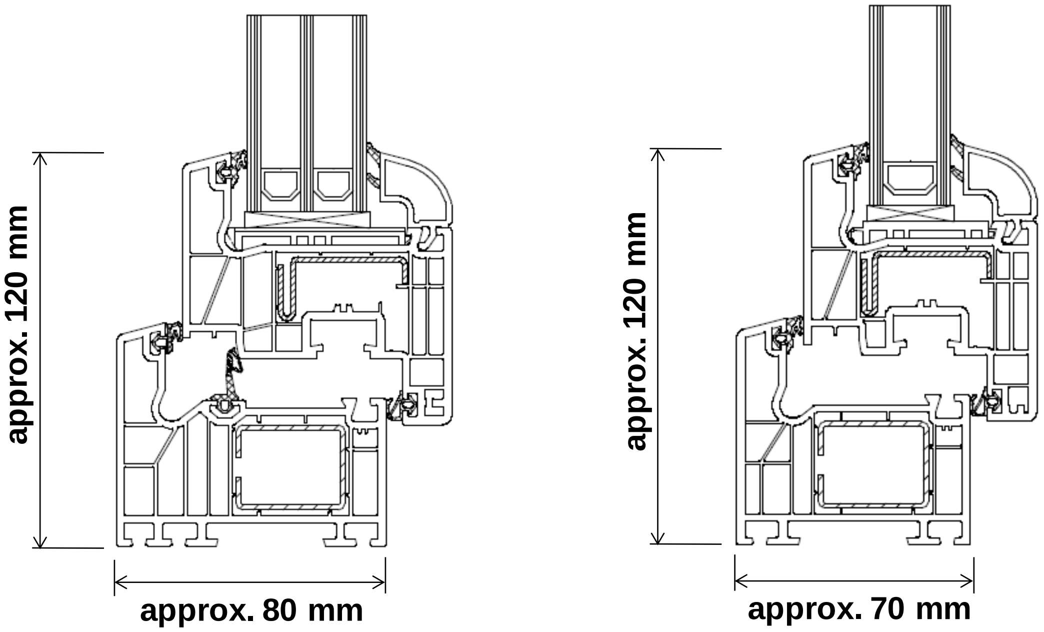


Figure 3-5: Vertical sections of PVC window systems (left: Berlin, right: Rome)

PVC double tilt & turn window system

- The extruded PVC frames consist in multiple chambers with a depth of approx. 80 mm for Berlin and 70 mm for Rome, according to glazing depth, (steel reinforcements).
- Welded corner connections.
- Centre profile with welded profile joint connection.
- Inner continuous vapour tight membrane connection to sub-structure.
- Outer continuous breather membrane and water tight connection to sub-structure
- Surface untreated.

3.2 Curtain wall system for office buildings

3.2.1 General properties of curtain wall systems

The study analyses curtain walling systems made out of three different framing materials: aluminium, glued laminated timber either covered by a wood cap or covered by an aluminium cap.

The light-weight capped stick system is based on a 1,335 mm wide grid, hung from the primary structure to accommodate vertical slab edge deflections out of live-load.

The reference curtain wall of this study is defined as a 3-axis mullion-transom construction for an office area of approximately 20 m² including a tilt and turn window. The general curtain wall specifications are defined for Berlin and Rome as follows:

Dimension:

- Mullion grid: 1,335 mm
- Storey height: 3,500 mm
- Window height: 1,900 mm
- Profile width: 0,050 mm

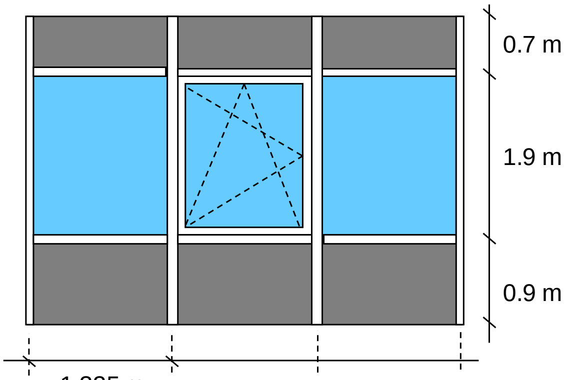


Figure 3-6: Reference curtain wall dimension - Office

Building Physics:	Berlin	Rome
– Glazing:	double-glazing	double-glazing
– U_{cw} reference value:	1.1 W/m²K	1.5 W/m²K
– U_g guidance value:	1.1 W/m²K	1.8 W/m²K
– $U_{f\ Mullion/Transom}$ guidance value:	1.0 W/m²K	1.6 W/m²K
– $U_{f\ Window}$ guidance value:	<1.8 W/m²K	<1.8 W/m²K
– g_{gl} value:	60%	70%
– Light transmission:	>65%	>65%
– Acoustic requirement R_w:	34 dB	34 dB
– Air permeability EN 12207:	Category 4	Category 4

3.2.2 Specific properties of curtain wall systems

The opaque parapet insulated sandwich panel was designed for all three curtain wall systems equally. The parapet consisting of 25 mm plasterboard, 3 mm steel sheets flush and vapour tight with the inner mullion flange, approx. 140 mm mineral wool insulation (thermal conductivity 035) and a cement plate on the outside.

Aluminium mullion and transom system

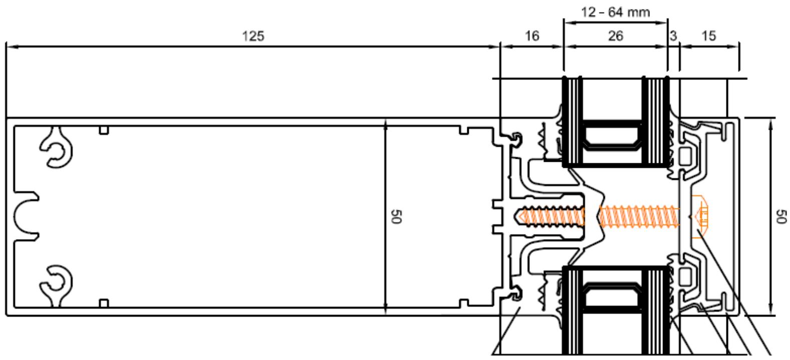


Figure 3-7: Aluminium mullion and transom system (horizontal section)

The curtain wall is mainly a glazed construction providing the primary air and weather tight envelope to the building.

The precise framing details can vary depending on the construction method selected. However, typically, the curtain wall consists in:

- A horizontally continuous floor to ceiling height aluminium stick system installed as curtain wall.
- Capped (50 mm wide and approx. 15 mm deep vertical and 12 mm in depth horizontal aluminium caps) aluminium extruded mullion and transom system hung from steel bracketry fixed to the concrete slab edge and three dimensional adjustable.
- Additional parapet transom acting as safety barrier according to local safety barrier standards.
- Tilt and turn window with U_f < 1.8 W/m²K.
- The glazing is retained with traditional aluminium and EPDM components. The decorative aluminium cap is clipped onto a hidden aluminium profile.
- Mullion dimensions: 50 mm x 125 mm extruded rectangular hollow sections at 1335 mm centres spanning 3500 mm. U_f = approx. 1.0 W/m²K (with Foam) for Berlin approx. 1.6 W/m²K for Rome.
- Transom dimensions: 50 mm x 125 mm extruded aluminium hollow sections at 1600/1900 mm centres.
- Storey height: 3.5 m
- External vertical beads (aluminium) applied to the outside of the mullions.
- External horizontal beads (aluminium) applied to the outside of the transoms.

- Inner vapour tight membrane connection to sub-structure.
- Outer breather membrane and water tight connection to sub-structure.
- Allowance must be made for external replacement of glazing.
- All beads capped at the end.
- Profile surface: aluminium powder-coating.

Timber/Aluminium mullion and transom system

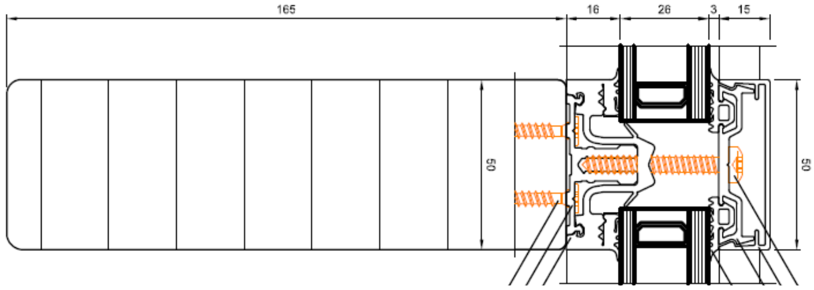


Figure 3-8: Glued-Laminated-Timber mullion and transom system (horizontal section)

The capped timber/aluminium mullion and transom system is based on a 1335 mm wide grid, typically bottom fixed to and in front of the primary structure.

Detailed technical performance description:

- Capped mullion and transom system fixed to the concrete slab edge.
- The caps are 50 mm wide and the vertical caps 15 mm in depth and the horizontal ones 12 mm.
- The glazing is retained by an add-on construction thermally broken including foam core fixed to the substructure with traditional aluminium and EPDM components. The decorative aluminium cover profile is retained by a hidden aluminium profile.
- Tilt and turn window with U_f < 1.8 W/m²K
- Mullion dimensions: 50 mm x 165 mm solid rectangular sections at 1335 mm centres spanning 3500 mm made of glued-laminated timber. Pine tree profiles, U_f = approx. 1.0 W/m²K (with Foam) for Berlin approx. 1.6 W/m²K for Rome.
- Transom dimensions: 50 mm x 165 mm solid rectangular sections at top and bottom of the glazing unit with wooden pins.
- Storey height: 3.5 m
- Inner vapour tight connection to sub-structure.
- Outer breather membrane and water tight connection to sub-structure.
- Profile surface: aluminium powder-coating.
- Timber profile surface: breathable transparent timber stain.

Timber mullion and transom system

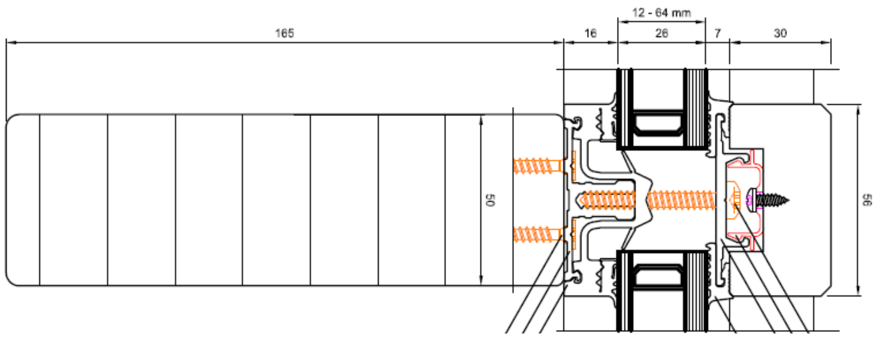


Figure 3-9: Glued-Laminated-Timber mullion and transom system (horizontal section)

The capped timber mullion and transom system is defined with the same specifications as the capped timber/aluminium mullion and transom system, excluding the caps and outer parapet material.

Detailed technical performance description; same construction as Timber/Aluminium curtain wall with the following changes and additions:

- The timber caps are 50 mm wide and 30 mm depth.
- Timber cover cap surface: weather resistant stain.
- Timber profile surface: breathable transparent timber stain.

4 Thermal simulation

The analysis of life cycle assessment (LCA) and life cycle cost (LCC) requires inputs about the energy balance and the CO_2 emission during the use-phase of the studied facade systems. These values will be determined by numerical building simulation using the TRNSYS software. The building simulation will also provide precise values to evaluate indoor thermal comfort with different facade systems. The simulation results are evaluated in units per m² net floor area and anno (unit/m²·a).

4.1 Summary

Thermal simulations are performed either with a reference office room for the different curtain wall systems (aluminium, timber and timber-aluminium) or with a reference residential room using the different selected windows (aluminium, timber, timber-aluminium and PVC).

The compliance of thermal comfort depends mainly on an appropriate heating and cooling concept. All analysed cases reach good thermal comfort level of category I (highest level) for all orientations according to criteria of EN 15251. The simulation does not show any relevant differences on thermal comfort between the curtain wall and window constructions.

Due to the very similar energy performance specifications of the analysed systems, the total energy consumptions resulting from the simulation are almost equal for the various systems compared. For office building, the timber curtain wall reaches a slightly lower energy demand due to lower heat losses. Between the residential systems, the aluminium window achieves the best energy performance, mainly through the slightly greater gain of solar energy in winter resulting from a bigger transparent area (see end energy demand and CO_2- Equivalent in Table 4-1 and Table 4-2.)

Table 4-1: Energy demand of Offices

Office		End energy demand		CO2 emission	
Location	System	Gas	Electricity	Gas	Electricity
		[kWh/m²a]	[kWh/m²a]	[kgCO$_2$/m²a]	[kgCO$_2$/m²a]
Berlin	Aluminium	36,6	17,0	9,5	8,3
	Timber	35,8	17,0	9,3	8,3
	Timber/Aluminium	36,6	16,9	9,5	8,3
Rome	Aluminium	25,1	16,2	6,5	7,9
	Timber	24,9	16,2	6,5	7,9
	Timber/Aluminium	25,1	16,1	6,5	7,9

Table 4-2: Energy demand of Housing

Housing		End energy demand		CO2 emission	
Location	System	Gas	Electricity	Gas	Electricity
		[kWh/m²a]	[kWh/m²a]	[$kgCO_2$/m²a]	[$kgCO_2$/m²a]
Berlin	Aluminium	69,5	7,7	18,1	4,8
	PVC	70,1	7,7	18,3	4,8
	Timber	70,7	7,7	18,4	4,8
	Timber/Aluminium	71,1	7,7	18,6	4,8
Rome	Aluminium	25,9	9,2	6,9	5,1
	PVC	26,5	9,1	7,0	5,0
	Timber	26,8	9,1	7,1	5,0
	Timber/Aluminium	27,0	9,1	7,2	5,0

4.2 Thermal building simulation

The task of thermal building simulation is to model the interaction of HVAC and facade concepts under boundary conditions for typical use scenarios and climates. Using hourly weather data, four office rooms of the building are modelled to compare different office curtain walls and window systems. The main focus is on the resulting room temperatures to evaluate thermal comfort and energy demand for the different curtain wall and window systems serving as boundary condition for the life cycle assessment and life cycle cost for European climates (Berlin and Rome):

- Thermal comfort of room climate over the whole year, basing on room operative temperature. The assessment is carried out according to criteria of EN 15251.
- Specific energy demand in kWh/(m²·a) based on typical use scenarios. CO_2-emission and energy costs will be determined derived from the energy demand.

4.2.1 Simulation model

The reference office and residential room are defined with standard characteristics. Figure 4-1 to Figure 4-4 show the designed office and residential room simulation models and also the energy concept modelled in the simulation.

The office room is designed for two people with a curtain wall in three axes with 1.335 m and 3.5 m height. The curtain wall is equipped with two fixed transparent windows and one openable tilt-turn sash in the middle axis above an opaque parapet insulated sandwich panel. This simulation model will be calculated for four orientations, North, East, South and West, resulting in an average energy demand based on a respective contribution of 15%, 25%, 35% and 25%of each orientation from North to West.

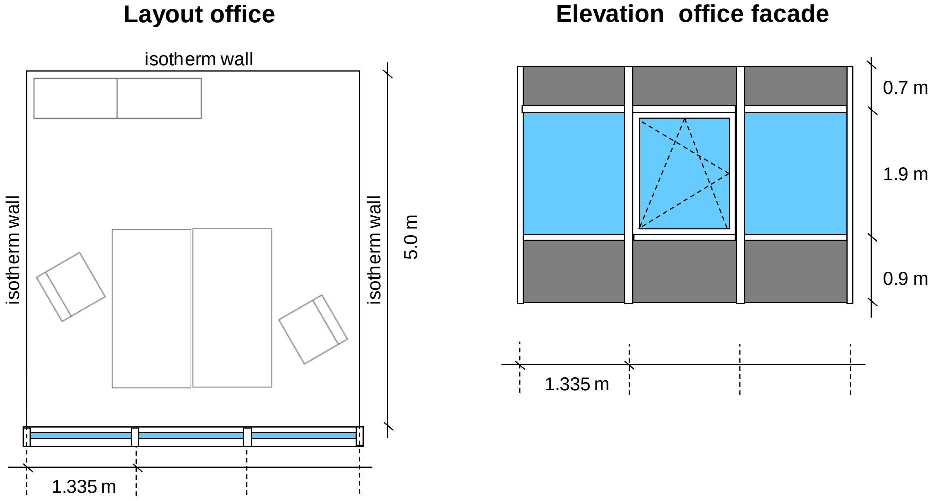


Figure 4-1: Reference office: Layout and Elevation

The main characteristics of the indoor environment concept for office are:

- Double glazing in Berlin, g_{gl}-value = 0.6, U_{cw} = 1.1 W/m²K,
- Double glazing in Rome, g_{gl}-value = 0.7, U_{cw} = 1.5 W/m²K,
- External shading, Fc = 0.25 (average value),
- Forced ventilation by AHU system,
- Radiator below the opening window/panel to cover the heating loads,
- Cooling ceiling.

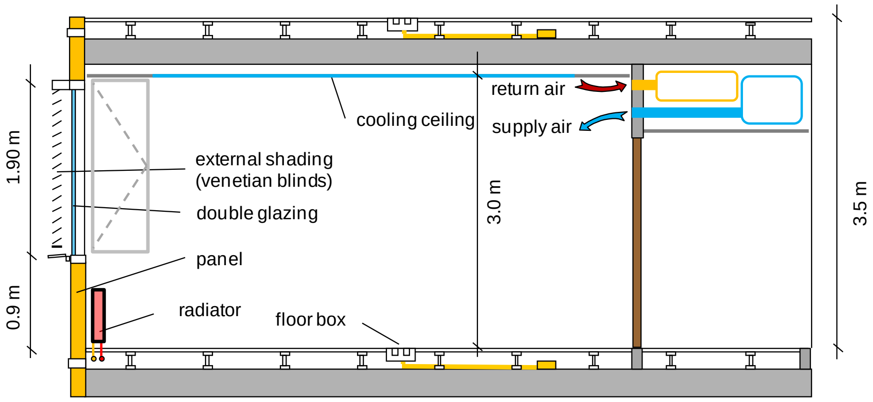


Figure 4-2: Reference office: Energy concept.

The analysis of typical residential rooms is based on a standard casement window measuring 2.5 m x 1.5 m. The window is designed with one tilt-turn and one turn sash installed in a room with 25 m². This simulation model will be calculated for four orientations, North, East, South and West, considering a mean energy demand as sum of each orientation and its respectively fraction as 15 %, 25 %, 35 % and 25 %.

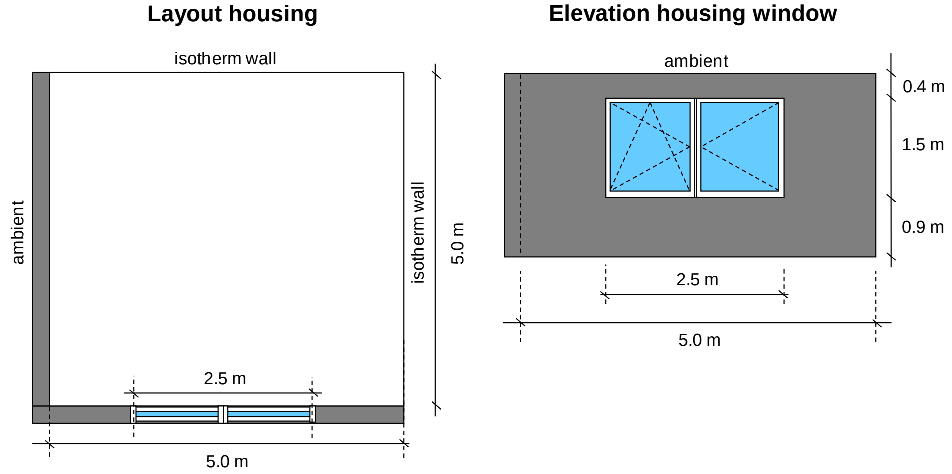


Figure 4-3: Reference housing room: Layout and Elevation

The main characteristics of the indoor environment concept for housing are:

- Triple glazing in Berlin, g_{gl}-value 0.6, Uw = 1.0 W/m²K,
- Double glazing in Rome, g_{gl}-value 0.6, Uw = 2.0 W/m²K,
- External roller/shutter, Fc = 0.3 (average value),
- Natural ventilation by manually operated opening vent,
- Radiator below the opening window/panel to cover the heating loads,
- No cooling in Berlin,
- Split-cooling system in Rome, approx. 9,000 Btu.

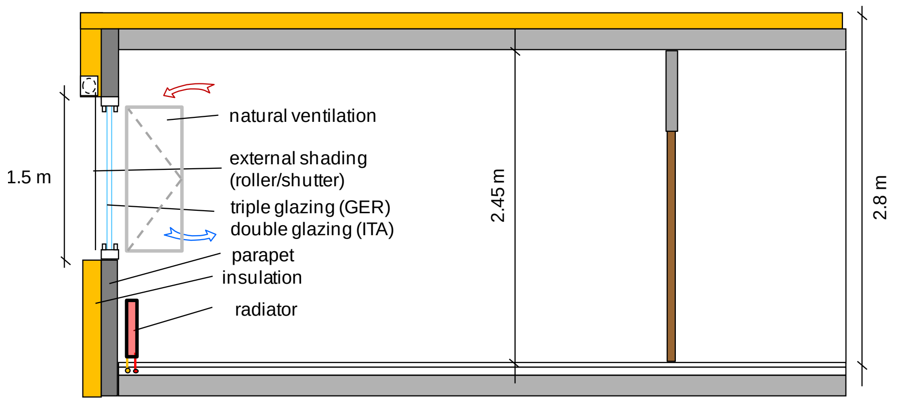


Figure 4-4: Reference housing room: Energy concept

4.2.2 Boundary conditions

The main simulation boundary conditions are summarized in the following sections.

