UNIVERSIDADE TÉCNICA DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

LIFE CYCLE ASSESSMENT "FROM CRADLE TO CRADLE" OF BUILDING ASSEMBLIES - APPLICATION TO EXTERNAL WALLS

JOSÉ DINIS SILVESTRE

Supervisor: Doctor Jorge Manuel Caliço Lopes de Brito

Co-Supervisor: Doctor Manuel Guilherme Caras Altas Duarte Pinheiro

Thesis approved in public session to obtain the PhD Degree in Civil Engineering

Jury final classification: Pass with Distinction

Jury

Chairperson: Chairman of the IST Scientific Board

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Volume II – Appendixes

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Appendix 3.I

Composition, dimensions and thermal performance of the external walls solutions

Table 3.I.1 - Single-leaf walls - External insulation

External cladding	Internal coating	Insulation: Material [Density (kg/m^3)]	Insulation: λ [W/(m.ºC)]	Insulation: Thickness (mm)	Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [$W/(m^2.ºC)$]
Adherent (i.e. cement-based, ceramic or natural stone) within a ETICS	Adherent (i.e. gypsum or cement-based, ceramic or natural stone)	EPS (15-20)	0.040	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.67
				40		0.58
				60		0.45
				80		0.37
				40	NCB (0.20 to 0.30)	0.65
				60		0.49
				80		0.40
				60	CW (0.10 to 0.20)	0.56
				80		0.44
		MW (100-180)	0.042	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.69
				40		0.59
				60		0.46
				80		0.38
				40	NCB (0.20 to 0.30)	0.68
				60		0.51
				80		0.41
				60	CW (0.10 to 0.20)	0.59
				80		0.46
Fastened to a supporting structure - VRF (i.e. metallic sheet, wood-based, ceramic or natural stone, creating a ventilated cavity)[1]		XPS (25-40)	0.037	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.67
				40		0.59
				60		0.47
				80		0.40
				40	NCB (0.20 to 0.30)	0.65
				60		0.51
				80		0.42
				60	CW (0.10 to 0.20)	0.55
				80		0.44

External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Fastened to a supporting structure - VRF (i.e. metallic sheet, wood-based, ceramic or natural stone, creating a ventilated cavity)[1]	Adherent (i.e. gypsum or cement-based, ceramic or natural stone)	EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.70
				40		0.61
				60		0.49
				80		0.41
				40	NCB (0.20 to 0.30)	0.68
				60		0.53
				80		0.44
				60	CW (0.10 to 0.20)	0.60
				80		0.48
		EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	40	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.62
				60		0.50
				80		0.43
				40	NCB (0.20 to 0.30)	0.70
				60		0.55
				80		0.46
				60	CW (0.10 to 0.20)	0.62
				80		0.50
		ICB (90-140)	0.045	40	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.65
				60		0.52
				80		0.44
				60	NCB (0.20 to 0.30)	0.57
				80		0.48
				60	CW (0.10 to 0.20)	0.65
				80		0.53

Notes to Table 3.I.1:

- Elements of the wall structure - CHB (Hollow fired-clay bricks, horizontally perforated), NCB (Normal concrete blocks, vertically perforated), LCB (Lightweight - with LECA - concrete blocks, vertically perforated) and CW (In-situ concrete - unreinforced or reinforced - walls);

[1] For these U-values, a surplus should be considered when: wood profiles interrupt the thermal insulation - surplus of 0.02; metallic profiles interrupt the thermal insulation - surplus of 0.08; wood or metallic profiles fastened to isolated metallic supports - surplus of 0.02).