4.2.2.1 Software

The used simulation software is TRNSYS version 15. TRNSYS is validated according to the BESTEST-method and used in the context of comparative calculations of VDI 6020. TRNSYS is also recommended by ASHRAE. The calculations are performed with a time step of one hour.

4.2.2.2 Weather

For Berlin and Rome, weather data files generated by Meteonorm 5 are considered in the simulation. The data sets provide hourly values for one year including outside temperature, outside humidity, wind speed and solar radiation on horizontal surface (diffuse and direct). It represents typical northern and southern European climates. The ambient temperature of the used weather databases vary between approx. -17 °C and 30 °C in Berlin and between -2 °C and 34 °C in Rome.

Heat-island-effects in cities are not considered.

The weather database contains hourly values of:

– Ambient temperature,
– Ambient humidity,
– Wind speed and direction,
– Diffuse and direct solar irradiation.

4.2.2.3 Building parts

Office

Floor slabs: 100 mm hollow floor; 300 mm concrete

Intern wall: 25 mm plasterboard; 50 mm mineral wool; 25 mm plasterboard

Panel: 140 mm insulation 0.035 W/mK

Curtain wall: see Table 4-3

Table 4-3: Boundary conditions of curtain wall systems (office) – Appendix 1.

Standard Façade	Aluminium		Timber		Timber/Aluminium	
	Berlin	Rome	Berlin	Rome	Berlin	Rome
Area glass/frame/panel	6.71 / 1.33 / 5.98 m²		6.67 / 1.39 / 5.89 m²		6.67 / 1.39 / 5.89 m²	
g_{gl}-value of glazing	0.6	0.7	0.6	0.7	0.6	0.7
Light transmission	70 %	75 %	70 %	75 %	70 %	75 %
U_{cw} curtain wall Reference value	1.1 W/m²K	1.5 W/m²K	1.1 W/m²K	1.5 W/m²K	1.1 W/m²K	1.5 W/m²K
U_g glazing Reference value	1.1 W/m²K	1.8 W/m²K	1.1 W/m²K	1.8 W/m²K	1.1 W/m²K	1.8 W/m²K
U_f Mullion/Transom guidance value	1.0 W/m²K	1.6 W/m²K	1.0 W/m²K	1.6 W/m²K	1.0 W/m²K	1.6 W/m²K
U_f window frame guidance value	< 1.8 W/m²K		< 1.8 W/m²K		< 1.8 W/m²K	
Psi-value stainless steel spacer	0.06 W/mK		0.05 W/mK		0.05 W/mK	
Profile facing width	50 mm standard profile 120 mm window profile		50 mm standard profile 130 mm window profile		50 mm standard profile 130 mm window profile	
Profile depth	125 mm		165 mm		165 mm	
Total curtain wall depth	375 mm		425 mm		415 mm	

Housing

Floor slabs: 10 mm flooring; 60 mm screed; 80 mm impact insulation; 200 mm concrete

Roof: 180 mm insulation; 250 mm concrete;

Partition wall: 100 mm brick

Outside wall: 150 mm concrete; 140 mm insulation 0.035 W/mK

Window: see Table 4-4

Table 4-4: Boundary condition of window systems (housing)

Standard Window	Aluminium		PVC		Timber		Timber/Aluminium	
	Berlin	Rome	Berlin	Rome	Berlin	Rome	Berlin	Rome
Area Window/Frame	3.75 / 1.04 m²		3.75 / 1.13 m²		3.75 / 1.21 m²		3.75 / 1.21 m²	
g_{gl} glazing	0.6		0.6		0.6		0.6	
U_g glazing	0.7 W/m²K	1.8 W/m²K	0.7 W/m²K	1.8 W/m²K	0.7 W/m²K	1.8 W/m²K	0.7 W/m²K	1.8 W/m²K
U_f frame	1.3 W/m²K	2.0 W/m²K	1.3 W/m²K	2.0 W/m²K	1.3 W/m²K	2.0 W/m²K	1.3 W/m²K	2.0 W/m²K
U_w window	1.0 W/m²K	2.0 W/m²K	1.0 W/m²K	2.0 W/m²K	1.0 W/m²K	2.0 W/m²K	1.0 W/m²K	2.0 W/m²K
Psi-value stainless steel spacer 1)	0.067 W/mK		0.052 W/mK		0.052 W/mK		0.058 W/mK	
Frame width	110 mm standard frame		120 mm standard frame		130 mm standard frame		130 mm standard frame	

Remark: 1) Source [01]: Measurement from IFT Rosenheim, University of Applied Sciences

4.2.2.4 Shading

Office shading: The shading is controlled according to the incident solar radiation of its curtain wall orientation. The solar shading system is activated, if solar radiation on curtain wall exceeds 200 W/m², and deactivated, if solar irradiation on curtain wall falls below 150 W/m². At night, between 7pm and 7am shading devices are closed.

Housing roller/shutter: activated during the summer and if solar radiation on window exceeds 200 W/m²; deactivated, if solar radiation on window orientation falls below 150 W/m².

A wind-dependent control of the sun shading is not considered in the simulations.

4.2.2.5 Internal load

Office

The occupied period is considered in the simulation on week days from Monday to Friday, from 8 am to 6 pm. A low occupation time of 33 % is considered from 8 am to 9 am, from 5 pm to 6 pm and during the lunch break from 12 to 1 pm. This consideration corresponds to an occupied time period of 8 hours per day.

The office room is occupied by two people and heat loads of 70 W/person and 100 W/workplace for equipments.

Lightings are switched on during the occupied time with 8 W/m², if solar radiation horizontal < 150 W/m² and with 12 W/m² if solar radiation horizontal < 50 W/m².

Housing

The occupied period is from 7 pm to 6 am from Monday to Friday, and 24 h during weekends.

The room is occupied by a theoretical 0.5 person and heat loads of 70 W/person and 2.5 W/m² for equipments.

Lightings are switched on during the occupied time with 5 W/m² between 6 am and 10 pm if solar radiation horizontal < 50 W/m².

General

The occupation profile considers the following conditions:

- The year begins on Monday.
- Holidays are neglected.
- Temperature corrections caused by heat-island-effect are not considered.

4.2.2.6 Air handling unit

Only the office room is equipped with an air handling unit (AHU) with heating and cooling functions and heat recovery of 70 %. Humidity control is not considered. A natural air dehumidification can occur at high ambient humidity. The mean temperature at the cooling coil is 9 °C.

The essential characteristics of mechanical ventilation are considered in the simulation as follows:

- Supply air temperature: 20 °C,
- Operating time period: from Monday to Friday, from 6 am to 8 pm,
- Specific air change rate: 4.5 m³/h.m².

4.2.2.7 Natural ventilation and infiltration

An infiltration rate of 0.1 $^{1}/_{h}$ is considered for all cases as an average value of new and 30 years old facade systems. Increased infiltration of wood or PVC windows over the time will be neglected.

For housing only additionally natural ventilation is considered with air change rate dependant on the air ambient temperature and air temperature gradient between inside and outside, as follow:

- average natural ventilation: 0.5 $^{1}/_{h,}$
- if room air temperature > 25 °C, till 4.0 $^{1}/_{h}$.

4.2.2.8 Heating and cooling

The office rooms in Germany (GER) and Italy (ITA) are equipped with heating and cooling systems. For the estimation of total energy demands, central heating and cooling systems will be taken into account.

Only for housing in Italy air-conditioning is considered as standard system. In Germany there is usually no cooling system in residential buildings. The boundary conditions of the building heating and cooling systems are:

Office

- Specific heating power: max. 40 W/m²
- Heating period: September 1st to April 30th GER
- October 19th to April 30th ITA
- Set point temperature heating: 21.5 °C (Mo-Fr, 5:00 to 19:00)
  18 °C (Mo-Fr, 19:00 to 5:00 and weekend)
- Cooling ceiling: 70 % of net ceiling space
- Specific cooling power: 80 W/m² active area (dT 10K) GER
  90 W/m² active area (dT 10K) ITA
- Set point temperature cooling: 24.5 °C

Housing

- Specific heating power: max. 40 W/m²
- Heating period: September 1st to April 30th GER
  October 19th to April 30th ITA
- Set point temperature heating: 22 °C (Mo-Su, 6:00 to 22:00)
  18 °C (Mo-Su, 22:00 to 6:00)
  18 °C (unoccupied room)
- Cooling system: Split
- Set point temperature cooling: 26.0 °C
- Cooling period: Mo-Fr, 7 pm to 6 am and Weekend 24 h, if occupied

Energy generation

– Heating	Gas boiler (natural gas), efficiency 95% Heating losses 15 %
– Cooling office	Chiller, SEER 4.5 (screw compressor) Cooling losses 5 %
– Cooling housing	Split, SEER 3 (only for ITA)
– Cost of gas:	0.07 €/kWh (GER and ITA)
– Cost of electricity:	0.25 €/kWh (GER) 0.20 €/kWh (ITA)

4.2.3 Thermal comfort according to EN 15251

The EN 15251 describes criteria for categorizing room comfort. On the basis of the Predicted Percentage of Dissatisfied (PPD, ISO 7730), boundary values for room temperature, humidity and indoor air quality are determined for four categories of room comfort. The criteria from category I to category IV are detailed in the following table.

Table 4-5: Design Recommendation according to DIN EN 15251 for Offices

Category	Description	Design indoor temperature	Ventilation rates
I	High expectations, recommended for rooms, for sensitive people with special needs	Winter : 21 °C Summer: 25.5 °C	1.7 – 2.0 l/s m²
II	**Normal expectations, recommended in new buildings and in renovated buildings**	**Winter : 20 °C** **Summer: 26 °C**	**1.2 – 1.4 l/s m²**
III	Acceptable, moderate expectations can be applied in existing buildings	Winter : 19 °C Summer: 27°C	0.7 -0.8 l/s m²
IV	-	-	Values outside of the above categories. This category should occur only for a limited part of the year.

The indoor air quality, draft, temperature asymmetry, gradient of air temperature and mean operative room temperature are the thermal values to describe and to evaluate thermal comfort, which can be influenced by the facade. Due to similar characteristics of the studied systems (e.g. air rate, infiltration etc.), only the operative room temperatures will be taken into account for the thermal comfort assessment. The European norm 15251 recommends thermal comfort of category II for new buildings. This criterion is fulfilled, if the time period with operative room temperature above 26 °C does not exceed 3 %, approx. 80 h/a.

4.3 Results

The results are given in Figure 4-5 to Figure 4-17 as a set of diagrams to compare the curtain wall and window system in Berlin and Rome for office and housing for the south orientation (complete simulation results see appendix 2). The sets of diagrams include:

- **Temperature profiles**
  Diagrams show the evolution of the inner temperature during one week in summer and winter for all systems. The outside temperature is given as well on the right axis. The dashed line shows the operating time as on/off.

- **Frequencies of inner temperature exceeding limits**
  There are two diagrams per curtain wall/window type and room showing frequencies of inner temperatures exceeding upper or lower limits:
  - exceeding upper limits applying standard weather data,
  - undercutting lower limits applying standard weather data.

- **Classification according to EN 15251**
  There are six diagrams showing the classification according to comfort criteria for office of EN 15231. On the x-axis is the moving average of the ambient temperature and on the y-axis the operative room temperature. The red dots represent one hour each during one year of occupied time. The areas coloured blue, green and yellow mark the criteria for the different comfort categories. For example if a red dot is within the blue area, it fulfils the criteria for category I.
  At the bottom there is an evaluation showing the percentage of occurrence for each category during the occupation period. The criteria for a category are fulfilled, when the exceeding of the limits is below 3 % of the occupied time.
  The classification applies only for office buildings.

- **Energy demand, CO_2-emission, Energy cost**
  The graphics show the specific gas and electricity energy demand in kWh per m² net floor area per year, the corresponding emission of carbon dioxide in kg CO_2/m²·a and the corresponding energy cost in €/m²·a .
  Gas consumption: only for heating
  Electricity consumption: for cooling, ventilation and lighting

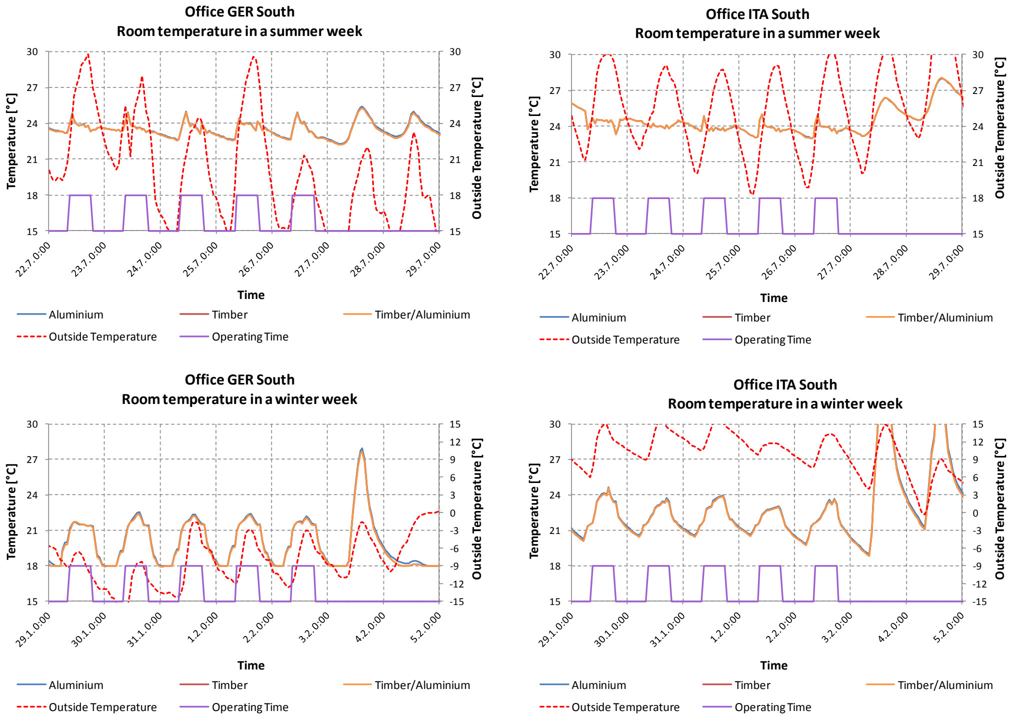


Figure 4-5: Inner and outer Temperature profiles: Office South, summer/winter, GER/ITA

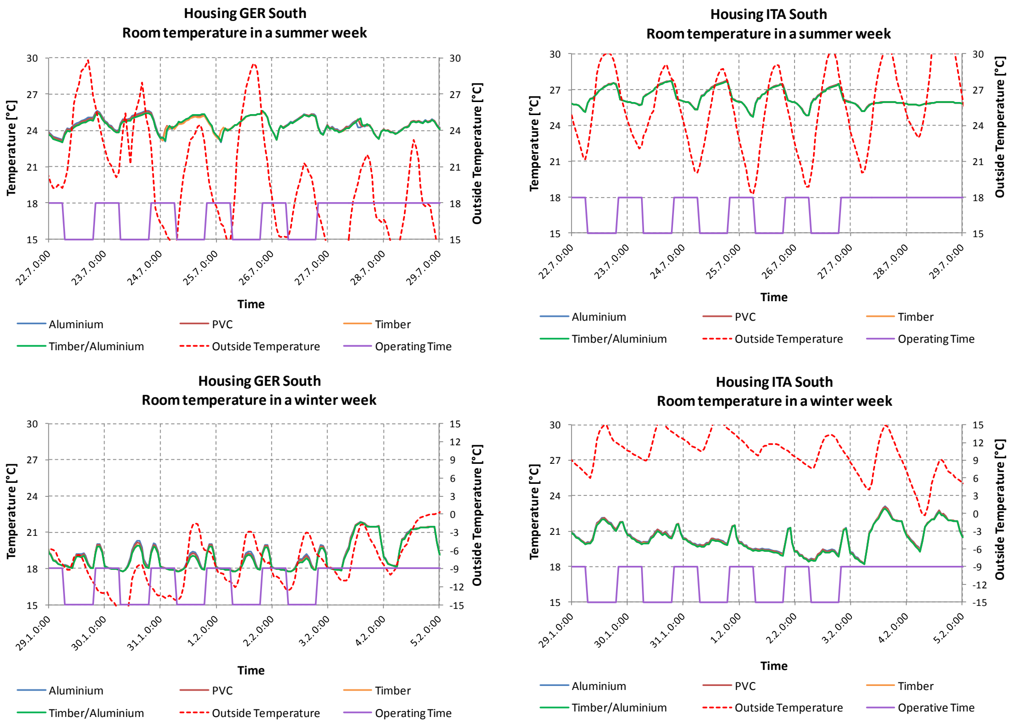


Figure 4-6: Inner and Outer Temperature profiles: Housing South, summer/winter, GER/ITA

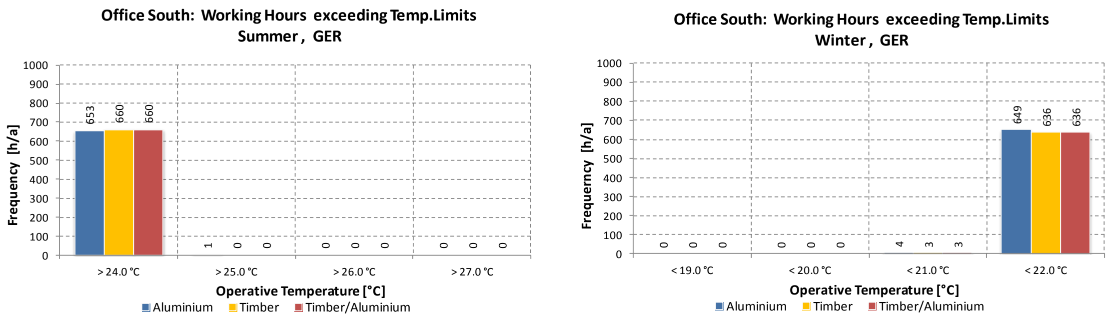


Figure 4-7: Frequency of Operative Temperatures: Office South GER, summer/winter

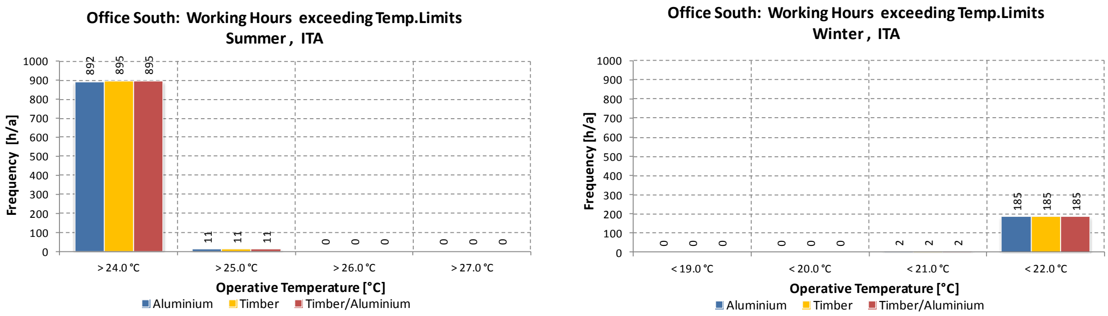


Figure 4-8: Frequency of Operative Temperatures: Office South ITA, summer/winter

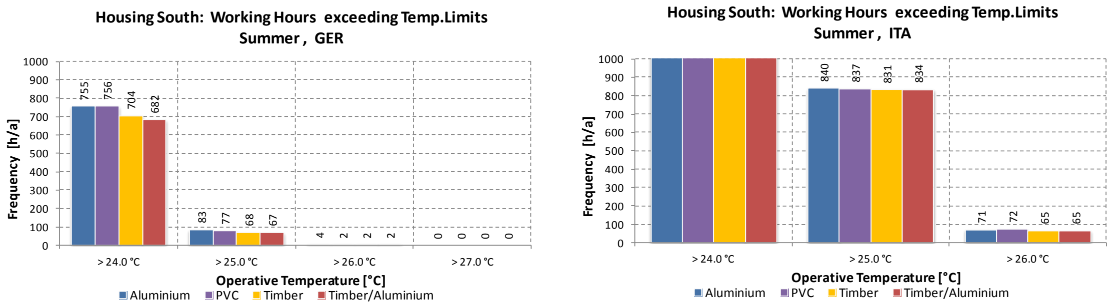


Figure 4-9: Frequency of Operative Temperatures: Housing South GER/ITA, summer/winter