Table 3.I.2 - Single-leaf walls - Internal insulation

External cladding	**Internal coating**	**Insulation**			**Elements of the wall structure [Thickness (m)]**	**Heat transfer coefficient (U-value) [W/(m².ºC)]**
		Material [Density (kg/m³)]	**λ [W/(m.ºC)]**	**Thickness (mm)**		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent to the insulation material or fastened to a supporting structure (e.g. gypsum or wood-based)[2]	XPS (25-40)	0.037	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.63
				40		0.54
				60		0.42
				80		0.34
				40	NCB (0.20 to 0.30)	0.61
				60		0.46
				80		0.37
				60	CW (0.10 to 0.20)	0.52
				80		0.40
		EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.66
				40		0.56
				60		0.44
				80		0.36
				40	NCB (0.20 to 0.30)	0.64
				60		0.48
				80		0.39
				60	CW (0.10 to 0.20)	0.55
				80		0.43
		EPS (13-15)	0.042	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.67
				40		0.58
				60		0.45
				80		0.37
				40	NCB (0.20 to 0.30)	0.66
				60		0.50
				80		0.41
				60	CW (0.10 to 0.20)	0.58
				80		0.45

External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent to the insulation material or fastened to a supporting structure (e.g. gypsum or wood-based)[2]	ICB (90-140)	0.045	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.69
				40		0.60
				60		0.47
				80		0.39
				40	NCB (0.20 to 0.30)	0.69
				60		0.53
				80		0.43
		ICB (90-140)	0.045	60	CW (0.10 to 0.20)	0.61
				80		0.48
	Adherent to the insulation material (e.g. gypsum or wood-based) and creating a non-ventilated cavity (with a thickness higher than 15 mm) between the latter and the elements of the wall structure[3]	XPS (25-40)	0.037	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.57
				40		0.49
				60		0.39
				80		0.32
				30	NCB (0.20 to 0.30)	0.64
				40		0.55
				60		0.42
				80		0.34
				40	CW (0.10 to 0.20)	0.64
				60		0.47
				80		0.38
		EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.59
				40		0.51
				60		0.41
				80		0.34
				30	NCB (0.20 to 0.30)	0.67
				40		0.57
				60		0.45
				80		0.36
				40	CW (0.10 to 0.20)	0.67
				60		0.50
				80		0.40

External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	**λ [W/(m.ºC)]**	**Thickness (mm)**		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent to the insulation material (e.g. gypsum or wood-based or sandwich panel) and creating a non-ventilated cavity (with a thickness higher than 15 mm) between the latter and the elements of the wall structure[3]	EPS (13-15)	0.042	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.60
				40		0.52
				60		0.42
				80		0.35
				30	NCB (0.20 to 0.30)	0.69
				40		0.59
				60		0.46
				80		0.38
				40	CW (0.10 to 0.20)	0.69
				60		0.52
				80		0.42
		ICB (90-140)	0.045	30	CHB (0.20 to 0.24); LCB (0.20 to 0.30)	0.62
				40		0.54
				60		0.44
				80		0.37
				40	NCB (0.20 to 0.30)	0.61
				60		0.48
				80		0.40
				60	CW (0.10 to 0.20)	0.55
				80		0.44

Notes to Table 3.I.2:

- Elements of the wall structure - CHB (Hollow fired-clay bricks, horizontally perforated), NCB (Normal concrete blocks, vertically perforated), LCB (Lightweight - with LECA - concrete blocks, vertically perforated) and CW (In-situ concrete - unreinforced or reinforced - walls);

[2] For these U-values, a surplus should be considered when: the internal coating is fastened to a wood structure that interrupts the thermal insulation - surplus of 0.13; the internal coating is fastened to a metallic structure that interrupts the thermal insulation - surplus of 0.25;

[3] For these U-values, a surplus should be considered when: the internal coating is fastened to a wood structure that interrupts the thermal insulation (which is fastened to the element of the wall structure) and creates a non-ventilated cavity (with a thickness higher than 15 mm) between it and the internal coating - surplus of 0.13; the internal coating is fastened to a metallic structure that interrupts the thermal insulation (which is fastened to the element of the wall structure) and creates a non-ventilated cavity (with a thickness higher than 15 mm) between it and the internal coating - surplus of 0.25.