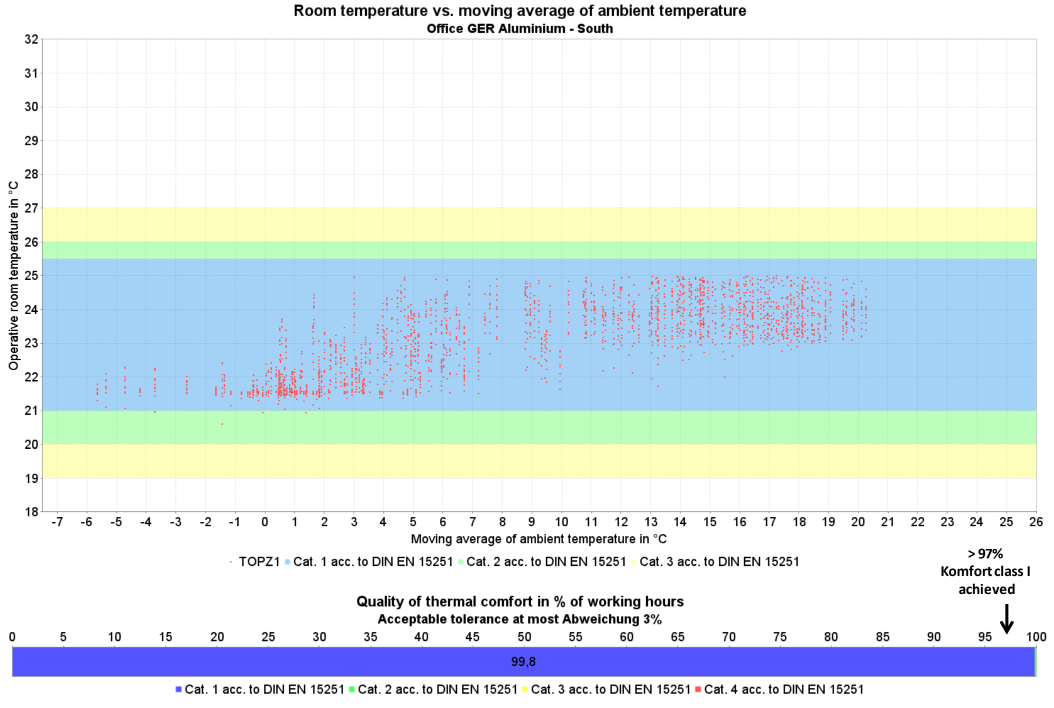


Figure 4-10: Comfort Classification: Office GER Aluminium - South

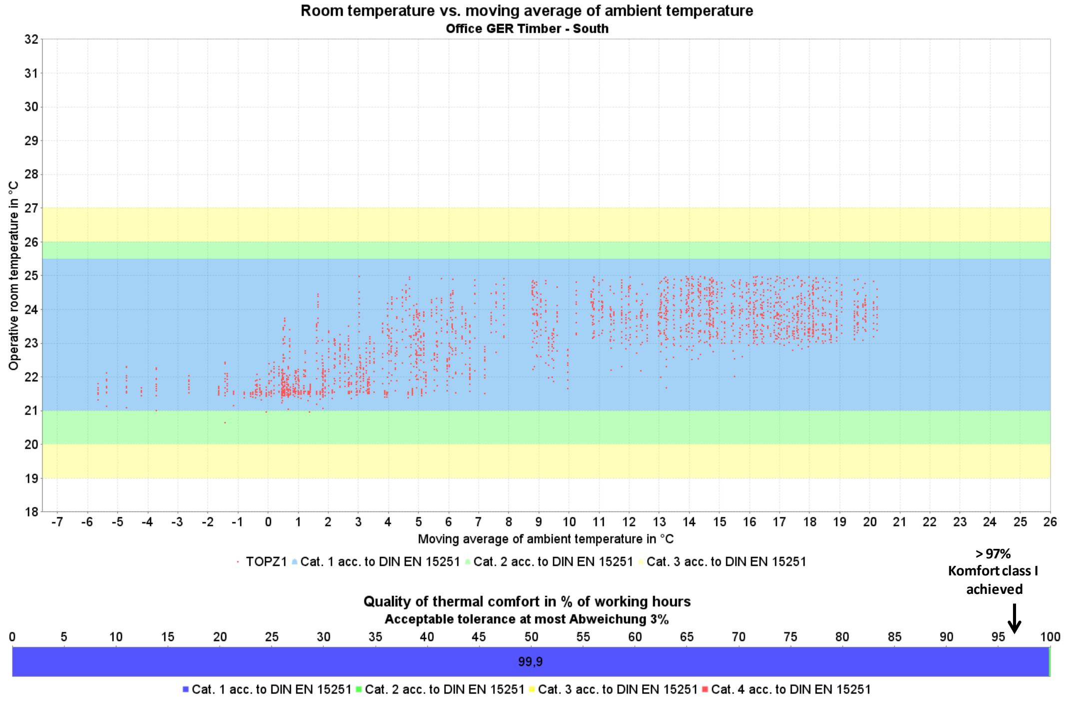


Figure 4-11: Comfort Classification: Office GER Timber - South

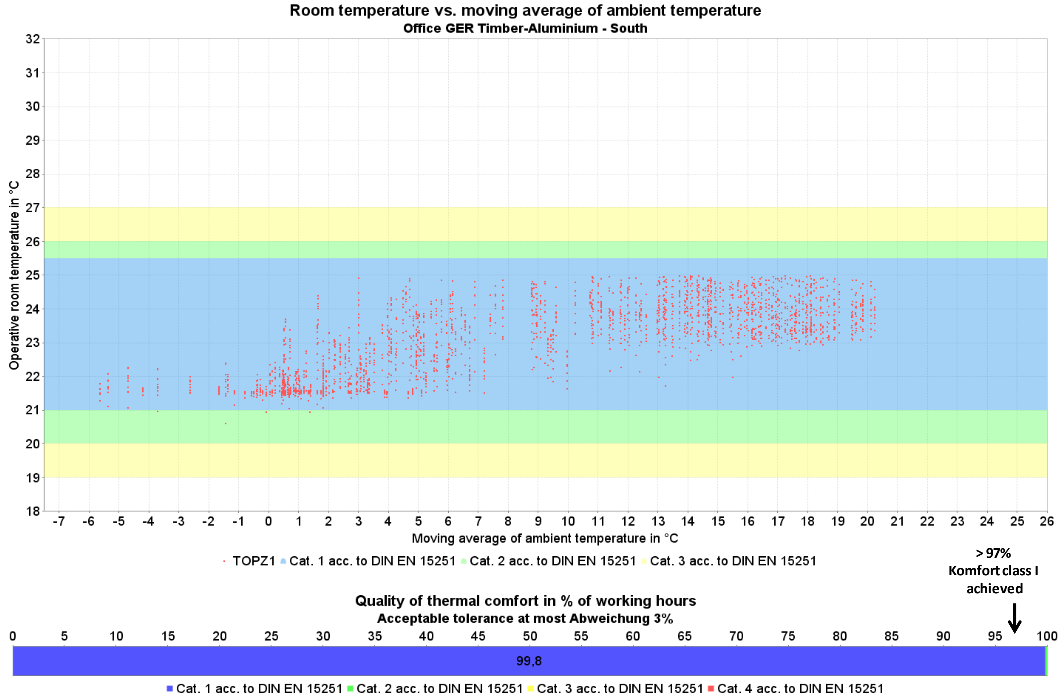


Figure 4-12: Comfort Classification: Office GER Timber-Aluminium - South

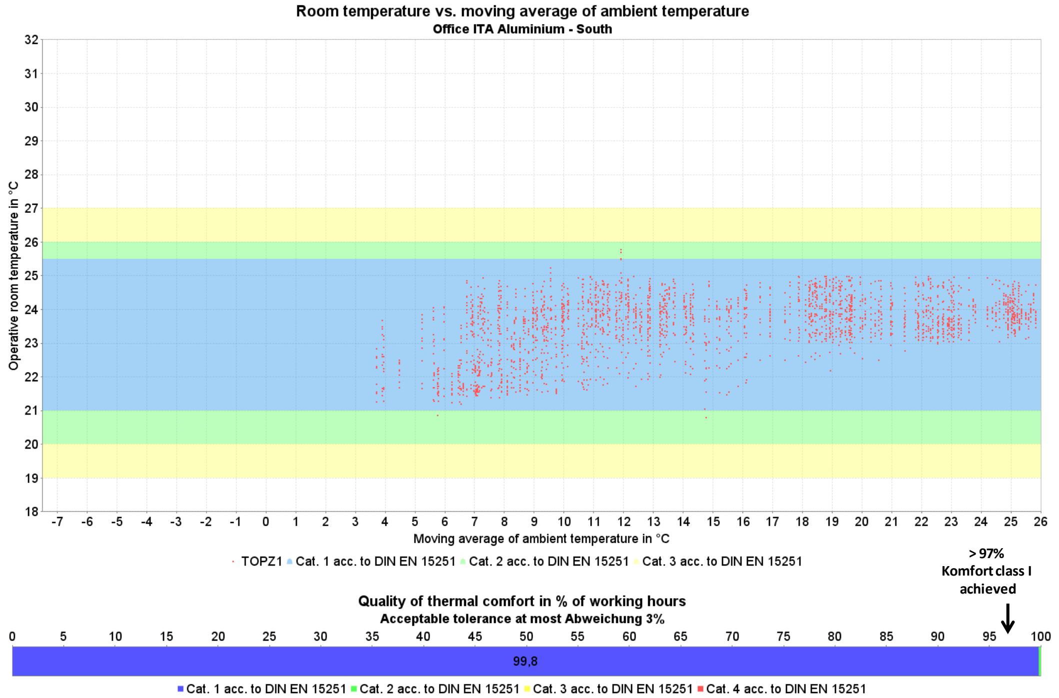


Figure 4-13: Comfort Classification: Office ITA Aluminium – South

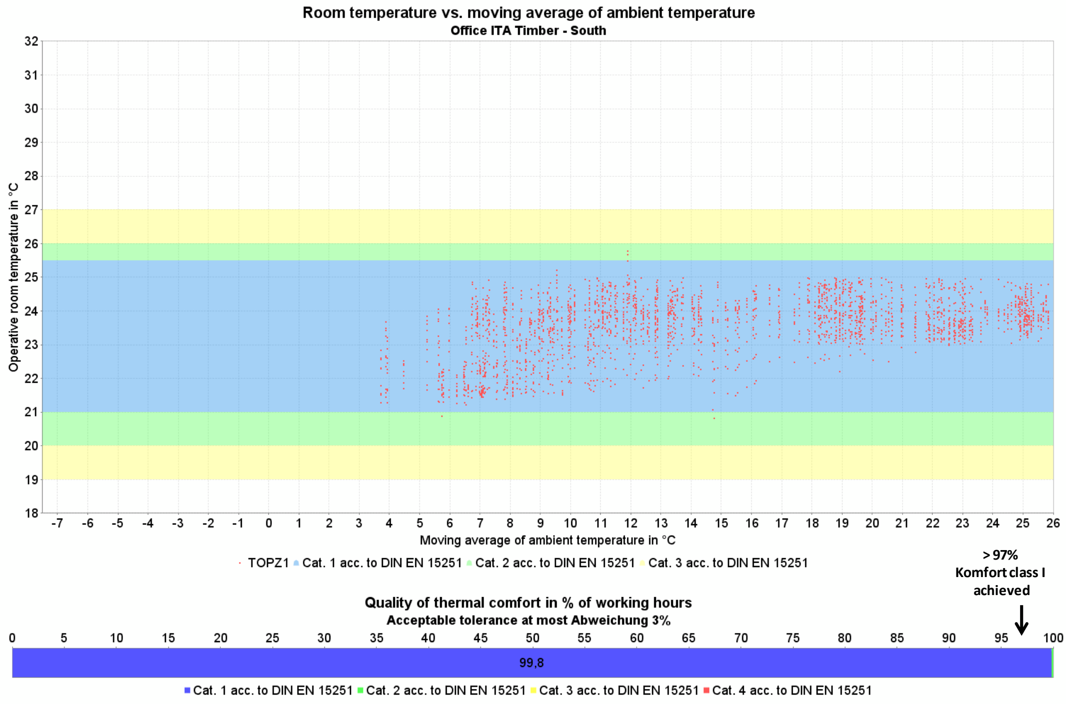


Figure 4-14: Comfort Classification: Office ITA Timber – South

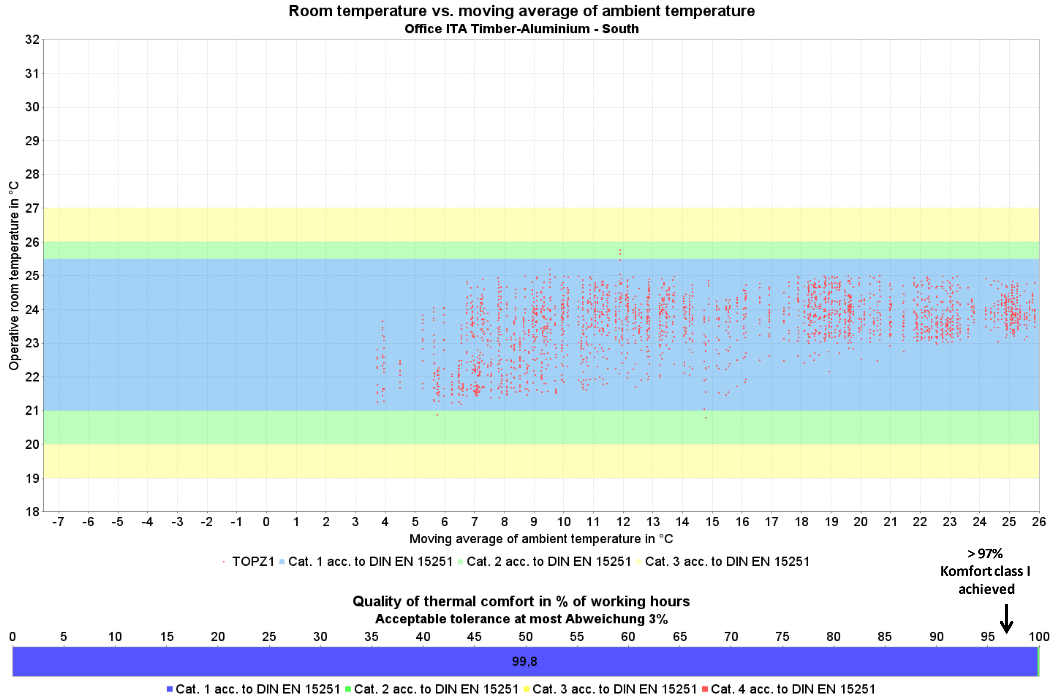


Figure 4-15: Comfort Classification: Office ITA Timber-Aluminium - South

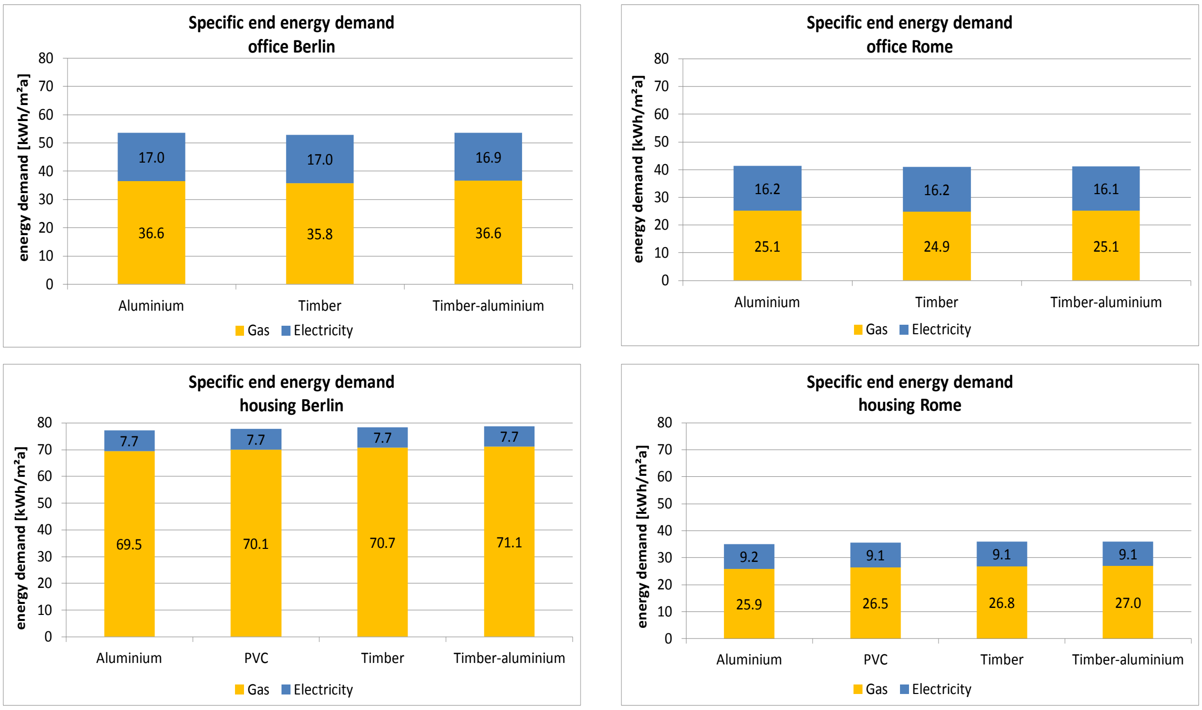


Figure 4-16: **Energy demand in kWh/m²·a (net floor area)**

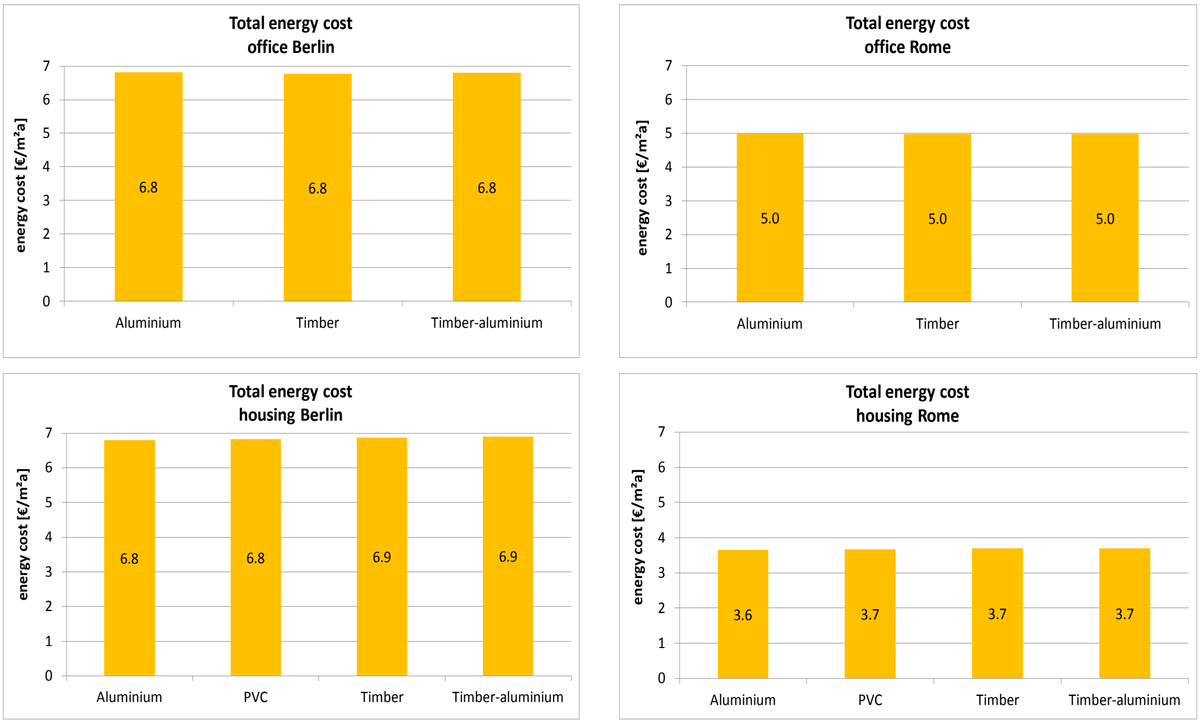


Figure 4-17: **Energy cost in €/m²·a (net floor area)**

5 LCC – Life Cycle Cost analysis

Life-cycle costing is a valuable technique used for predicting and assessing the cost performance of constructed assets. Life-cycle costing is one form of analysis for determining whether a project meets the client's performance requirements (ISO 15686-Part 5).

All costs, from project development to construction and handover of the building, are defined as acquisition costs.

Maintenance and operation costs are determined at net present value over a period of 50 years. Costs are given as a net value per square meter.

The following selected cost categories should be taken into account when calculating building-related life-cycle costs:

- Selected construction costs,
- Selected operation costs,
  - supply and disposal,
  - cleaning,
  - energy consumption,
  - operation,
  - inspection,
  - maintenance,
- Selected residual.

5.1 Summary

For office buildings aluminium has the lowest investment and lowest maintenance costs. Timber is in total about 19% more expensive mainly due to higher maintenance costs for coating every 5 years. Aluminium/timber is rather more expensive (6%) than aluminium due to higher investment costs. Costs for Italy are lower due to lower energy demand and lower investment costs, compared to Germany.

For residential buildings PVC system has the lowest investment costs. Timber is in total 12% and timber-aluminium 5% more expensive than PVC window mainly due to higher maintenance costs for coating every 5 years. Aluminium window is despite lower maintenance costs 3% more expensive than PVC due to significantly higher investment costs. Costs for Italy are lower due to lower energy demand and lower investment costs, compared to Germany.

5.2 Boundary conditions

5.2.1 Investment, maintenance costs and residual value

The investment and maintenance costs consider project experiences and the fair market. The prices at the market may vary, but the differences between the materials are comparable. For this investigation only net values are considered.

The investment costs for office buildings are generally lower for aluminium curtain walls because of the high degree of pre-fabrication and the fast mounting on the construction site. For housing, PVC windows have the lowest investment costs because of the low raw materials costs.

The lifespan of the studied systems is defined according to the German sustainable building rating system [02]. Deviating from [02], the lifespan of PVC window was economically optimized. According to previous calculation, the most economical time for a frame retrofit is 30 years, when glazing must be replaced anyway.

Previously LCC calculation for PVC system was performed assuming a lifespan of 40 years for PVC frame and 30 for glazing. This assumption leads to higher cost than considering a complete retrofit after 30 years (frame + glazing). Therefore, the most economical retrofit model for each material was used in this study. PVC lifespan of 30 years was also assumed in [03].

At the end of life, aluminium frames still get a positive economic value which can be estimated to 75% of the London Metal Exchange (LME) price when using best practices for deconstruction, i.e. when aluminium frames are dismantled and collected in specific containers. Based on today LME price, 1 €/kg of old aluminium profile appears as a reasonable price estimate. The aluminium curtain wall contains about 78 kg of Al, the timber-aluminium façade about 24 kg Al and timber façade 14 kg Al. The aluminium window contains about 32 kg Al and timber-aluminium 12.5 kg Al and timber window 1.5 kg Al. This gives a residual value per m² net floor area of 3.85 €/m^2 for the aluminium façade, 1.19 €/m^2 for timber-aluminium façade, 0.69 €/m^2 (neglected) for timber façade, 1.28 €/m^2 for the aluminium window, 0.5 €/m^2 for timber-aluminium window and 0.06 €/m² (neglected) for timber window. There is no difference of Al quantities between the 2 regions: Rome or Berlin.

Other materials have no residual value.

Table 5-1: Investment, maintenance costs

Net Values	Investment cost		Lifespan		Maintenance description	Maintenance Interval		Maintenance Costs Office	Maintenance Costs Housing
	[€/m² facade]	[€/m² window]	[year]			[year]		[€/m² facade]	[€/m² window]
Investment Costs	Office	Housing	Office	Housing		Office	Housing	Facade 14 m² double glazing 7.1 m²	window 3.75 m³ triple glazing GER double glazing ITA
Aluminium A: GER B: ITA	A: 500 B: 450	A: 380 B: 330	50 years	50 years	1: Fitting check-up and maintenance + 20% Fitting exchange 2: Change of glazing + sealing profile (gasket), frame screew + dismantling, installation and disposal 3: Maintenance raffstore/Roller shutter	1: 10 years 2: 30 years 3: 15 years	1: 10 years 2: 30 years 3: 15 years	1: 4 + 3.5 = 7.5 2A: 77 + 10 = 87 2B: 77 + 10 = 87 3: 7	1: 8 + 7 = 15 2A: 130+20 = 150 2B: 100+20 = 120 3: 27
Timber/Aluminium A: GER B: ITA	A: 550 B: 500	A: 355 B: 310	50 years	50 years	1: Fitting check-up and maintenance + 20% Fitting exchange 2: Change of glazing + sealing profile (gasket), frame screew + dismantling, installation and disposal 3: Maintenance raffstore/Roller shutter 4: Change of Aluminium cover profile	1: 10 years 2: 30 years 3: 15 years 4: 30 years	1: 10 years 2: 30 years 3: 15 years 4: 30 years	1: 4 + 3.5 = 7.5 2A: 77 + 10 = 87 2B: 77 + 10 = 87 3: 7 4: 36	1: 8 + 7 = 15 2A: 130+20 =150 2B: 100+20 = 120 3: 27 4: 36
Timber A: GER B: ITA	A: 550 B: 500	A: 275 B: 245	40 years	30 years	1: Fitting check-up and maintenance + 20% Fitting exchange 2: Installation of new window + dismantling, installation and disposal 3: Maintenance raffstore/Roller shutter 4: Timber Coating	1: 10 years 2: 30 years 3: 15 years 4: 05 years	1: 10 years 2: 30 years 3: 15 years 4: 05 years	1: 4 + 3.5 = 7.5 2A: 77 + 10 = 107 2B: 77 + 10 = 107 3: 7 4: 34	1: 8 + 7 = 15 2A: 275+20 =295 2B: 245+20 = 265 3: 27 4: 45
PVC A: GER B: ITA	NA	A: 220 B: 200	NA	30 years	1: Fitting check-up and maintenance + 20% Fitting exchange 2: Installation of new window + dismantling, installation and disposal 3: Maintenance raffstore/Roller shutter	NA	1: 10 years 2: 30 years 3: 15 years	NA	1: 8 + 7 = 15 2A: 220+20 = 240 2B: 200+20 = 220 3: 27
Raffstores A - 80 mm raffstore, electric motor (GER) B - 80 mm raffstore, electric motor (ITA)	A: 120 B: 135	NA	20 years	NA					
Roller Shutter B - manual control	NA	B: 75	NA	50 years					

Maintenance measures are considered for the exchange of fitting, glazing, sealant profile, raff store/roller shutter for all type of curtain walls and windows. For aluminium/timber frames a change of the aluminium cover profile is considered. For timber frames the necessary coatings are additionally considered [04]. Investment costs indicated above per m2 of window are compatible with cost data reported in the Entranze project[1]. Maintenance and replacement costs and scenarios reported above are also in line with the recent paper published in the Austrian Journal for Engineers and Architects[2].

The difference between façades in Germany and Italy is also considered. For residential buildings they differ in investment and maintenance costs for the dismantling, installation and disposal at exchange of the window due to different price developments at the market.

5.2.2 Interests, energy prices and additional information

These values are based on typical European interest rates and energy prices. The values might differ for different regions and countries but the main objective, the different costs between the frame materials, is representative and independent of the location.

For residential buildings, no cleaning hours are considered because usually windows are cleaned by the occupant.

[1] Fernandez Boneta M., Lapillonne B (2013), Cost of energy efficiency measures in buildings refurbishment: a summary report on target countries, CENER & Enerdata, www.entranze.eu
[2] Lebenszykluskosten von Fenstern – Einfluss der Wartungskosten (Life cycle costs of windows – influence of maintenance costs) Christian Schranz und Hans Georg Jodl, Wien Österreichische Ingenieur- und Architekten-Zeitschrift, 157. Jg., Heft 7–12/2012

The values for the energy demand are separated into gas and electricity and taken over from Table 4-1 and Table 4-2.

Table 5-2: Interests, energy prices and additional information

Description	Office	Housing
Interest rate for discounting (cash value calculation)	4,0%	
General price increase (inflation)	2,0%	
Price increase for energy	5,0%	
Electricity	0,25 €/kWh (GER) / 0,20 €/kWh (ITA)	
Gas	0,07 €/kWh	
Tax Berlin / Rome	19% / 21%	
Hourly rate for cleaning jobs	22,50 €	-

5.3 Results

The boundary conditions gave already a hint about the main differences of the results.

For office buildings the aluminium construction is cheapest choice due to following reasons:

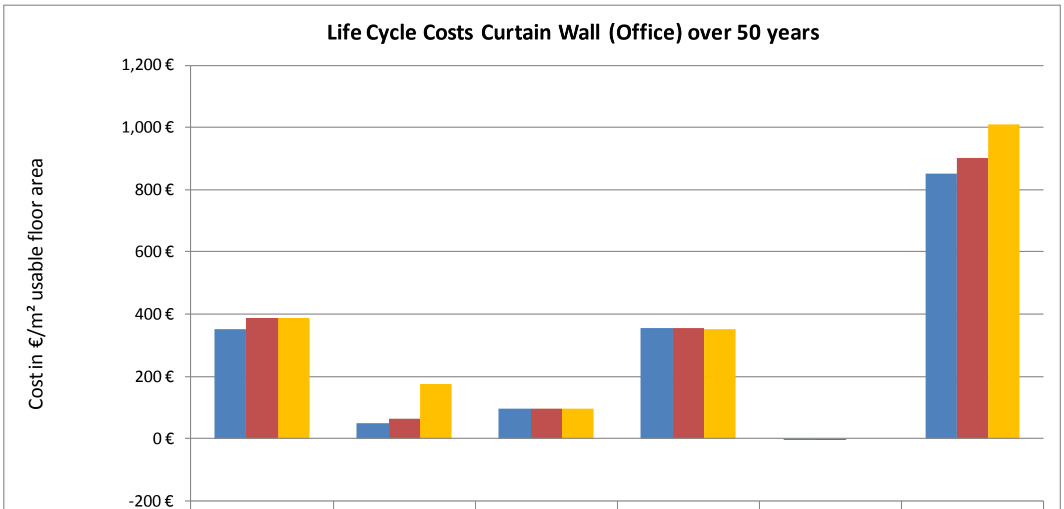
- Lower investment costs,
- Lower irregular costs, which are mainly caused by the coating for timber.

The difference between Germany and Italy results as mentioned already at the boundary conditions from the lower investment costs and lower energy demand.

For residential buildings the PVC window is the cheapest choice because of the low investment costs and the low maintenance costs.

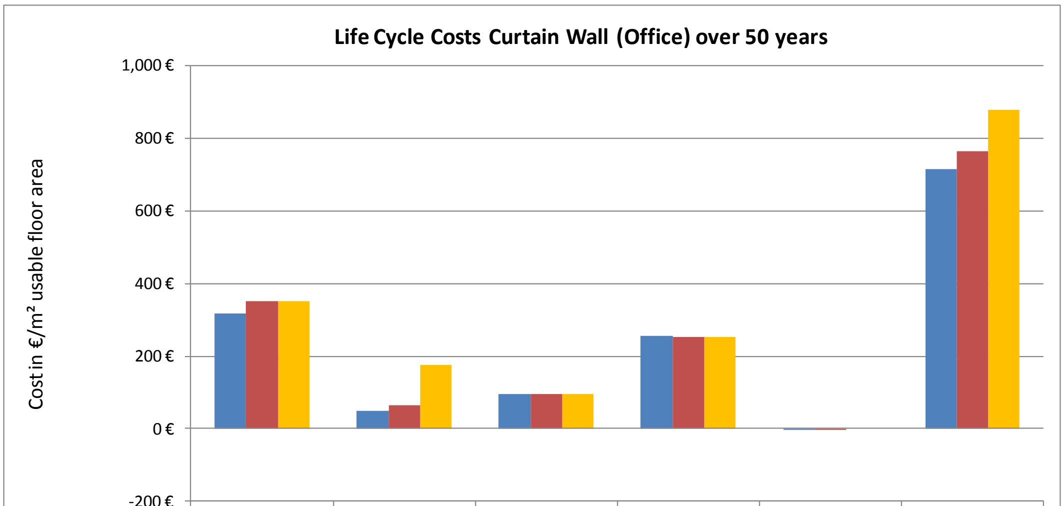
The energy cost for housing indeed a higher influence on the amount of the total result but not on the difference because of the similar values.

The results for Italy are again lower than for Germany because of the reasons mentioned for office buildings.



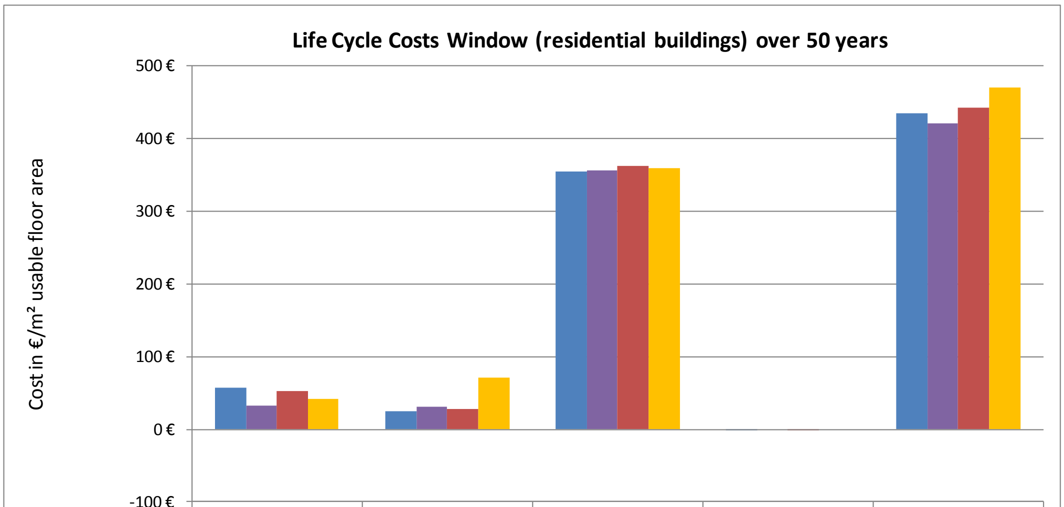
	Investment costs	Maintenance costs	Cleaning costs	Energy costs	Residual value	Total costs
Aluminium	352 €/m²	51 €/m²	96 €/m²	356 €/m²	-4 €/m²	850 €/m²
Aluminium/Timber	386 €/m²	64 €/m²	96 €/m²	354 €/m²	-1 €/m²	900 €/m²
Timber	386 €/m²	175 €/m²	96 €/m²	353 €/m²	0 €/m²	1,010 €/m²

Figure 5-1: Result life-cycle costs office buildings - Germany



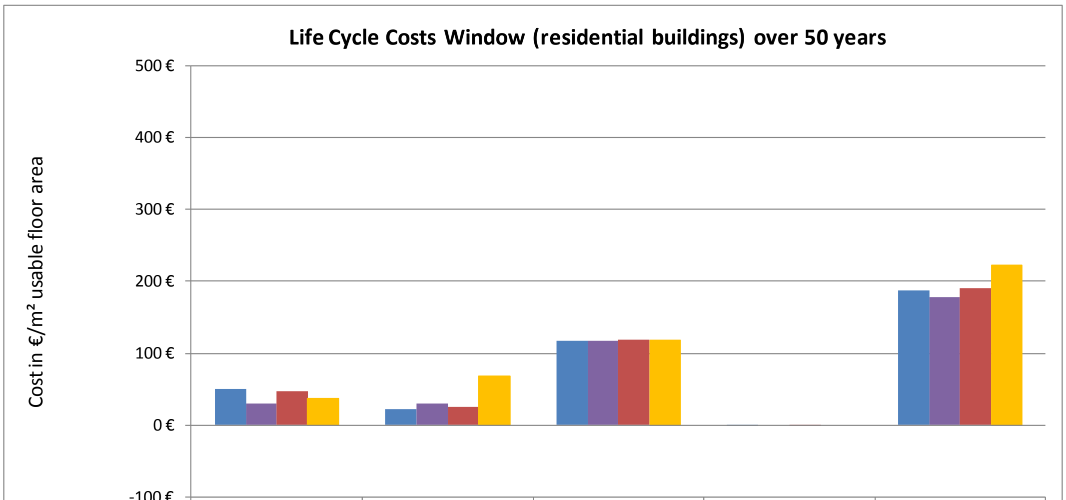
	Investment costs	Maintenance costs	Cleaning costs	Energy costs	Residual value	Total costs
Aluminium	318 €/m²	51 €/m²	96 €/m²	254 €/m²	-4 €/m²	715 €/m²
Aluminium/Timber	352 €/m²	64 €/m²	96 €/m²	253 €/m²	-1 €/m²	765 €/m²
Timber	352 €/m²	175 €/m²	96 €/m²	254 €/m²	0 €/m²	877 €/m²

Figure 5-2: Result life-cycle costs office buildings - Italy



	Investment costs	Maintenance costs	Energy costs	Residual value	Total costs
Aluminium	57 €/m²	25 €/m²	354 €/m²	-1 €/m²	435 €/m²
PVC	33 €/m²	31 €/m²	357 €/m²	0 €/m²	421 €/m²
Aluminium/Timber	53 €/m²	28 €/m²	362 €/m²	-1 €/m²	443 €/m²
Timber	41 €/m²	71 €/m²	359 €/m²	0 €/m²	471 €/m²

Figure 5-3: Result life-cycle costs residential buildings – Germany



	Investment costs	Maintenance costs	Energy costs	Resdual value	Total costs
Aluminium	50 €/m²	23 €/m²	117 €/m²	-1 €/m²	188 €/m²
PVC	30 €/m²	30 €/m²	118 €/m²	0 €/m²	178 €/m²
Aluminium/Timber	47 €/m²	26 €/m²	119 €/m²	-1 €/m²	190 €/m²
Timber	37 €/m²	68 €/m²	118 €/m²	0 €/m²	223 €/m²

Figure 5-4: Result life-cycle costs residential buildings - Italy

6 LCA – Life cycle assessment

Life Cycle Assessment (LCA) is a method to calculate and quantify potential environmental impacts of products and services. The procedures of LCA are part of the ISO 14000 environmental management standards. ISO standard 14040:2006 and 14044:2006 form the framework. A LCA is carried out in four phases.

In the Goal & Scope phase the functional unit is defined, as well as the system boundaries and any limitations and assumptions.

Life Cycle Inventory involves creating the inventory of flows going in and out of the system under study (material and energy balance). This inventory is modelled in the LCA software system GaBi 5.0.

The Life Cycle Impact Assessment phase of LCA is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results. This analysis is done by the LCA software system GaBi 5.0.

In the interpretation phase the results from the LCI and LCA phase are summarized. This is done in this study in Chapter 6.

Results are expressed in category indicators such as Global Warming Potential (GWP) or the Acidification Potential (AP). The calculation of these impacts enables producers and consumers to get knowledge of the potential environmental impacts of their products and services and to get a deep understanding of the key drivers throughout the whole life cycle.

6.1 Summary

A Life Cycle Assessment was done to evaluate the potential environmental impacts of curtain walls and windows. The main goal of this study is to analyse the cradle-to-grave environmental performance of aluminium windows and glazed curtain walls in comparison to competing alternatives. Environmental indicators were calculated with a LCA according to ISO 14044.

Based on standard systems, several curtain walls for office buildings and double tilt/turn windows for residential buildings either for warm (Mediterranean climate, in this study named climate zone Rome) or for cold European climates (Temperate climate, in this study named climate zone Berlin) were analysed. The examined systems are described in more detail in chapter 3. The values of the energy demand are detailed in chapter 4.1. Using this data, a model with the LCA software GaBi 5 was made and the different scenarios were then analysed. In this report the in-depth analysis was done for Global Warming Potential, other indicator results can be found in the Appendix 3.

The most important findings regarding Global Warming Potential are:

When combining manufacturing and end-of-life stages (excluding the energy demand during the use-phase), the LCA results shows that the difference between Global Warming Potential of the same window system in Rome and Berlin is negligible. The outcome does not change significantly if comparing mean and good practice end of life. When the energy demand during the use-phase is included in the

LCA, the overall greenhouse gas emission can vary up to 92 % due to distinct climate conditions.

Under the boundary conditions used in the LCA for this study, results for the entire life cycle of the various window systems show approximately the same Global Warming Potential of 22.4 kg CO_2-eqv./m²·a for climate zone Berlin and 11.6 kg CO_2-eqv./m²·a for climate zone Rome.

Analysing the good practice scenario for curtain walls in Berlin, the Global Warming Potential of the entire life cycle is almost identical for the 3 analysed alternatives since results range only between 19.4 kg CO_2-eqv./m²·a for the timber curtain wall, 19.1 kg CO_2-eqv./m²·a for the timber-aluminium curtain wall and 19.4 kg CO_2-eqv./m²·a for the aluminium curtain wall. For climate zone Rome, the Global Warming Potential ranges 16.2 kg CO_2-eqv./m²·a for the timber façade, 15.7 kg CO_2-eqv./m²·a for the timber-aluminium façade and 16.0 kg CO_2-eqv./m²·a for the aluminium façade. If the energy demand during use phase is excluded from the result, there is a difference of up to 40% between the timber and the timber-aluminium curtain wall and 24% between aluminium and timber-aluminium curtain wall, with timber-aluminium façade having the lowest and timber façade having the highest impact and aluminium curtain wall the middle impact.

The calculation with the scenario mean practice end of life does not change the overall result significantly.

Energy demand during the use phase is the dominant impact in the results of the life cycle assessment. The percentage of the impact of energy demand on the total Global Warming Potential ranges for curtain walls from 88% in Italy up to-93% in Germany and for windows from 97% in Italy up to 98% in Germany.

While the GWP results at manufacturing and end of life stages can appear quite different between the various analysed systems, these differences almost disappear once the contribution of the use phase is included in the LCA results. Indeed, the energy demand of the reference room or reference office largely dominates the overall environmental impact, especially for the GWP indicator. As a result, these differences at manufacturing and end of life stages are not significant from a full LCA perspective.

6.2 System boundaries

The system boundaries were defined following the system description and the ISO 14044:2006.

The product system under study is assessed through a cradle-to-grave LCA. This means covering process steps from construction of the curtain walls/window systems to the End of Life (incineration, landfill, recycling). The following life cycle steps were considered:

- Materials used for the production of the window and curtain wall systems,
- Assembly of the window and curtain wall systems,
- Energy demand during service life,
- Maintenance of window and curtain wall systems (including relevant materials and chemicals)

– End of Life including landfill, incineration and recycling options,
– Handling of production wastes generated in the cradle-to-gate system.

Elements excluded from the system are the energy demand for assembling the window/curtain wall systems, disassembly and separation and transports between supplier, manufacturer, building site and End of Life scenarios. These elements were neglected for the analysis, as they do not have a significant impact to the general results.