Table 3.I.3 - Cavity walls - Thermal insulation completely filling the cavity

External cladding	**Internal coating**	**Insulation**			**Elements of the wall structure - external/internal [Thickness (m)]**	**Heat transfer coefficient (U-value) [W/(m^2.ºC)]**
		Material [Density (kg/m^3)]	**λ [W/(m.ºC)]**	**Thickness (mm)**		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	XPS (25-40)	0.037	30	CHB (0.11/0.11)	0.64
				40		0.55
				60		0.42
				80		0.34
				30	CHB (0.11/0.15)	0.60
				40		0.51
				60		0.40
				80		0.33
				30	CHB (0.15/0.15)	0.56
				40		0.48
				60		0.38
				80		0.32
				40	CHB (0.11)/ CB (0.11)	0.60
				60		0.45
				80		0.36
				30	CHB (0.15)/ CB (0.11)	0.66
				40		0.56
				60		0.43
				80		0.35
				40	NCB (0.11/0.11)	0.62
				60		0.47
				80		0.37
				40	NCB (0.11/0.15)	0.61
				60		0.46
				80		0.37
				40	NCB (0.15/0.15)	0.59
				60		0.45
				80		0.36

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	XPS (25-40)	0.037	30	LCB (0.11/0.11)	0.64
				40		0.55
				60		0.42
				80		0.34
				30	LCB (0.15/0.11)	0.63
				40		0.54
				60		0.42
				80		0.34
				30	LCB (0.15/0.15)	0.61
				40		0.52
				60		0.41
				80		0.33
				40	CW (0.10 to 0.20) / CHB (0.11)[4]	0.61
				60		0.46
				80		0.37
				30	CW (0.10 to 0.20) / CHB (0.15)[4]	0.67
				40		0.57
				60		0.44
				80		0.35
				40	CW (0.10 to 0.20) / CB (0.11)[4]	0.68
				60		0.50
				80		0.39
				40	CW (0.10 to 0.20) / NCB (0.11)[4]	0.65
				60		0.48
				80		0.38
				40	CW (0.10 to 0.20) / NCB (0.15)[4]	0.64
				60		0.47
				80		0.38
				40	CW (0.10 to 0.20) / LCB (0.11)[4]	0.61
				60		0.46
				80		0.37

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	XPS (25-40)	0.037	40	CW (0.10 to 0.20) / LCB (0.15)[4]	0.60
				60		0.45
				80		0.36
		EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CHB (0.11/0.11)	0.67
				40		0.57
				60		0.45
				80		0.36
				30	CHB (0.11/0.15)	0.62
				40		0.54
				60		0.42
				80		0.35
				30	CHB (0.15/0.15)	0.58
				40		0.50
				60		0.40
				80		0.33
				40	CHB (0.11)/ CB (0.11)	0.63
				60		0.48
				80		0.39
				30	CHB (0.15)/ CB (0.11)	0.68
				40		0.58
				60		0.45
				80		0.37
				40	NCB (0.11/0.11)	0.66
				60		0.49
				80		0.40
				40	NCB (0.11/0.15)	0.64
				60		0.48
				80		0.39
				40	NCB (0.15/0.15)	0.62
				60		0.47
				80		0.38

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	LCB (0.11/0.11)	0.67
				40		0.57
				60		0.45
				80		0.36
				30	LCB (0.15/0.11)	0.65
				40		0.56
				60		0.44
				80		0.36
				30	LCB (0.15/0.15)	0.63
				40		0.55
				60		0.43
				80		0.35
				40	CW (0.10 to 0.20) / CHB (0.11)[4]	0.64
				60		0.49
				80		0.39
				40	CW (0.10 to 0.20) / CHB (0.15)[4]	0.60
				60		0.46
				80		0.37
				60	CW (0.10 to 0.20) / CB (0.11)[4]	0.53
				80		0.42
				40	CW (0.10 to 0.20) / NCB (0.11)[4]	0.69
				60		0.51
				80		0.41
				40	CW (0.10 to 0.20) / NCB (0.15)[4]	0.67
				60		0.50
				80		0.40
				40	CW (0.10 to 0.20) / LCB (0.11)[4]	0.64
				60		0.49
				80		0.39

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	40	CW (0.10 to 0.20) / LCB (0.15)[4]	0.63
				60		0.48
				80		0.39
		EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	30	CHB (0.11/0.11)	0.68
				40		0.59
				60		0.46
				80		0.38
				30	CHB (0.11/0.15)	0.63
				40		0.55
				60		0.44
				80		0.36
				30	CHB (0.15/0.15)	0.59
				40		0.52
				60		0.41
				80		0.35
				40	CHB (0.11)/ CB (0.11)	0.65
				60		0.50
				80		0.40
				30	CHB (0.15)/ CB (0.11)	0.70
				40		0.60
				60		0.47
				80		0.38
				40	NCB (0.11/0.11)	0.68
				60		0.51
				80		0.41
				40	NCB (0.11/0.15)	0.66
				60		0.50
				80		0.40
				40	NCB (0.15/0.15)	0.64
				60		0.49
				80		0.40

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	30	LCB (0.11/0.11)	0.68
				40		0.59
				60		0.46
				80		0.38
				30	LCB (0.15/0.11)	0.67
				40		0.58
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				80		0.37
				30	LCB (0.15/0.15)	0.65
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				40	CW (0.10 to 0.20) / CHB (0.11)[4]	0.66
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				60	CW (0.10 to 0.20) / NCB (0.11)[4]	0.53
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				60	CW (0.10 to 0.20) / NCB (0.15)[4]	0.52
				80		0.42
				40	CW (0.10 to 0.20) / LCB (0.11)[4]	0.66
				60		0.50
				80		0.41
				40	CW (0.10 to 0.20) / LCB (0.15)[4]	0.65
				60		0.49
				80		0.40

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	ICB (90-140)	0.045	40	CHB (0.11/0.11)	0.61
				60		0.48
				80		0.40
				30	CHB (0.11/0.15)	0.65
				40		0.57
				60		0.45
				80		0.38
				30	CHB (0.15/0.15)	0.61
				40		0.53
				60		0.43
				80		0.36
				40	CHB (0.11)/ CB (0.11)	0.68
				60		0.52
				80		0.42
				40	CHB (0.15)/ CB (0.11)	0.63
				60		0.49
				80		0.40
				60	NCB (0.11/0.11)	0.54
				80		0.43
				40	NCB (0.11/0.15)	0.69
				60		0.53
				80		0.43
				40	NCB (0.15/0.15)	0.67
				60		0.52
				80		0.42
				40	LCB (0.11/0.11)	0.61
				60		0.48
				80		0.40

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	ICB (90-140)	0.045	30	LCB (0.15/0.11)	0.69
				40		0.60
				60		0.47
				80		0.39
				30	LCB (0.15/0.15)	0.67
				40		0.58
				60		0.46
				80		0.38
				40	CW (0.10 to 0.20) / CHB (0.11)[4]	0.69
				60		0.53
				80		0.43
				40	CW (0.10 to 0.20) / CHB (0.15)[4]	0.64
				60		0.50
				80		0.41
				60	CW (0.10 to 0.20) / CB (0.11)[4]	0.58
				80		0.46
				60	CW (0.10 to 0.20) / NCB (0.11)[4]	0.56
				80		0.45
				60	CW (0.10 to 0.20) / NCB (0.15)[4]	0.55
				80		0.44
				40	CW (0.10 to 0.20) / LCB (0.11)[4]	0.69
				60		0.53
				80		0.43
				40	CW (0.10 to 0.20) / LCB (0.15)[4]	0.67
				60		0.52
				80		0.42

Notes to Table 3.I.3:

- Elements of the wall structure - CHB (Hollow fired-clay bricks, horizontally perforated), CB (Clay brick); NCB (Normal concrete blocks, vertically perforated), LCB (Lightweight - with LECA - concrete blocks, vertically perforated) and CW (In-situ concrete - unreinforced or reinforced - walls);

[4] For these U-values, the relative position of the elements of the wall structure (external/internal) does not matter and they can be used for solutions of external walls without cladding in one or both faces.