Furthermore production capital equipment, human labour and commuting were excluded. These elements are excluded from the product-LCAs, since they are assumed to fall below the cut-off criteria.

6.3 Function and Functional Unit

The function of the facade is generally to provide the primary air and weather tight envelope to the building.

The curtain wall can be made of different materials such as timber, aluminium, glass or steel and can but does not have to include openings. Office curtain walls can be constructed in different ways, this study focuses on different transom-mullion curtain walls which have been identified as market representative based on Drees & Sommer's experience.

The function of a window is to be a transparent or translucent opening in a wall or curtain wall that allows the passage of light and, if not closed or sealed, air and sound

The functional unit in this study is: "Square meter net floor area per year".

The housing room area is 25 m^2 and the office room area is 20 m^2. Total service lifetime is 50 years.

6.4 Data

Data for the aluminium curtain wall (Rome and Berlin) as well as data for the aluminium window and the PVC window (Rome and Berlin) are based on data provided by aluminium and PVC window and façade system companies.

In Europe, the aluminium supply is based on 40% on recycled aluminium[1]. The Aluminium mix (later identified as Aluminium mix.) describes the use of Aluminium with a recycled content of 40%, i.e. the European average, and 60% of primary aluminium. Primary aluminium describes the use of 100% primary aluminium.

Data for PVC Extrusion Profile is based on literature data from Plastics Europe 2010[2]. The used background datasets come from the PE International database. 100% virgin PVC was assumed.

Data for the timber curtain wall and window comes from studies done by PE International. They are calculated based on timber profiles (e.g. IV68 for double glazing

[1] See http://www.alueurope.eu/aluminium-sector-in-europe-2010/
[2] „Eco-profiles oft he European Plastics Industry: PVC Profile Extrusion", TNO, April 2010

windows), cross sections are shown in figure 3.3 and 3.4. Data for the timber curtain wall are dimensioned by Drees & Sommer and calculated from these geometrical data shown in figure 3.8 and 3.9 (curtain wall).

The following data contains the basis for the Life Cycle Assessment.

6.4.1 Construction stage

The Bill of Materials shows the materials needed for the first production of a window or curtain wall, including first time lacquering and fittings. Raff store and shutters are not included. It excludes any material needed for the maintenance or replacement.

Although transparent surface of PVC window is smaller than aluminium window, PVC window has more glazing area due to higher insertion depth than aluminium systems. The table 6-1 shows the total glazing area considered in the LCA calculation.

Table 6-1 Glazing and transparent area of window systems

	PVC	Aluminium	Timber	Timber-aluminium
Glazing area [m^2]	2.82	2.78	2.64	2.59
Transparent area [m^2]	2.62	2.71	2.54	2.54

Table 6-2 Bill of Materials for Aluminium window system (Berlin and Rome)

Window type Aluminium	Climate zone Berlin	Climate zone Rome
Material	[Total kg per window]	[Total kg per window]
Aluminium	32.0	32.8
Timber	0	0
Steel	0.1	0.1
EPDM	5.6	4.5
Zinc die casting	0.2	0.2
Glass	111.3	83.5
Lacquer	0	0
Powder coating	1.9	2.0
PA	8.2	5.8
Insulation foam (PE, PP)	0.3	0.3
PVC	0	0
Total	159.6	129.2

Table 6-3 Bill of Materials for Timber window system

Window type Timber	Climate Zone Berlin	Climate Zone Rome
Material	[Total kg per window]	[Total kg per window]
Aluminium	1.5	1.5
Timber	54.6	43.0
Steel	3.3	3.3
EPDM	1.8	1.8
Zinc die casting	0.5	0.5
Glass	105.6	79.2
Lacquer	2.0	2.0
Powder coating	0.2	0.2
PA	0	0
Insulation foam (PE, PP)	0	0
PVC	0	0
Total	169.5	131.5

Table 6-4 Bill of Materials for Timber-Aluminium window system

Window type Timber-Aluminium	Climate Zone Berlin	Climate Zone Rome
Material	[Total kg per window]	[Total kg per window]
Aluminium	12.5	12.5
Timber	41.1	32.4
Steel	4.9	4.9
EPDM	3.6	3.6
Zinc die casting	0.6	0.6
Glass	103.6	77.7
Lacquer	2.0	2.0
Powder coating	0.8	0.8
PA	0.1	0.1
Insulation foam (PE, PP)	0	0
PVC	0	0
Total	169.2	134.6

Table 6-5 Bill of Materials for PVC window system

Window type PVC	Climate zone Berlin	Climate zone Rome
Material	[Total kg per window]	[Total kg per window]
Aluminium	0	0
Timber	0	0
Steel	23.0	21.7
EPDM	0	0
Zinc die casting	0.1	0.1
Glass	112.8	84.6
Lacquer	0	0
Powder coating	0	0
PA	0	0
Insulation foam (PE, PP)	0	0
PVC	26.7	30.0
Total	162.6	136.4

Table 6-6 Bill of Materials for Aluminium curtain wall system

Curtain wall type Aluminium	Climate zone Berlin	Climate zone Rome
Material	[Total kg per curtain wall]	[Total kg per curtain wall]
Aluminium	77.6	78.0
Timber	0	0
Steel	131.8	131.6
EPDM	15.9	12.6
Zinc die casting	0.8	0.8
Glass	205.1	205.1
Lacquer	0	0
Powder coating	4.7	4.7
PA	5.3	4.2
PVC, PP	1.9	4.6
Mineral wool	38.5	38.5
Butyl rubber	0	1.3
Cement panel (Eternit)	194.3	194.3
Gypsum board	74.7	74.7
Spacer strip	16.8	16.8
Total	767.5	767.2

Table 6-7 Bill of Materials for Timber-Aluminium curtain wall system

Curtain wall type Tim-ber/Aluminium	Climate zone Berlin	Climate zone Rome
Material	[Total kg per curtain wall]	[Total kg per curtain wall]
Aluminium	24.1	24.1
Timber	76.0	60.2
Steel	134.2	134.2
EPDM	8.4	8.4
Zinc die casting	0.3	0.3
Glass	203.8	203.8
Lacquer	2.2	2.2
Powder coating	1.4	1.4
PA	0	0
Insulating foam (PE.PP) (Berlin)	0	0
PVC. PP (Rome)	0	0
Mineral wool	38.5	38.5
Butyl rubber	0	0
Cement panel (Eternit)	194.3	194.3
Gypsum board	74.7	74.7
Spacer strip	16.8	16.8
Total	774.8	759.0

Table 6-8 Bill of Materials for Timber curtain wall system

Curtain wall type Timber	Climate zone Berlin	Climate zone Rome
Material	[Total kg per curtain wall]	[Total kg per curtain wall]
Aluminium	14.2	14.2
Timber	95.3	75.7
Steel	133.4	133.4
EPDM	7.6	7.6
Zinc die casting	0.2	0.2
Glass	198.8	198.8
Lacquer	4.3	4.3
Powder coating	0.9	0.9
PA	0	0
Insulating foam (PE,PP)	0	0
Mineral wool	38.5	38.5
Butyl rubber	0	0
Cement panel (Eternit)	194.3	194.3
Gypsum board	74.7	74.7
Spacer strip (PP)	16.8	16.8
Total	779.1	759.5

6.4.2 Use and Maintenance

Energy values are based on the calculated energy demand (see Chapter 4). Energy demand was separated in electricity demand and demand of thermal energy and modelled accordingly in the GaBi software.

The LCA calculation have been performed based on Maintenance and replacement scenarios reported in Table 6-9 and Table 6-10. These scenarios are the same as those used for the life cycle costing which are reported in Table 5-1. In the table the replacement and maintenance scenarios can be seen. After a certain amount of years (as seen in the first column) either a maintenance or replacement action will take place. Fittings 20% means, that 20% of the fittings by weight are replaced.

After the typical lifespan of a window or curtain wall is elapsed, a full new unit was used (Replacement). Timber and PVC windows are replaced once, the timber curtain wall is also replaced once. Since the turn/tilt window would have been replaced after 30 years and the complete curtain wall after 40 years, instead the complete curtain wall is exchanged after 30 years.

Table 6-9 Maintenance and replacement scenarios - Window

Window				
Year	Timber (30 years)*	Timber/Aluminium (50 years)*	PVC (30 years)*	Aluminium (50 years)*
5	Lacquer outside			
10	Lacquer inside Lacquer outside	Lacquer inside	Fittings 20%	Fittings 20%
	Fittings 20%	Fittings 20%		
15	Lacquer outside			
20	Lacquer inside Lacquer outside	Lacquer inside	Fittings 20%	Fittings 20%
	Fittings 20%	Fittings 20%		
25	Lacquer outside			
30	Replacement of window	Renew gaskets and glazing	Replacement of window	Renew gaskets and glazing
		Renew Aluminium cover profile (window)		Fittings 20%
		Fittings 20%		Screws for frame
		Lacquer inside		
		Screws for frame (window)		
35	Lacquer outside			
40	Lacquer inside Lacquer outside	Lacquer inside	Fittings 20%	Fittings 20%
	Fittings 20%	Fittings 20%		
45	Lacquer outside			
50	EOL	EOL	EOL	EOL

*Typical life span of the window

Table 6-10 Maintenance and replacement scenarios - Curtain wall

Curtain wall			
Year	Timber (40 years)*	Timber/Aluminium (50 years)*	Aluminium (50 years)*
5	Lacquer outside		
10	Lacquer inside/outside	Lacquer inside	Fittings 20%
	Fittings 20%	Fittings 20%	
15	Lacquer outside		
20	Lacquer inside/outside	Lacquer inside	Fittings 20%
	Fittings 20%	Fittings 20%	
25	Lacquer outside		
30	Replacement of curtain wall	Renew gaskets and glaz-ing	Renew gaskets and glaz-ing
		Renew Aluminium cover profile (window)	Fittings 20%
		Fittings 20%	Screws for frame
		Lacquer inside	
		Screws for frame	
35	Lacquer outside		
40	Lacquer inside/outside	Lacquer inside	Fittings 20%
	Fittings 20%	Fittings 20%	
45	Lacquer outside		
50	EOL	EOL	EOL

***Typical life span of the curtain wall**

6.4.3 End of Life (EoL)

Following scenarios were assumed for the End of Life:

Table 6-11 Good Practice End of Life Scenarios

Material	Collection rate	Material recycling yield	Total EoL recycling rate	Substitution
Aluminium	99% for recycling 1% for landfill	98%	97%	Primary Aluminium ingot
PVC	90% for recycling 10% for landfill	77%	69%	PVC granulate
Steel	90% for recycling (*) 10% for landfill	90%	81%	Steel billet
Wood	90% for incineration 10% for landfill	0%	0%	Energy recovery
Glass	100% for landfill	0%	0%	Inert material
Mineral wool	100% for landfill	0%	0%	Inert material
Plastics (PP,PA,PE)	100% for incineration	0%	0%	Energy recovery
Cement panel	100% for landfill	0%	0%	Inert material
Gypsum board	100% for landfill	0%	0%	Inert material

(*) Steel is present in PVC and wood windows as reinforcement elements integrated into PVC or wood. Hence, end of life scenarios are the same as for PVC or wood. End of life scenarios for steel sheet from curtain wall were assumed to be the same as the scenario for steel components integrated in PVC or wood frames. These scenarios are not reflecting the usual high recycling rate for such big metal pieces. However, this simplification does not affect the comparison since all curtain walls contains almost the same quantity of steel sheet. It is assumed that small steel parts such as screws will not be separated and will go to the landfill.

Further explanation of assumptions of good practice end of life scenarios, Table 6-11:

Collection rates:

– The Collection rate of the Al-window/façade is 99% due to high price of Al scrap. Windows and curtain walls are big parts which are entirely collected (almost no loss at deconstruction site). Hence, only 1% loss is assumed from deconstruction/dismantling. This correlates properly with results from studies referenced below.[1] [2]
– The Collection rate of the PVC window is 90% considering the significant efforts of PVC producers to organise the collection of old PVC frames and to integrate recycled PVC in their material supply. The same collection rate is taken for steel in the PVC window.
– For the timber window and curtain wall as for the PVC window, a collection rate of 90% is assumed.

Recycling yield (materials not recycled are considered to be deposited):

– For Aluminium EAA recycling data for scrap is used.
– For PVC German data from the recycling plants are used, a yield of 77% regarding the PVC[3] [4]and 96% regarding the steel can be stated.

[1] Graue Energie von Bauprodukten unter Berücksichtigung der wertkorrigierten Substitution“, EMPA, 2004
[2] Collection of Aluminium from Buildings in Europe, TU Delft study for EAA , 2004
[3] Kunststofffenster Recycling in Zahlen 2011, Rewindo GmbH, 2011
[4] Progress report 2013, VinylPlus, 2013

- The timber frames are incinerated in a waste incineration plant with the required flue gas treatment (average European technology)[1]

Credits:

- Recycled Aluminium: substitutes primary aluminium ingot
- Recycled PVC substitutes primary PVC window compound and recycled steel from re-enforcing steel substitutes steel billet. It has to be noted that no correction factor (i.e. reflecting a downgrading or the inability to fully substitute primary PVC) has been applied for recycled PVC which is quite optimistic since PVC cannot fully substitute primary PVC in term of aesthetics (e.g. colour) and mechanical properties. On the other side, this assumption is balanced by the recycling yield of 77% which is probably quite low considering the recent efforts of the PVC industry in this area.
- No credits for energy recovery are taken into consideration for electricity from landfilled wood.
- Credits for energy recovery of wood and other plastics are taken into account.

Table 6-12 Mean Practice End of Life Scenarios

Material	Collection rate	Material recycling yield	Total EoL recycling rate	Substitution
Aluminium	97% for recycling 3% for landfill	98%	95%	Primary Aluminium ingot
PVC	50% for recycling 50% for landfill	50%	25%	PVC granulate
Steel (*)	50% for recycling 50% for landfill	90%	45%	Steel billet
Wood	50% for incineration 50% for landfill	0%	0%	Energy recovery
Glass	100% for landfill	0%	0%	Inert material
Mineral wool	100% for landfill	0%	0%	Inert material
Plastics (PP,PA,PE)	100% for incineration	0%	0%	Energy recovery
Cement panel	100% for landfill	0%	0%	Inert material
Gypsum board	100% for landfill	0%	0%	Inert material

(*) Steel is present in PVC and wood windows as hardware or reinforcement elements integrated into PVC or wood profiles. Hence, end of life scenarios are the same as for PVC or wood profiles. End of life Scenarios for steel sheet from curtain wall were assumed to be the same as the scenario for steel components integrated in PVC or wood frames. These scenarios are not reflecting the usual high recycling rate for such big metal pieces. However, this simplification does not affect the comparison since all curtain walls contains almost the same quantity of steel sheet. For other small steel parts (e.g. screws), it is assumed that they are not separated and will go to landfill.

The current scenario of end of life is described in the Table 6-12 (Mean practice end of life scenario). Further explanations regarding mean practice end of life:

Collection rates:

[1] Waste incineration of wood products (OSB, particle board), GaBi Database documentation: http://gabi-documentation-2013.gabi-software.com/xml-data/processes/39f61d7a-9cea-4e61-b292-50ad6ee05ccc.xml

- The Collection rate of the Al-window/façade is 97% due to high price of Al scrap. Studies[1] [2] have effectively shown that the collection rate of aluminium products from demolition sites was above 96% on average with a systematic collection of big elements like profiles or sheets. Hence, 97% is realistic estimate for aluminium framing parts.
- The Collection rate of the PVC window is 50% reflecting the average situation. The same collection rate is taken for steel in the PVC window.
- For the timber window/curtain wall the same scenario is assumed as for PVC.

Recycling yield:

- For Aluminium EAA recycling data for scrap is used which result in 2% of metal losses from the scrap reparation (i.e. mainly cutting/crushing) and melting.
- For PVC windows, a material recycling yield of 50% regarding the PVC and 90% regarding the steel can be stated.
- The timber frames are incinerated in a waste incineration plant with the required flue gas treatment (average European technology)[3]

Credits:

- Recycled Aluminium: substitutes primary aluminium ingot
- Recycled PVC substitutes primary PVC window compound and steel recycled from re-enforcement parts substitutes steel billet. It has to be noted that no correction factor (i.e. reflecting a downgrading or the inability to fully substitute primary PVC) has been applied for recycled PVC which is quite optimistic since PVC cannot fully substitute primary PVC in term of aesthetics (e.g. colour) and mechanical properties. The low recycling yield balances to some extent this optimistic assumption.
- No credits for energy recovery are taken into consideration for electricity from landfilling wood.
- Credits for energy recovery of wood and other plastics are taken into account.

[1] Collection of Aluminium from Buildings in Europe, TU Delft study for EAA , 2004
[2] Graue Energie von Bauprodukten unter Berücksichtigung der wertkorrigierten Substitution“, EMPA, 2004
[3] Waste incineration of wood products (OSB, particle board), GaBi Database documentation: http://gabi-documentation-2013.gabi-software.com/xml-data/processes/39f61d7a-9cea-4e61-b292-50ad6ee05ccc.xml

6.5 Software and database

The LCA model is created using the GaBi 5 Software system for life cycle engineering, developed by PE International. The GaBi database provides the life cycle inventory data for ancillary materials, fuels and energy obtained from the background system.

6.6 Results

The following section describes, discusses and interprets the results. The results are specific for this study due to the boundary conditions used. The details of the boundary conditions for the use phase can be found in Chapter 4.2.2. For each impact category, the corresponding indicator is calculated per square meter room area per year of office or housing. The housing room area is 25 m^2 and the office room area is 20 m^2. Total service lifetime is 50 years. The results include manufacturing, use phase and End of Life. Table 6-13 below summarizes the main indicators used in the life cycle impact assessment and provides abbreviations and units used in all relevant graphs and tables below.

Table 6-13 Category Indicators measured, short names and units

Method used	Category Indicators	Short name	Unit
CML2001 Nov. 2010	Acidification Potential	AP	[kg SO_2-Equiv.]
CML2001 Nov. 2010	Eutrophication Potential	EP	[kg Phosphate-Equiv.]
CML2001 Nov. 2010	Global Warming Potential (100 years)	GWP	[kg CO_2-Equiv.]
CML2001 Nov. 2010	Ozone Layer Depletion Potential	ODP	[kg R11-Equiv.]
CML2001 Nov. 2010	Photochemical Ozone Creation Potential	POCP	[kg Ethene-Equiv.]
	Primary energy demand from renewable and non-renewable resources (net calorific value)	PED	[MJ]
	Primary energy from non-renewable resources (net calorific value)	PED nr	[MJ]

The Tables 6-14 to 6-17 show the global warming potential for curtain walls and windows in kg CO_2 - Equiv. per sqm per year for good and mean practice end-of-life scenarios. The results are separated in total, manufacturing, use phase energy demand, use phase maintenance and end-of-life. The result tables for other impact categories can be found in Appendix 3.

Table 6-14 Global warming potential for Curtain walls (Good Practice End of Life)

Global Warming Potential in kg CO_2-Eqv. per sqm per year (Good Practice End of Life)					
Curtain walls	Total	Manufacturing	Use Phase Energy demand	Use Phase Maintenance	EoL
Timber/Aluminium Berlin (Alu mix.)	19.06	1.03	17.80	0.41	-0.18
Timber/Aluminium Rome (Alu mix.)	15.67	1.05	14.41	0.41	-0.20
Timber Berlin	19.41	1.03	17.64	0.90	-0.16
Timber Rome	16.18	1.03	14.41	0.90	-0.16
Aluminium Berlin (Alu. mix.)	19.41	1.65	17.85	0.42	-0.51
Aluminium Rome (Alu. mix.)	16.00	1.66	14.46	0.40	-0.52

Table 6-15 Global warming potential for Curtain walls (Mean Practice End of Life)

Global Warming Potential in kg CO_2-Eqv. per sqm per year (Mean Practice End of Life)					
Curtain walls	Total	Manufacturing	Use Phase Energy demand	Use Phase Maintenance	EoL
Timber/Aluminium Berlin (Alu mix.)	19.15	1.03	17.80	0.41	-0.09
Timber/Aluminium Rome (Alu mix.)	15.76	1.05	14.41	0.41	-0.11
Timber Berlin	19.60	1.03	17.64	0.99	-0.07
Timber Rome	16.36	1.03	14.41	0.99	-0.07
Aluminium Berlin (Alu. mix.)	19.50	1.65	17.85	0.42	-0.42
Aluminium Rome (Alu. mix.)	16.10	1.66	14.46	0.40	-0.42

Following conclusions can be done for the GWP of curtain wall systems:

For the same curtain wall system, there is no difference between Rome and Berlin during the manufacturing phase, use phase maintenance and the end-of-life since the bill of material is quite similar for the two locations. Due to the different climate the GWP resulting from the energy demand during the use-phase is different between Rome and Berlin. Therefore, for the same curtain wall system, the overall result can differ approx. 21% between the two locations.

Over the entire lifecycle for Berlin location, timber-aluminium curtain wall reaches the lowest Global Warming Potential with 19.06 CO_2-eqv./m²·a (Good practice scenario). Regarding the scenario good practice and mean practice of end-of-life aluminium curtain wall (aluminium mix) emits in total approx. 1.8% more CO_2-equiv. than timber-aluminium curtain wall. For the Berlin location, results vary for the mean-type scenario, from 19.15 kg for the timber/Alu curtain wall up to 19.60 kg of CO_2-eqv./m²·a for the timber curtain wall, i.e.; a variation of less than 3%. The same trend is observed for Rome location. Hence, these results show that the GWP of the various curtain wall systems depend mainly on its energy performances during the use phase while the fabrication and end-of-life impacts are quite negligible at least regarding GWP.