Table 3.I.4 - Cavity walls - Thermal insulation partially filling the cavity (cavity with a thickness higher than 15 mm)

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	XPS (25-40)	0.037	30	CHB (0.11/0.11)	0.58
				40		0.50
				60		0.39
				80		0.32
				30	CHB (0.11/0.15)	0.54
				40		0.47
				60		0.37
				80		0.31
				30	CHB (0.15/0.15)	0.51
				40		0.45
				60		0.36
				80		0.30
				30	CHB (0.11)/ CB (0.11)	0.63
				40		0.54
				60		0.42
				80		0.34
				30	CHB (0.15)/ CB (0.11)	0.59
				40		0.51
				60		0.40
				80		0.33
				30	NCB (0.11/0.11)	0.66
				40		0.56
				60		0.43
				80		0.35
				30	NCB (0.11/0.15)	0.64
				40		0.55
				60		0.42
				80		0.34

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	XPS (25-40)	0.037	30	NCB (0.15/0.15)	0.63
				40		0.54
				60		0.42
				80		0.34
				30	LCB (0.11/0.11)	0.58
				40		0.50
				60		0.39
				80		0.32
				30	LCB (0.15/0.11)	0.56
				40		0.49
				60		0.39
				80		0.32
				30	LCB (0.15/0.15)	0.55
				40		0.48
				60		0.38
				80		0.32
				30	CW (0.10 to 0.20) / CHB (0.11)[4]	0.65
				40		0.55
				60		0.42
				80		0.35
				30	CW (0.10 to 0.20) / CHB (0.15)[4]	0.60
				40		0.52
				60		0.40
				80		0.33
				40	CW (0.10 to 0.20) / CB (0.11)[4]	0.59
				60		0.44
				80		0.36
				30	CW (0.10 to 0.20) / NCB (0.11)[4]	0.70
				40		0.59
				60		0.44
				80		0.36

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	XPS (25-40)	0.037	30	CW (0.10 to 0.20) / NCB (0.15)[4]	0.68
				40		0.57
				60		0.44
				80		0.35
				30	CW (0.10 to 0.20) / LCB (0.11)[4]	0.65
				40		0.55
				60		0.42
				80		0.35
				30	CW (0.10 to 0.20) / LCB (0.15)[4]	0.63
				40		0.54
				60		0.42
				80		0.34
		EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CHB (0.11/0.11)	0.60
				40		0.52
				60		0.41
				80		0.34
				30	CHB (0.11/0.15)	0.56
				40		0.49
				60		0.39
				80		0.33
				30	CHB (0.15/0.15)	0.52
				40		0.56
				60		0.38
				80		0.32
				30	CHB (0.11)/ CB (0.11)	0.66
				40		0.56
				60		0.44
				80		0.36

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CHB (0.15)/ CB (0.11)	0.68
				40		0.53
				60		0.42
				80		0.35
				30	NCB (0.11/0.11)	0.69
				40		0.59
				60		0.44
				80		0.37
				30	NCB (0.11/0.15)	0.67
				40		0.57
				60		0.45
				80		0.36
				30	NCB (0.15/0.15)	0.65
				40		0.56
				60		0.44
				80		0.36
				30	LCB (0.11/0.11)	0.60
				40		0.52
				60		0.41
				80		0.34
				30	LCB (0.15/0.11)	0.58
				40		0.51
				60		0.41
				80		0.34
				30	LCB (0.15/0.15)	0.57
				40		0.50
				60		0.40
				80		0.33

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (15-20); MW (35-100); PIR/PUR (20-50)	0.040	30	CW (0.10 to 0.20) / CHB (0.11)[4]	0.67
				40		0.58
				60		0.45
				80		0.37
				30	CW (0.10 to 0.20) / CHB (0.15)[4]	0.62
				40		0.54
				60		0.42
				80		0.35
				40	CW (0.10 to 0.20) / CB (0.11)[4]	0.63
				60		0.48
				80		0.39
				40	CW (0.10 to 0.20) / NCB (0.11)[4]	0.62
				60		0.47
				80		0.38
				40	CW (0.10 to 0.20) / NCB (0.15)[4]	0.60
				60		0.46
				80		0.38
				30	CW (0.10 to 0.20) / LCB (0.11)[4]	0.67
				40		0.58
				60		0.45
				80		0.37
				30	CW (0.10 to 0.20) / LCB (0.15)[4]	0.66
				40		0.56
				60		0.44
				80		0.36
		EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	30	CHB (0.11/0.11)	0.61
				40		0.53
				60		0.42
				80		0.35

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	30	CHB (0.11/0.15)	0.57
				40		0.50
				60		0.40
				80		0.34
				30	CHB (0.15/0.15)	0.53
				40		0.47
				60		0.39
				80		0.33
				30	CHB (0.11)/ CB (0.11)	0.67
				40		0.58
				60		0.45
				80		0.37
				30	CHB (0.15)/ CB (0.11)	0.62
				40		0.54
				60		0.43
				80		0.36
				30	NCB (0.11/0.11)	0.70
				40		0.60
				60		0.47
				80		0.38
				30	NCB (0.11/0.15)	0.68
				40		0.59
				60		0.46
				80		0.38
				30	NCB (0.15/0.15)	0.67
				40		0.58
				60		0.45
				80		0.37

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	30	LCB (0.11/0.11)	0.61
				40		0.53
				60		0.42
				80		0.35
				30	LCB (0.15/0.11)	0.60
				40		0.52
				60		0.42
				80		0.35
				30	LCB (0.15/0.15)	0.58
				40		0.51
				60		0.41
				80		0.34
				30	CW (0.10 to 0.20) / CHB (0.11)[4]	0.69
				40		0.59
				60		0.46
				80		0.38
				30	CW (0.10 to 0.20) / CHB (0.15)[4]	0.64
				40		0.55
				60		0.44
				80		0.36
				40	CW (0.10 to 0.20) / CB (0.11)[4]	0.65
				60		0.50
				80		0.40
				40	CW (0.10 to 0.20) / NCB (0.11)[4]	0.63
				60		0.49
				80		0.40
				40	CW (0.10 to 0.20) / NCB (0.15)[4]	0.62
				60		0.48
				80		0.39

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	EPS (13-15); MW (100-180); PIR/PUR (Projected; 20-50)	0.042	30	CW (0.10 to 0.20) / LCB (0.11)[4]	0.69
				40		0.59
				60		0.46
				80		0.38
				30	CW (0.10 to 0.20) / LCB (0.15)[4]	0.67
				40		0.58
				60		0.45
				80		0.37
		ICB (90-140)	0.045	30	CHB (0.11/0.11)	0.63
				40		0.55
				60		0.44
				80		0.37
				30	CHB (0.11/0.15)	0.58
				40		0.52
				60		0.42
				80		0.35
				30	CHB (0.15/0.15)	0.55
				40		0.49
				60		0.40
				80		0.34
				30	CHB (0.11)/ CB (0.11)	0.70
				40		0.60
				60		0.48
				80		0.39
				30	CHB (0.15)/ CB (0.11)	0.64
				40		0.56
				60		0.45
				80		0.37
				40	NCB (0.11/0.11)	0.64
				60		0.49
				80		0.40

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]
		Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	ICB (90-140)	0.045	40	NCB (0.11/0.15)	0.61
				60		0.48
				80		0.40
				30	NCB (0.15/0.15)	0.69
				40		0.60
				60		0.47
				80		0.39
				30	LCB (0.11/0.11)	0.63
				40		0.55
				60		0.44
				80		0.37
				30	LCB (0.15/0.11)	0.61
				40		0.54
				60		0.43
				80		0.36
				30	LCB (0.15/0.15)	0.60
				40		0.53
				60		0.43
				80		0.36
				40	CW (0.10 to 0.20) / CHB (0.11)[4]	0.62
				60		0.48
				80		0.40
				30	CW (0.10 to 0.20) / CHB (0.15)[4]	0.66
				40		0.57
				60		0.46
				80		0.38
				40	CW (0.10 to 0.20) / CB (0.11)[4]	0.68
				60		0.52
				80		0.42