Table 6-16 Global warming potential for Windows (Good Practice End of Life)

Global Warming Potential in kg CO_2-Eqv. per sqm per year (Good Practice End of Life)					
Window	Total	Manufacturing	Use Phase Energy demand	Use Phase Maintenance	EoL
Timber Berlin	22.54	0.13	22.19	0.18	0.04
Timber Rome	11.71	0.11	11.43	0.15	0.03
Timber/Alu Berlin	22.69	0.25	22.29	0.19	-0.04
Timber/Alu Berlin (Alu. mix.)	22.69	0.21	22.29	0.20	-0.01
Timber/Alu Rome	11.82	0.22	11.48	0.16	-0.05
Timber/Aluminium Rome (Alu. mix.)	11.82	0.19	11.48	0.16	-0.02
PVC Berlin	22.44	0.25	22.03	0.21	-0.05
PVC Rome	11.70	0.22	11.35	0.17	-0.05
Aluminium Berlin	22.38	0.54	21.87	0.17	-0.21
Aluminium Berlin (Alu. mix.)	22.38	0.44	21.87	0.17	-0.12
Aluminium Rome	11.64	0.49	11.25	0.13	-0.22
Aluminium Rome (Alu. mix.)	11.64	0.39	11.25	0.13	-0.12

Table 6-17 Global warming potential for Windows (Mean Practice End of Life)

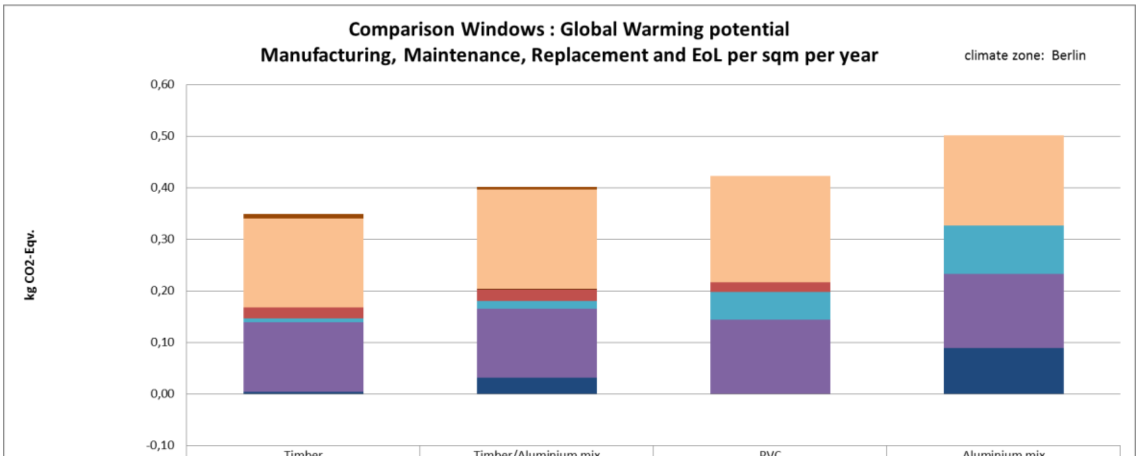
Global Warming Potential in kg CO_2-Eqv. per sqm per year (Mean Practice End of Life)					
Windows	Total	Manufacturing	Use Phase Energy demand	Use Phase Maintenance	EoL
Timber Berlin	22.54	0.13	22.19	0.18	0.04
Timber Rome	11.72	0.11	11.43	0.15	0.03
Timber/Alu Berlin	22.70	0.25	22.29	0.19	-0.04
Timber/Alu Berlin (Alu. mix.)	22.70	0.21	22.29	0.20	0.00
Timber/Alu Rome	11.82	0.21	11.48	0.16	-0.04
Timber/Alu Rome (Alu. mix.)	11.82	0.19	11.48	0.16	0.01
PVC Berlin	22.48	0.25	22.03	0.21	0.00
PVC Rome	11.74	0.22	11.35	0.17	0.00
Aluminium Berlin	22.38	0.54	21.87	0.17	-0.20
Aluminium Berlin (Alu. mix.)	22.38	0.44	21.87	0.17	-0.11
Aluminium Rome	11.65	0.49	11.25	0.13	-0.21
Aluminium Rome (Alu. mix.)	11.64	0.39	11.25	0.13	-0.12

The following conclusions can be drawn for the GWP of window systems:
For the same window system, there is no difference between Rome and Berlin during the manufacturing phase and the end of life since the bill of material of both systems are quite similar. Due to the different climate the energy demand is much higher in Berlin than in Rome. Therefore the overall result can differ up to 92% between the same systems due to the different climatic conditions.

As observed for curtain walls, the GWP results over the entire life cycle depend mainly on the location and are only slightly affected by the window type. As example, GWP results for the mean scenario in Berlin vary from 22.38 CO_2-eqv./m²·a (Alu) up to 22.70 CO_2-eqv./m²·a (Alu/timber), i.e. less than 2% variation. The LCA results of good and mean end of life scenarios indicates almost the same total global warming potential (GWP) between the windows. The system with the lowest GWP is aluminium window. The highest GWP impact was observed by timber-aluminium window with approx. 1.5% higher than the aluminium window.

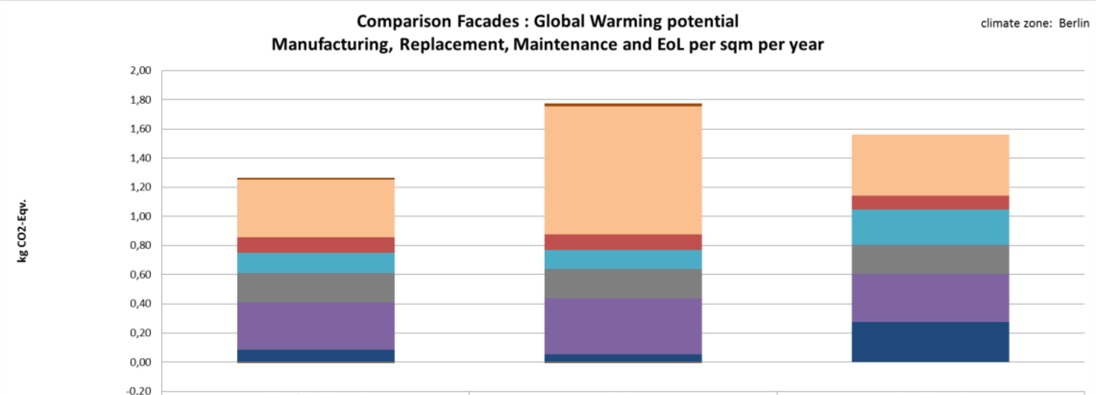
The figures 6-1 and 6-2 show the comparison of GWP of the windows and curtain walls of Berlin for good practice end-of-life scenario without energy demand. The figures 6-3 and 6-4 show a GWP comparison including energy demand.

The “use phase – replacement” category integrates all the replacements taking place during the use phase like the fittings, glazing units, gaskets or the whole window. The use – phase – maintenance integrates all the other aspects which are not linked to the energy demand during the use phase, e.g. painting activities.



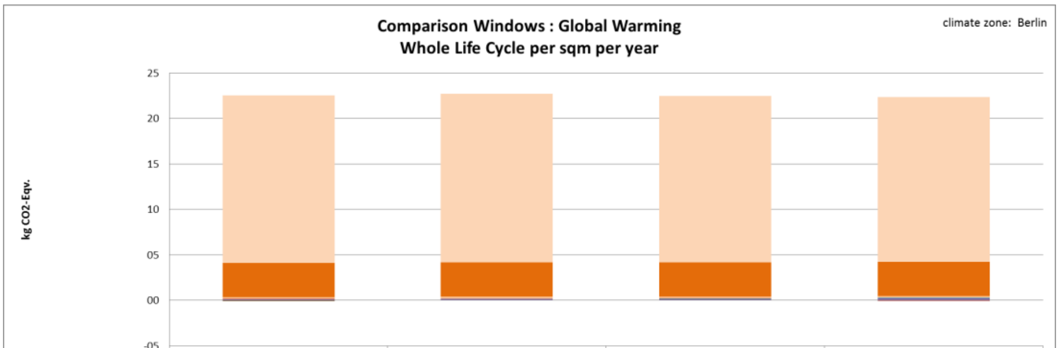
	Timber	Timber/Aluminium mix	PVC	Aluminium mix
Use Phase - Maintenance	0,01	0,01	0,00	0,00
Use Phase - Replacement	0,17	0,19	0,21	0,17
Wood	0,00	0,00	0,00	0,00
Steel	0,02	0,02	0,02	0,00
Plastics	0,01	0,02	0,05	0,09
Glass	0,14	0,13	0,14	0,14
Aluminium	0,00	0,03	0,00	0,09

Figure 6-1 Comparison windows (GWP) – Manufacturing, Replacement, Maintenance and EoL (Good Practice End of Life)



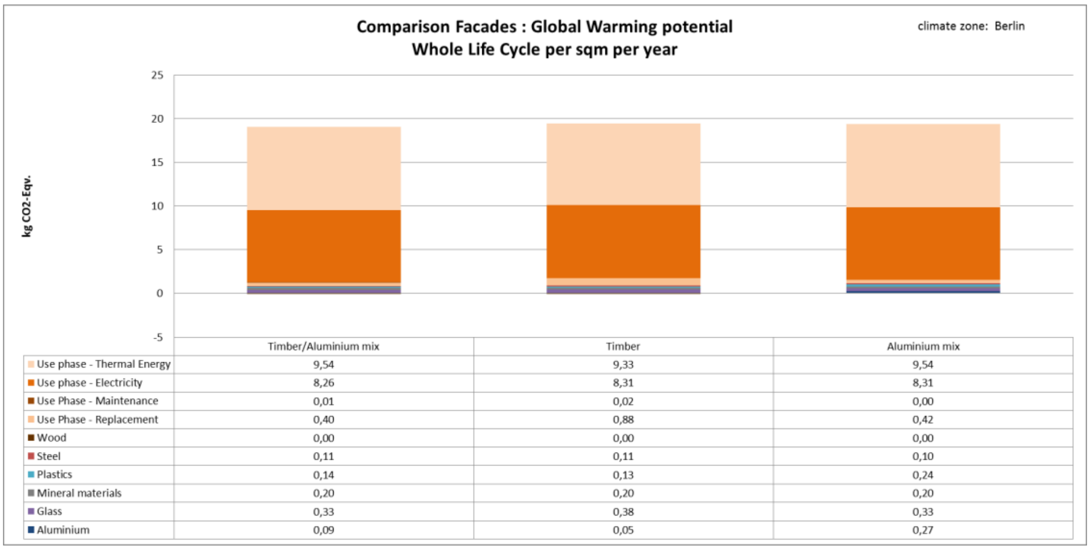
	Timber/Aluminium mix	Timber	Aluminium mix
Use Phase - Maintenance	0,01	0,02	0,00
Use Phase - Replacement	0,40	0,88	0,42
Wood	0,00	0,00	0,00
Steel	0,11	0,11	0,10
Plastics	0,14	0,13	0,24
Mineral materials	0,20	0,20	0,20
Glass	0,33	0,38	0,33
Aluminium	0,09	0,05	0,27

Figure 6-2 Comparison curtain walls (GWP) – Manufacturing, Replacement, Maintenance and EoL (Good Practice End of Life)



	Timber	Timber/Aluminium mix	PVC	Aluminium mix
Use phase - Thermal Energy	18,42	18,53	18,27	18,11
Use phase - Electricity	3,76	3,76	3,76	3,76
Use Phase - Maintenance	0,01	0,01	0,00	0,00
Use Phase - Replacement	0,17	0,19	0,21	0,17
Wood	0,00	0,00	0,00	0,00
Steel	0,02	0,02	0,02	0,00
Plastics	0,01	0,02	0,05	0,09
Glass	0,14	0,13	0,14	0,14
Aluminium	0,00	0,03	0,00	0,09

Figure 6-3 Comparison Windows (GWP) Whole Life Cycle (Good Practice End of Life)



	Timber/Aluminium mix	Timber	Aluminium mix
Use phase - Thermal Energy	9,54	9,33	9,54
Use phase - Electricity	8,26	8,31	8,31
Use Phase - Maintenance	0,01	0,02	0,00
Use Phase - Replacement	0,40	0,88	0,42
Wood	0,00	0,00	0,00
Steel	0,11	0,11	0,10
Plastics	0,14	0,13	0,24
Mineral materials	0,20	0,20	0,20
Glass	0,33	0,38	0,33
Aluminium	0,09	0,05	0,27

Figure 6-4 Comparison Curtain walls (GWP) Whole Life Cycle (Good Practice End of Life)

The Global Warming Potential during the use phase is dominant for all analysed window and curtain wall types. The impact of the energy consumption is in all cases more than one order of magnitude higher than the manufacturing, maintenance, exchange of building elements and the end-of-Life. The tables for the other impact categories can be found in Appendix 3.

7 In-depth facade assessment

7.1 Method

For the in-depth facade assessment, a typical residential building and typical office building are considered. To carry out the façade assessment, a full set of criteria and indicators needs to be defined. This process is worked out with a two-step methodology.

In a first step, the common Green Building Rating Schemes used on the European and International market are investigated regarding criteria used. The influence from façade and window quality on the total result of the rating is identified. Finally, the most important criteria from the Rating Schemes are reported into one evaluation matrix.

In a second step, further criteria which are important for sustainable assessment derived from daily business work are identified and also integrated into the evaluation matrix. To be conform to EN 15643/1 (Sustainability of construction works - Sustainability assessment of buildings), the chosen criteria are assigned into categories for environmental, economical, social, technical and process performance. Finally, the DGNB scheme has been chosen to perform our analysis since it is in line with the structure of EN 15643 and is following LCA according to ISO 14040.

The evaluation matrix will be used to assess the different framing materials under study. An overall score is consciously derived according to a simple analysis: The advantages and disadvantages of examined systems are systematically analysed for the different categories and are then rated by incremental credits: 0 (negative), 1 (neutral) and 2 (positive) for each criteria, excepting the economic indicator which is derived linearly from the LCC analysis. All credits are then summed up together to one single score, which is compared to a maximum of 100%.

The principle of facade assessment methodology is shown In the Figure 7-1.

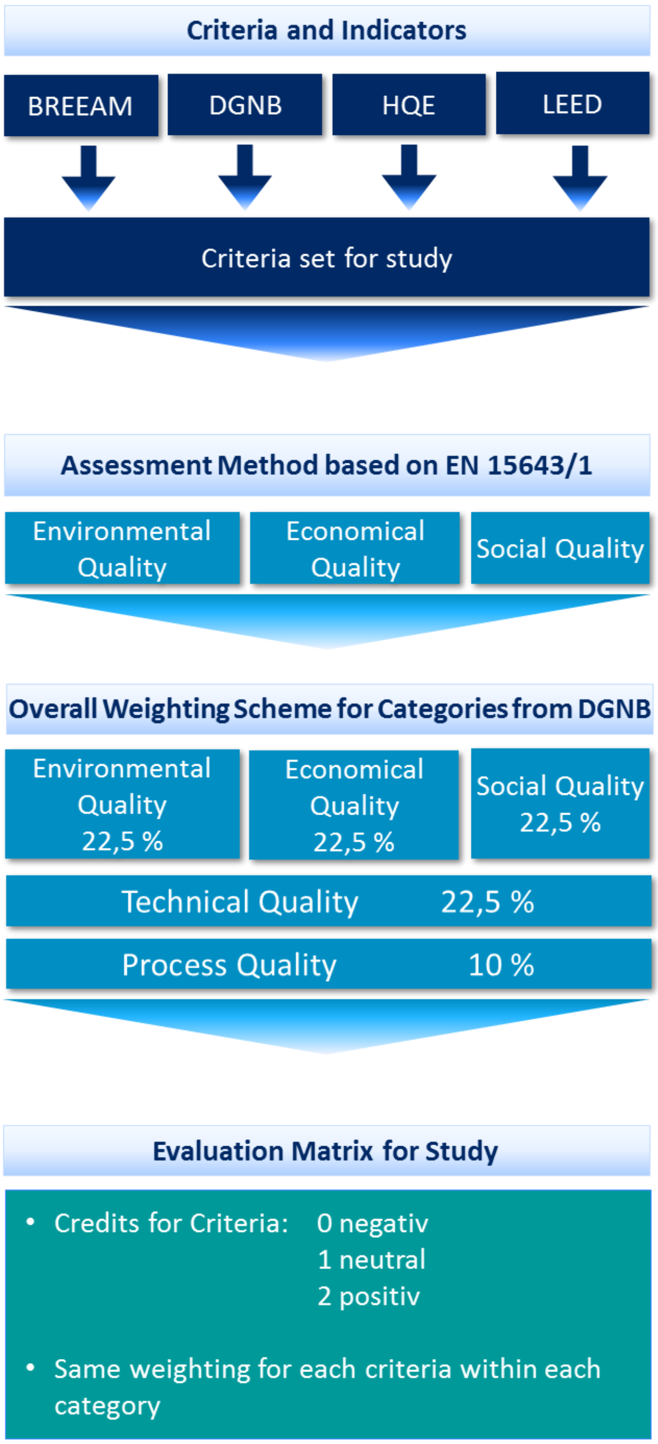


Figure 7-1: **Façade assessment methodology**

7.2 Influence of curtain wall and window systems within Green Building Schemes

Green Buildings use our resources (energy, water and materials) in an efficient way. They provide usually high overall comfort (thermal, daylight, acoustic, air quality) for human beings with harmless effects on health and the environment. Therefore, the Green Building Rating Schemes (GBRS) are a suitable literature source from where criteria can be derived to use for assessment of sustainable performance for this study.

The GBRS-systems are differently influenced by the curtain wall and window systems, hence several systems are investigated:

– LEED, Design and Construction, 2009,
– BREEAM, Non-Domestic Buildings, 2011,
– DGNB, New Office and Administrative Buildings, 2012,
– HQE, Non-Residential Buildings, 2012.

In a first step, each single criterion of those certification systems is investigated whether the facade has an effective influence or not. This is simply assessed by a yes/no evaluation. In such way, the maximum level of impact of curtain wall and window systems within each GBRS can be evaluated and the important criteria for this study are identified.

In the LEED certification scheme, the facade has its main impact in the “Energy and Atmosphere” category where the whole building simulation has to be executed. In the “Material and Resources” category, additional credits are attributed to timber with FSC/PEFC certification. This sustainable sourcing criterion is current only applicable for timber facades. Certification systems for other materials are not considered yet. This is similar for all other investigated GBRS.

For the “Indoor Environmental Quality” category, the design of the facade and its impact on the thermal comfort are considered. At the “Innovation and Design” category, advantages from regional and recycled material use can be taken positively into account. The recyclability at the end-of-life is not considered till now.

In the BREEAM scheme, the life cycle costing is influenced by the facade at the “Management” category. The criterion “Health and Wellbeing” is similar to the “Indoor Environmental Quality” from the LEED system. The emissions of volatile organic compounds are likewise considered as well. The “Energy” category is similar to the “Energy and Atmosphere” from LEED.

The energy efficiency is also considered in the “Innovation” part where carbon footprint is investigated. Also visual comfort is mainly affected by the facade which is also considered. The impact of the facade during the life cycle regarding emissions and risks is considered in the part “Material 1”. Here, the environmental impact is determined either with the “Green Guide” by BREEAM or an independent life cycle assessment tool. End of life processes need to be regarded for both tools. The Green Guide rating for timber curtain wall system is better than for aluminium. For domestic buildings, PVC has the same rating “A” as aluminium (profile <1.08 kg/m) [05]. This result is not proved by other LCA-tools which also are allowed to be used for the BREEAM scheme.

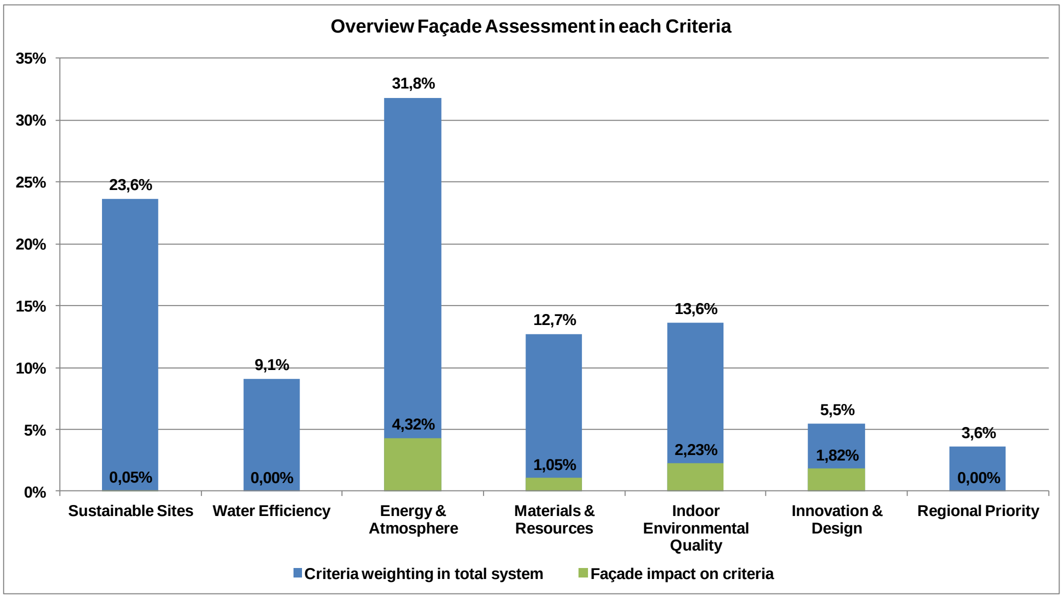


Figure 7-2: **Facade impact on each category in LEED system**

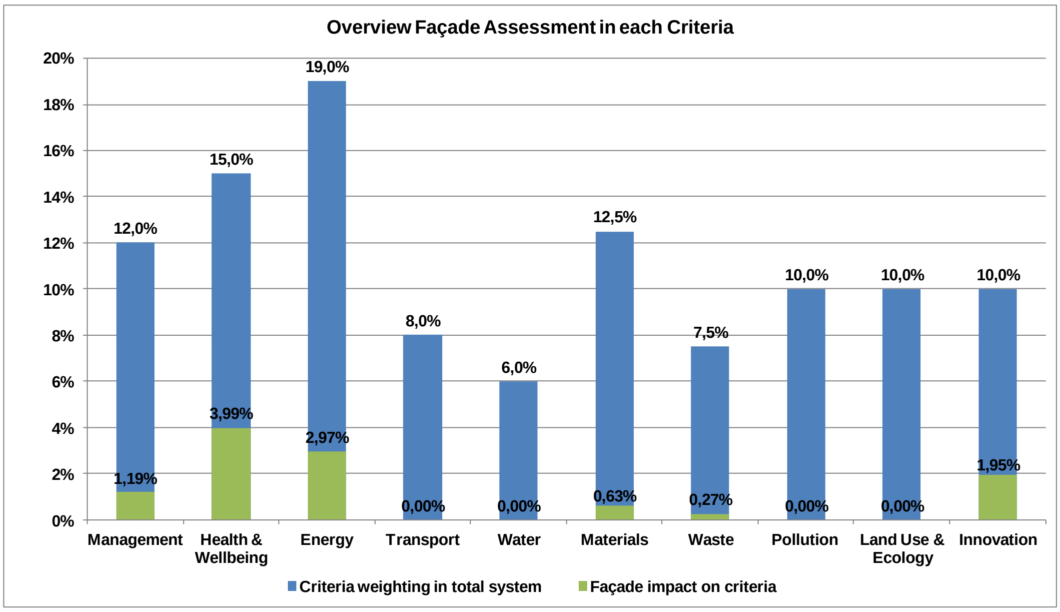


Figure 7-3: **Facade impact on each category in BREEAM system**

In the DGNB-system, additional criteria with impact of the facade are the overall life cycle assessment as well as noise and acoustical comfort. The environmental performance of the building by means of applying life cycle assessment methodology (LCA) from production, use and end-of-life stages is used also for this study since the method is the most advanced developed evaluation method in this field, see chapter 6. Furthermore, the method is based on the actual European codes and knowledge level.

All other impacts are similar to the already mentioned criteria.

The HQE system considers likewise the already mentioned criteria. Recyclability at the end-of-life is not assessed yet.

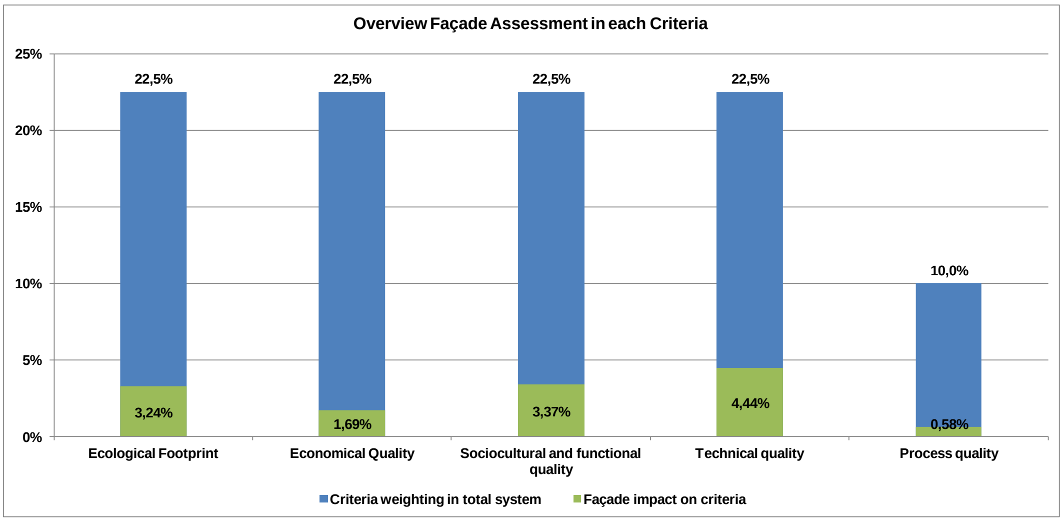


Figure 7-4: Facade impact on each category in DGNB system

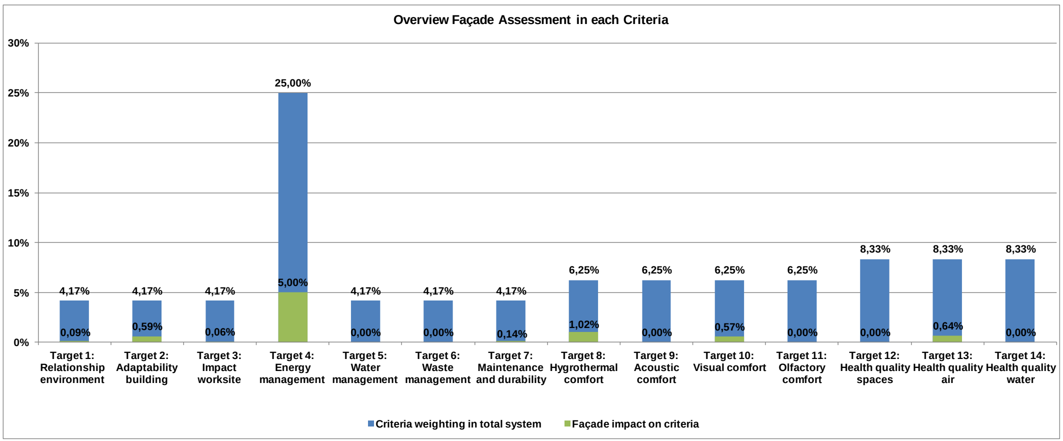


Figure 7-5: Facade impact on each category in HQE system

The common maximum influence of the facade in all Rating schemes is about 10 %. There are lots of criteria which are quite similar, but the indicators, methods and the weighting is different. All major criteria concerning the curtain walls and windows are put into an evaluation matrix, which is the basis that is used to assess the profile materials within this study.

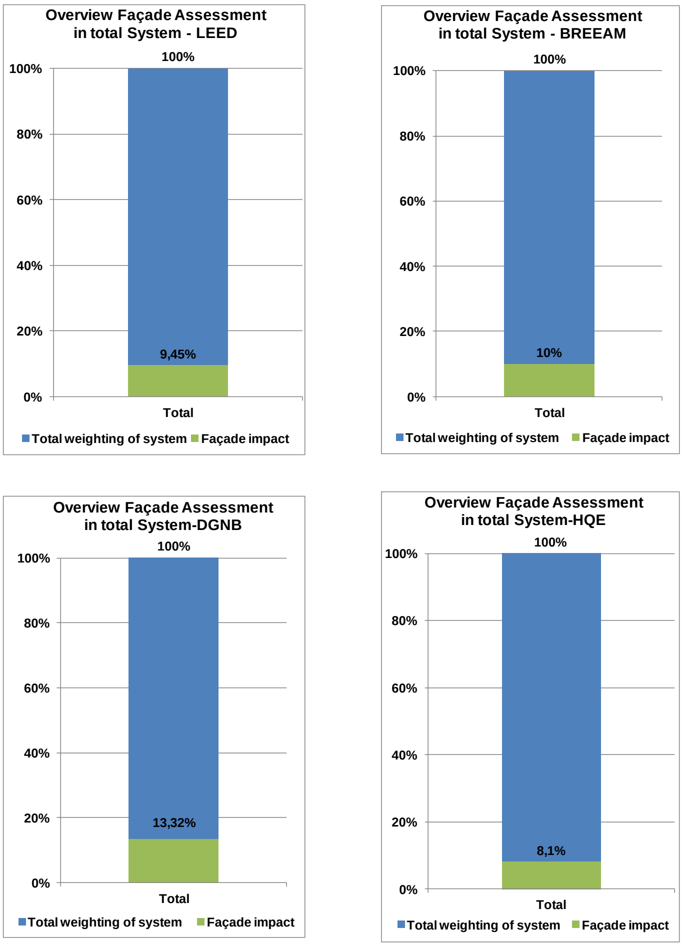


Figure 7-6: Complete results of assessment for all investigated Green Building Systems

7.3 Evaluation matrix (in-depth facade assessment)

All identified criteria in chapter 7.2 with influence on the façade and window as well as further criteria from common practice in real estate are integrated into an evaluation matrix used for this study. For every construction described in chapter 3, each criterion is used for assessment. Furthermore, a **typical** and a **best practice** construction are taken into account to show the mean and maximum impact possible of the material products. The results of the investigations are concentrated in a matrix for office and residential buildings. All criteria are sorted into categories according to EN 15643/1 (Sustainability of construction works - Sustainability assessment of buildings):

- Environmental quality 22.5 %
- Economical quality 22.5 %
- Social quality 22.5 %
- Technical quality 22.5 %
- Process quality 10 %

The categories are weighted equally besides the process quality. The reason is that process criteria are considered to have a lower influence in the final product performance than the other categories.

Except for the economical quality, several specific performance criteria are analysed within each category and a score of 2, 1 or 0 is given according to this analysis:

- A negative evaluation gives → 0 credit
- A neutral evaluation gives→ 1 credit
- A positive evaluation gives → 2 credits

Within one category, all the credits are then consolidated and converted in percentage according to the weight of the category. As an example, the environmental quality is composed of 4 different criteria (i.e. LCA, local risk, sustainable use of resources, energy demand) meaning that the maximum score is 8 credits. Hence, 8 credits will give 22.5% while 7 credits would provide 7/8 of 22.5%, i.e. 19.7%. The percentages of each category are then added to give the overall score.

For the economical quality, the crediting method is not a step-wise method since this category is based exclusively on LCC results which show quite limited differences between the various systems. Indeed, the incremental crediting methodology applied to other categories would then influence significantly the final results while the differences are quite limited, i.e. a maximum variation of 20% is observed in the LCC results. Hence, the crediting method for the economical quality uses instead a linear weighting process where the cheapest system gets a credit of 2 and the other options get a discount rate in proportion to the percentage of the LCC increase. As an example, if an alternative system is 20% more expensive, it receives 80% of the credits, i.e. 1,6 on 2. Beyond 100% of price increased, the credit is blocked to 0. The Berlin location has been chosen as reference to make such calculation.

7.4 Description of criteria assessments

7.4.1 Environmental quality

1.1 - Life-cycle assessment - environmental impacts

The assessment is based on the LCA results in chapter 6. The facade and window system with the best result gets two credits. The system with 2 to 4% GWP than the lowest impact gets one credit. System with 4% or more GWP than the lowest impact gets no credit. Each system, facade and window, are evaluated separately from each other.

Curtain wall system:

Aluminium curtain wall (sec. aluminium) and timber curtain wall reach a global warming potential of 19.41 kg CO_2eqv./m²·a (1.8% higher than timber-aluminium curtain wall) and timber-aluminium 19.06 kg CO_2eqv./m²·a , resulting in two credits for all curtain wall systems.

Window system:

Aluminium window has a global warming potential of 22.38 kg CO_2eqv./m²·a , whereas PVC window 22.44 kg CO_2eqv./m²·a (0.3% higher than aluminium window), timber window 22.54 kg CO_2eqv./m²·a (0.7% higher than aluminium window) and timber-aluminium 22.69 kg CO_2eqv./m²·a (1.4% higher than aluminium window), resulting in two credits for all window systems.

This homogeneous crediting value for all types of systems confirms that a differentiation between the various systems at environmental level makes no sense considering that the use phase is still largely dominant, especially for the GWP indicator.

For further details see chapter 6.

1.2 - Risks to the local environment

Certain materials, construction products and preparations containing dangerous substances may represent a danger to soil, air, groundwater and surface water and human health, flora and fauna. In order to minimize risks to human health and the local environment, materials and building products which use dangerous substances should be avoided or substituted. This criterion evaluates only material and product contents. Ecological and human-toxicological impact cannot be applied yet.

Typically a powder coating is used for aluminium and anodized coatings for best-practice. Both alternatives are Chrome-VI free [06] and aluminium systems are evaluated with one credit.

PVC systems contain mostly calcium and zinc as stabilizer and are evaluated with one credit.

Timber contains typically biocides and solvents which increase its emission decay time (no credit). At best practice low toxic contents are used what leads to one credit.

Another credit is related to the toxicity evaluation during the use phase. For aluminium and PVC systems, no painting operation is needed while timber system needs painting on regular intervals which generates some toxic emissions. Hence, PVC and aluminium get one credit while wood gets no credit. Best practice for wood gets one credit, assuming that paints with no toxic emissions are used.

1.3 - Sustainable use of resources

- Wood (typical: 1, best practice: 2): From a sourcing perspective, wood appears as a sustainable material since it is renewable. The large use of certified wood, e.g. Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification schemes (PEFC) and the management of the forest areas in Europe in the last years, indicate effectively a sustainable management of wood resources [08]. However, from an end-of-life perspective, wood frames are still mostly landfilled without any treatment [07]. As a result, wood-based framing gets one credit for the mean practice. Best practice should aim at collecting and treating wood frames at end-of-life (e.g. for energy recovery) and gets then two credits.

- Aluminium (typical: 1, best practice: 2): Primary aluminium production is energy intensive. Even if aluminium recycling is a very efficient business, there is still today a big fraction of aluminium supply which comes from primary sources due to the lack of scrap availability. Hence from a sourcing viewpoint, aluminium suffers from this energy intensity of the primary production. However, from the end-of-life perspective, aluminium frames are today systematically recycled into new aluminium products. Aluminium profiles have currently a collection rate that is close to 100% due to their high economic value and ability to be efficiently recycled. Therefore, aluminium is rated with one credit as typical scenario. The best practice case gets a score of two to reflect optimised practices in term of recycling and aluminium sourcing.

- PVC (typical: 0, best practice: 1): PVC production is quite an energy intensive process based on non-renewable feedstock material, especially crude oil. In addition recycled PVC, does not fully substitute virgin PVC. Indeed, when producing new profiles, the recycled PVC must be encapsulated in virgin PVC for aesthetical reasons. Furthermore, today, a significant fraction of PVC frames still escapes the collection scheme implemented and promoted by the PVC industry. Therefore the typical PVC system is evaluated as poorly sustainable in term of resources with no credit while the best practice gets one credit, assuming that it is collected at end of life for further recycling.

1.4 - Energy demand

The energy demand is determined in chapter 4. All materials get two credits because all calculated energy demands have a similar performance. For further details see chapter 4.

7.4.2 Economical quality – Life cycle costing LCC

The life cycle costs are determined in chapter 5. The material with the lowest LCC gets 100% of the score while the other materials get a score which is reduced according to their respective LCC result in comparison to the best score. As an example, if a system is 20% more expensive than the system presenting the lowest LCC, it will get 80% (100%-20%) of the maximum score. Beyond 100% of LCC increase, the credit is fixed to 0%, i.e. no credit.

Curtain wall system (Berlin):

Aluminium curtain wall gets a score of 2 (100%, i.e. 846 €/m²), whereas timber-aluminium curtain wall gets a score of 1.9 since 898 €/m² is 6% higher than aluminium curtain wall and timber curtain wall gets 1.6 since 1010 €/m² is 19% higher than aluminium curtain wall.

Window system (Berlin):

PVC window gets a score of 2 (100%, i.e. 421 €/m^2) while aluminium window gets 1.92 since 435 €/m² is 3% higher than PVC window. Timber window gets 1.76 with a LCC cost of 471 €/m² and timber-aluminium gets a score 1.88 with a LCC of 443 €/m².

For further details see chapter 5.

7.4.3 Social quality

3.1 - Thermal Comfort

The thermal comfort is determined in chapter 4.2.3. All materials get two credits because all achieved comfort categories are similar. For further details see chapter 4.2.3.

3.2 - Indoor air quality

For this criterion, the harmful emissions of the different frames after the construction phase of the building are assessed. Aluminium powder coating contains no dangerous substances [06, 09 and 10], so one credit is given. Timber typically needs paint, biocides and solvents which cause a long emission decay time (no credit). PVC emits no dangerous substances resulting in one credit.

Furthermore, the ventilation performances of the rooms are assessed. The ventilation rate is ensured by mechanical ventilation and openable windows independent of the frame material. Hence, every construction gets additional one credit.

3.3. - Visual comfort

The visual comfort depends on the window ratio of the complete building and of the depth of the room. The profile depth and the profile width are the only characteristics of the curtain wall which a small influence on day lighting. The aluminium curtain wall has generally profiles with a lower depth than wooden ones (40-50 mm less). The influence of 40-50 mm less depth on visual aspects is negligible.

All investigated rooms achieve the highest category for visual comfort and therefore all frames get two credits.

3.4 - Design / User Comfort / Aesthetics

This criterion assesses design variety, flexibility, user comfort and aesthetics.

Aluminium offers a high flexibility for design, aesthetics and comfort for handling purposes of the user which results in two credits. Timber has a limited flexibility for design with lower comfort in handling what leads to one credit. PVC has a good flexibility for design and aesthetics, limited for special constructions, which leads also to one credit.

7.4.4 Technical quality

4.1 - Fire safety

The assessment of fire safety considers combustibility, smoke formation and dripping characteristics according to EN 13501-1 and DIN 4102-1. Aluminium fulfils all fire safety requirements with the highest degree (Reaction to fire Class A[1]). Timber and PVC are combustible (class B) and develop smoke in case of fire.

Therefore aluminium is rated with two credits, Timber and PVC with one credit.

4.2 - Sound protection

[1] European Commission Decision 94/611/EC and 96/603/EC

This criterion assesses the sound protection against the ambient air and the sound insulation of the flanks. The sound protection against the ambient air depends strongly on the glass since the frame has only a small ratio of the complete curtain wall. There is only small technological difference for the criterion between all materials.

Sound insulation of the aluminium flank, in case of best practice, can be improved by steel inserts up to 52 dB. This value is sufficient to fulfil high requirements, i.e. confidential rooms. Therefore aluminium curtain wall in best practice reaches two credits. All other curtain wall systems are evaluated with one credit.

The sound insulation of flanks is only crucial for office building because in residential building, windows are not placed at the flanks. All window systems are evaluated with two credits.

4.3 - Quality of the building envelope with regard to heat and humidity

The quality of the building envelope concerning thermal transmittance coefficients, thermal bridges, air permeability class, amount of condensation inside the structure and solar heat protection are mainly described in chapter 4. Every investigated room achieves the highest performance level and therefore all frames are assessed with two credits.

4.4. - Ease of dismantling and recycling

For these criteria, the effort for dismantling is assessed.

The analysis showed that the effort for disassembling and sorting into basic elements is not dependent on the frame material, but on the construction which is used. All curtain wall and window systems present satisfactory possibility of disassembling. As already stated, aluminium frames present higher recyclability quality than PVC or wood frames. This superiority of Al frames has been already reflected in 1.3. As a result, each system is assessed with one credit for the typical and best practice scenarios, except aluminium windows and curtain walls which get two credits for the best practice scenario assuming a fully optimised design for dismantling and recycling.

7.4.5 Process quality

5.1 - Optimal use and management

Aluminium is a dimensionally stable, corrosion resistant and durable material. Therefore it leads to very low maintenance effort which results in two credits for curtain wall and window systems.

Timber window need new coatings every 5 years to secure the expected lifespan while timber-aluminium window is less critical, even though still needs more maintenance effort than aluminium system. One credit is given for Timber-aluminium and no credit for timber window. Regarding the maintenance effort for curtain wall systems, it can be pointed a disadvantage by timber curtain wall, one credit.

PVC system is more propitious to failure and has lower durability than aluminium due to ageing effects [02], one credit is given.

5.2 - Construction site / process

For this criterion, the possibilities to reduce waste, noise and dust on the construction site are assessed for one credit. The second credit is given for the construction effort and construction time.

Our analysis of the different materials does not see any major difference for those criteria and evaluate all curtain wall and window systems with two credits.

5.3 - Material acquisition

In terms of material acquisition for a building construction, wooden curtain walls require according to our practical experience in general a longer delivery time in particular for large project developments. Aluminium curtain wall is evaluated with two credits and timber and timber-aluminium curtain wall with one credit.

All window systems are evaluated with two credits, due to their high availability on market.

7.4.6 Evaluation Matrix – Results

Table 7-1: Results curtain wall assessment – Office

Curtain wall Systems	Aluminium		Aluminium-Timber		Timber	
	typical	best practice	Typical	best practice	typical	best practice
1 Ecological Quality						
1.1. Life-cycle assessment - environmental impacts resulting from emissions	2	2	2	2	2	2
1.2. Risks to the local environment	2	2	1	2	1	2
1.3. Sustainable use of resources	1	2	1	2	1	2
1.4. Energy demand	2	2	2	2	2	2
2 Economical Quality						
2.1. Building related life cycle costs	2,0	2,0	1,9	1,9	1,6	1,6
3 Social Quality						
3.1. Thermal comfort	2	2	2	2	2	2
3.2. Indoor air quality	2	2	1	2	1	2
3.3. Visual comfort	2	2	2	2	2	2
3.4. Design / User comfort / Aesthetics	2	2	2	2	2	2
4 Technical Quality						
4.1. Fire safety	2	2	1	1	1	1
4.2 .Sound insulation	1	2	1	1	1	1
4.3. Quality of the building envelope with regard to heat and humidity	2	2	2	2	2	2
4.4. Ease of dismantling and recycling	1	2	1	1	1	1
5 Process Quality						
5.1. Creations of conditions for optimal use and management	2	2	2	2	1	1
5.2. Construction site / process	2	2	2	2	2	2
5.3. Material acquisition	2	2	1	1	1	1
Total Score						
1 Ecological Quality	7	8	6	8	6	8
2 Economical Quality	2,0	2,0	1,9	1,9	1,6	1,6
3 Social Quality	8	8	7	8	7	8
4 Technical Quality	6	8	5	5	5	5
5 Process Quality	6	6	5	5	4	4
Percentages						
Ecological footprint	19,7%	22,5%	16,9%	22,5%	16,9%	22,5%
Economical Quality	22,5%	22,5%	21,1%	21,1%	18,3%	18,3%
Social Quality	22,5%	22,5%	19,7%	22,5%	19,7%	22,5%
Technical Quality	16,9%	22,5%	14,1%	14,1%	14,1%	14,1%
Process Quality	10,0%	10,0%	8,3%	8,3%	6,7%	6,7%
Total	**91,6%**	**100,0%**	**80,1%**	**88,5%**	**75,6%**	**84,0%**

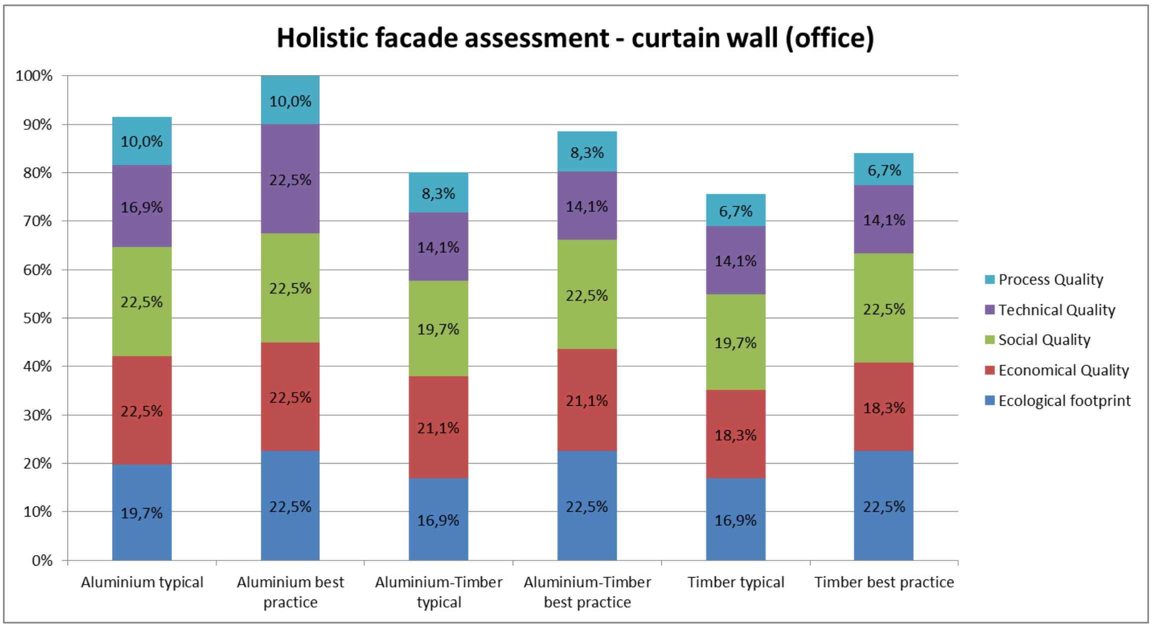


Figure 7-7: Results curtain wall assessment – Office curtain wall

Table 7-2: Results window assessment – Housing

Window Systems	Aluminium		Aluminium-Timber		Timber		PVC	
	typical	best practice	typical	best practice	typical	best practice	typical	best practice
1 Ecological Quality								
1.1. Life-cycle assessment - environmental impacts resulting from emissions	2	2	2	2	2	2	2	2
1.2. Risks to the local environment	2	2	1	2	1	2	2	2
1.3. Sustainable use of resources	1	2	1	2	1	2	0	1
1.4. Energy demand	2	2	2	2	2	2	2	2
2 Economical Quality								
2.1. Building related life cycle costs	1,92	1,92	1,88	1,88	1,76	1,76	2	2
3 Social Quality								
3.1. Thermal comfort	2	2	2	2	2	2	2	2
3.2. Indoor air quality	2	2	1	2	1	2	2	2
3.3. Visual comfort	2	2	2	2	2	2	2	2
3.4. Design / User comfort / Aesthetics	2	2	2	2	2	2	1	1
4 Technical Quality								
4.1. Fire safety	2	2	1	1	1	1	1	1
4.2 .Sound insulation	2	2	2	2	2	2	2	2
4.3. Quality of the building envelope with regard to heat and humidity	2	2	2	2	2	2	2	2
4.4. Ease of dismantling and recycling	1	2	1	1	1	1	1	1
5 Process Quality								
5.1. Creations of conditions for optimal use and management	2	2	1	1	1	1	1	1
5.2. Construction site / process	2	2	2	2	2	2	2	2
5.3. Material acquisition	2	2	2	2	2	2	2	2
Total Scores								
1 Ecological Quality	7	8	6	8	6	8	6	7
2 Economical Quality	1,92	1,92	1,88	1,88	1,76	1,76	2	2
3 Social Quality	8	8	7	8	7	8	7	7
4 Technical Quality	7	8	6	6	6	6	6	6
5 Process Quality	6	6	5	5	5	5	5	5
Percentages								
1 Ecological Quality	19,7%	22,5%	16,9%	22,5%	16,9%	22,5%	16,9%	19,7%
2 Economical Quality	21,6%	21,6%	21,2%	21,2%	19,8%	19,8%	22,5%	22,5%
3 Social Quality	22,5%	22,5%	19,7%	22,5%	19,7%	22,5%	19,7%	19,7%
4 Technical Quality	19,7%	22,5%	16,9%	16,9%	16,9%	16,9%	16,9%	16,9%
5 Process Quality	10,0%	10,0%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%
Total	93,4%	99,1%	82,9%	91,4%	81,6%	90,0%	84,3%	87,1%

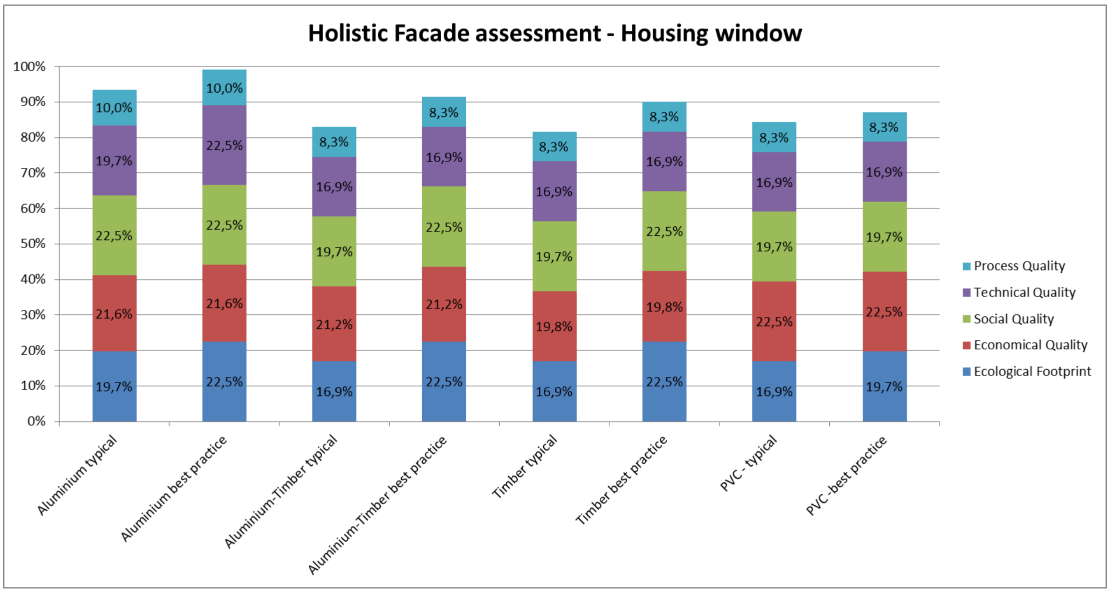


Figure 7-8: Results window assessment – Housing

7.5 Recommendations for Green Building Rating Schemes

The analysis of the common Green Building Rating Schemes as well as our practical experience on facades give us the possibility to clear up open issues that could be additionally addressed by the certification bodies in their schemes. Following recommendations can be derived from the study:

– Defining method for life cycle assessment (LCA): There is a variety of different methods used by the Green Building Rating Schemes to evaluate environmental performance of buildings. Often, the indicators and methods are strictly divided into production phase, use phase and end of life phase or re-use phase (BREEAM, LEED and HQE). Furthermore, new performance indicators are created (i.e. Green Guide), which end up in environmental assessments which are not clear for the market. For example, aluminium profiles are rated in BREEAM's Green Guide different for residential and non-residential buildings. From the environmental point of view, a different assessment dependent on its building use is rarely uncommon.
  Recommendations:
  – Use of life cycle assessment according to ISO 14044 or EN 15804.
  – Integration of production phase, use phase as well as end-of-life within one aggregated figure, so the design team can create best optimum solutions and innovations are not cut.
  – Consideration of energy consumption related to the use-phase of the building into the LCA.

– The assessment of sustainable use of resources should cover also other materials besides wood. The amount of collected material at the end of life stage and the corresponding environmental benefits related to their recycling or to their incineration with energy recovery should be considered.

– Architectural design: There is no criteria like “Design freedom / aesthetics” in all rating schemes. Since individual design is one of the most important qualities to create a high value of the building, it should be included within the Rating Schemes.

– Life Cycle Cost is fully included only in DGNB and BREEAM. To show the higher value for long lasting materials, it is a “must-have” within a rating scheme to integrate this criterion into the assessment.

8 References

[01] Datenblatt Psi-Wert Fenster, Arbeitskreis “Warme Kante”, October 2008

[02] BNB – Bewertungssystem für Nachhaltiges Bauen für Bundesgebäude (http://www.nachhaltigesbauen.de); DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen (http://www.dgnb.de)

[03] Final Report – Life cycle assessment of PVC and principal competing materials, European Commission, 2004

[04] Instandhaltung- und Pflegeanleitung, Bundesverband ProHolzfenster, September 2000.

[05] BREEAM Green Guide 2008 ratings

[06] DGNB Kriterium ENV1.2: Risiken für die lokale Umwelt

[07] Life cycle assessment - The whole story: from cradle to grave, TATA Steel

[08] Forest Paper 163 - Food and Agriculture Organization of the United Nations -, 2010

[09] Evaluation of impact of aluminium construction products on soil, surface and groundwater, EAA, 2011

[10] Etiquetage des émissions en polluants volatils d´une “Façade-Rideau à ossature aluminium” selon la norme ISO 16000, 2012

9 Critical Review Statement

The critical review statement is reported in the next pages. It has to be noted that the critical review statement has been performed on a version dated of 24 July 2014. This report dated of 8 Jan 2015 is identical of that previous version with the exception of the review statement which has been added under this section 9.

Sustainability assessment of windows and curtain walls

Critical Review Statement

prepared for

The European Aluminium Association

By

Stephanie Carlisle

Diana Fischer

Christian Donath

and

Anis Ghoumidh (Chair)

December 2014

Introduction

The European Aluminium Association (EAA) has commissioned a study called "Sustainability assessment of windows and curtain walls", which includes a comparative LCA. This study was carried out by DREES & SOMMER and PE International. Moreover, EAA has wished to have this study reviewed.

Therefore, EAA has contacted Ingenieurbüro Fischer, KieranTimberlake, Consulting Donath and Solinnen in order to have them conduct the critical review as panel members.

The following document is the statement of the critical review report.

It should be noted that this study cannot be considered as an LCA study in full accordance to ISO 14044. Indeed, an in-depth sensitivity analysis, especially regarding the product replacement schedule, as well as the involvement of interested parties, i.e. competing products, would be required for a comparative LCA study.

Composition of the panel

The critical review panel consisted of the following members:

	Company / Legal entity	**Main roles**
Stephanie Carlisle	KieranTimberlake	Technology, LCC, Thermal simulation review (chapters 3, 4, 5)
Diana Fischer	Ingenieurbüro Fischer	LCA review (chapter 6) and some general aspects
Christian Donath	Consulting Donath	Overall sustainability assessment (chapter 7)
Anis Ghoumidh	Solinnen	LCA review (chapter 6) Panel Chairperson

The roles listed above represent the primary focus of each reviewer. However, as there is considerable methodological and technical overlap, these roles did not prevent the collection of comments and discussion across report sections e.g. the technology reviewer was able to provide feedback on the LCA section, and the LCA reviewers could also provide comments on technology and overall sustainability assessment.

Procedural aspects

This critical review was ordered by EAA, "the commissioner," in September 2013. The study was conducted by both Drees & Sommer and PE International, "the practitioner".

The first version of the report and appendixes was sent at the same time as the order. It was named "Sustainability assessment of windows and curtain walls", version dated 11th June, 2013.

The kick-off meeting of the critical review took place on 9th October, 2013. The main targets of this phone meeting were the presentation and the validation of the review process.

A second phone meeting was conducted on 21st November, 2013 and the main reviewers' comments were presented to the commissioner at this time.

Comments prepared by the reviewers were sent to the commissioner on 2nd December 2013. They were presented as a table in an Excel file. The chapter and the line number related to each comment were mentioned. It was also indicated if the comment was related to a paragraph, figure or table. For each comment, the type (general, editorial, methodology, technology and modelling, data sources, calculation or interpretation) was indicated. Finally, the nature of comment (remark or objection), which provided an indication of the importance of the issue, was also mentioned.

On June 2014, the commissioner sent the second version of the report and both its answers and the practitioner ones. The report version was dated 12th June, 2014.

On 26th June 2014, a phone meeting was conducted by the reviewers with the commissioner in order to discuss the answers to the comments and finalise the critical review. The final phone meeting was conducted on 16th July in order to present the critical review conclusions. In September 2014, the commissioner and the reviewers reached an agreement on final conclusions.

This statement is based on the version of the report dated 24th July, 2014 and named "Sustainability assessment of windows and curtain walls".

Report review

This study presents a comparison of similar architectural assemblies serving the same function made of different framing material through an in-depth appraisal of trade-offs between material selection across the full life cycle from environmental, economic and design perspectives.

The methodologies, the assumptions, the scenarios and the data used in chapters 2 to 6 are transparent, realistic and up-to-date. Hence, results reported in such chapters regarding the environmental and economic aspects of the windows and curtain walls can be considered as robust and founded.

In particular, the technical data regarding window framing and curtain walling assemblies chosen for the study, as well as the energy modeling protocol are well documented. The assumptions made by the study regarding maintenance practices and useable life are clearly stated, appear to be reasonable from an architectural perspective, if not a little conservative in their assumptions of durability for aluminium and timber.

LCA-based results appear well reasoned and display clear methodology in the framework of this study. The primary data and results appear to be appropriate in relation to the goal of the study.

Regarding the LCA study performed in chapter 6, it should be noted that two requirements of ISO14044 are not fully respected. The first requirement relates to the sensitivity analyses, in particular on life-span values. Indeed, the choice of useable life-span and material replacement scenario schedule is a difficult aspect of any life cycle assessment, particularly in the building industry where there is no consensus on replacement rates. The second requirement relates to the involvement of third-party stakeholders in the review panel such as competitors. This approach enables to give more reliability and credibility on data and assumptions made for competing products, and finally to have a more-balanced study less prone to criticism once communicated.

In chapter 7, the methodology used to assess the overall sustainability is well-documented, transparent and covers the most relevant aspects of sustainability. However, the choice of a single-score methodology requires a weighting process which inevitably includes value-choice which can be seen as subjective. Indeed, there is no standardised or reference methodology to perform such single-score assessment. Hence, deriving a differentiation from such assessment between the various solutions should be done with caution. In this respect, splitting results between soft criteria and hard criteria would have been beneficial for a more transparent communication. All in all, the conclusions derived from this chapter 7 appears reasonable and appropriate since no material is considered as superior in term of sustainability even if aluminium solutions score best for the chosen methodology and weighting system.

Conclusions

From that study, the commissioner aims at communicating that each framing material presents different pros and cons so that no material appears as the most sustainable solution. In this context, the commissioner recommends focusing on the optimisation of the energy performance of the building during the use phase which remains a more important priority than the choice of framing material, each of which has their pros and cons.

Considering the results of the life cycle and sustainability assessment performed in that study, these main conclusions appear reasonable but would have been more robust if the two above standard requirements had been fully respected.

Diana Fischer (LCA-part and some general aspects)

I am happy to confirm EAA and the intended audience that the study is a well-performed piece of work. The study gives a good overview on the sustainability of different window and façade systems and therefore provides additional benefit regarding the sustainability assessment of buildings.

I am very satisfied with the methodology of the study and can confirm that the primary data and results appear to be appropriate and reasonable in relation to the goal of the study. The assumptions are clear, neutral, consistent and justifiable.

For further studies, improvements could be achieved, if the LCA-part would at least consider the energy demand as additional environmental impact (not only GWP).

Furthermore, we internally discussed the circumstance that competing parties had no chance to give their input during the review process. From my point of view, this deficit is negligible as I could not find any atypical assumptions which would lead to questionable conclusions.

Overall, the LCA-part will fill a gap for detailed and objective information on the environmental burdens connected to windows and façade systems.

Christian Donath (chapter 7, in-depth facade assessment)

In chapter 7, the methodology used to assess the overall sustainability is well-documented, transparent and covers the most relevant aspects of sustainability. However, the choice of a single-score methodology requires a weighting process which inevitably includes value-choice which can be seen as subjective. Indeed, there is no standardised or reference methodology to perform such single-score assessment. Hence, deriving a differentiation from such assessment between the various solutions should be done with caution. In this respect, splitting results between soft criteria and hard criteria would have been beneficial for a more transparent communication. All in all, the conclusions derived from this chapter 7 appears reasonable and appropriate since no material is considered as superior in term of sustainability even if aluminium solutions score best for the chosen methodology and weighting system.

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Stephanie Carlisle (chapter 3, 4 and 5)

I am quite pleased with the final version of the EAA report and am of the opinion that the report is well conducted and sound. The study attempts to present a well-rounded comparison of several distinct architectural assemblies and material choices. In doing so, the report present an in-depth appraisal of trade-offs between material selection choices across the full life cycle from environmental, economic and design perspectives.

I am very satisfied with the documentation and discussion of window framing and curtain walling assemblies chosen for the study, as well as the energy modeling protocol. Detailing and dimensions of assemblies appears to be reasonable and comparable. The choice of useable life and material replacement figures is a difficult aspect of any life cycle assessment, particularly in the building industry where there is no consensus on true replacement rates. The assumptions made by the study regarding maintenance practices and useable life are clearly stated, appear to be reasonable from an architectural perspective, if not a little conservative in their assumptions of durability for aluminium and timber. The report could be improved with the addition of a sensitivity assessment on the building life chosen, as well as the assembly lifespan and material replacement rates used.

While the LCA and LCC results appear well reasoned and display clear methodology, the methodology used in the In-depth façade assessment is less successful in communicating an objective comparison of materials and assemblies.

Even with similar assembly types, comparisons across materials are fraught with difficultly. This report provides a compelling analysis of material selection and systems performance for curtain walling and window framing.

Anis Ghoumidh (LCA-part)

As mentioned in the report, the Life-Cycle Assessment part is carried-out on the basis of ISO 14040, ISO 14044 and EN 15804. In other words, it is not meant to be conducted fully in accordance with these two standards. This approach is understandable. The study is a sustainability assessment with different dimensions. The environmental one is partly assessed with LCA.

In terms of calculation, the study is considered as strong. Indeed, the life cycle is defined in accordance with ISO 14040 and ISO 14044 requirements. Data related to elementary processes are chosen also in accordance with the same requirements. The calculation complies with ISO 14040 and ISO 14044 requirements.

One of EAA target is the use of results for communication issues. Hence, to improve this study, the reviewer recommended following ISO 14040 and ISO 14044 requirements related to this point. The key ones were as follows.

1/ The LCA part should contain a clear sensitivity and uncertainty analysis to identify the range of validity of the conclusions. In particular, the life-span of each product should be a subject of this sensitivity analysis. This approach enables to draw well-defined conclusions which are then more reliable.

2/ The study should involve third-party stakeholders such as competitors. This approach enables to give more reliability and credibility on data and assumptions made for the competing product, and finally to have the study less prone to criticism when results are communicated.

As reported in the scope of the document, these recommendations were not followed in the study.

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