External cladding	Internal coating	Insulation			Elements of the wall structure - external/internal [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]
		Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)		
Adherent (i.e. cement-based, ceramic or natural stone)	Adherent (i.e. gypsum, wood or cement-based, ceramic or natural stone)	ICB (90-140)	0.045	40	CW (0.10 to 0.20) / NCB (0.11)[4]	0.66
				60		0.51
				80		0.42
				40	CW (0.10 to 0.20) / NCB (0.15)[4]	0.64
				60		0.50
				80		0.41
				40	CW (0.10 to 0.20) / LCB (0.11)[4]	0.62
				60		0.48
				80		0.40
				30	CW (0.10 to 0.20) / LCB (0.15)[4]	0.69
				40		0.60
				60		0.47
				80		0.39

Notes to Table 3.I.4:

- Elements of the wall structure - CHB (Hollow fired-clay bricks, horizontally perforated), CB (Clay brick); NCB (Normal concrete blocks, vertically perforated), LCB (Lightweight - with LECA - concrete blocks, vertically perforated) and CW (In-situ concrete - unreinforced or reinforced - walls);

[4] For these U-values, the relative position of the elements of the wall structure (external/internal) does not matter and they can be used for solutions of external walls without cladding in one or both faces.

Appendix 4.I

LCI study - Form to support the collection of data from the production process

Unit process index - Production of a building product
(Company - City)

1	**RECEPTION AND STORAGE OF RAW MATERIALS**
2	**PRODUCTION PROCESS**
3	**PACKAGING AND PALLETISATION**

APPENDIX 4.Ia - QUANTITATIVE DATA CONSIDERED IN THE LCA STUDY

Notes to take into account when filing in this form:
a. The functional unit of the study and of each unit process is ***1 m^3*** of finished product; units to be used: mass - kg; volume - m^3; power - kW; energy - kWh or MJ.
b. All materials must be quantified in volume and mass, and not only in mass, when their bulk density is lower than 300 kg/m^3.
c. Indicate if each figure was collected from a random lot, if it is a daily/monthly/annual average, or if it was estimated, and its inherent uncertainty.
d. Indicate the total figures of the factory and justify the % of allocation to this product (e.g. for the energy for lighting, cooling and heating of the factory production area, for ancillary equipment such as bridge-cranes, or for maintenance operations of machines repeated every three years or more often).
e. This form can be modified but all the changes made must be adequately marked.
f. All recycled materials used in production must be adequately indicated and characterized.
g. The non-reused wastes of each material or raw material must be identified in the section “Outputs (solid products and wastes)” (for chemical substances - potential air emissions associated to their use must be identified).
h. All “Outputs” of unit processes must be characterized concerning the amount and type of hazardous substances that they contain.
i. Whenever possible, all non-material outputs that result from the unit processes must be recorded, namely waste energy or heat, radiation, noise, vibration or odour generated, or different types of land use.
j. All transport operations completed inside the plant, and all subsidiary operations that are needed for the production process, must be identified and characterized.

1. RECEPTION AND STORAGE OF RAW MATERIALS

1.1. Material balance

1.1.1. Description of raw materials, including their: composition and Chemical Abstracts Service (CAS) number, type of storage at plant and allocation (amount used in the production of the studied product compared with the total quantity delivered at plant):

Raw materials	Allocation	Storage
X	***Y***	*Z*

1.2. Water consumption

1.2.1. Volume of water used for cleaning the raw materials storage area - *no consumption*

1.3. Outputs (solid products and wastes) - *no flows identified*

1.4. Outputs (liquid products and wastes)

1.4.1. Characteristics and volume of effluents resulting from the cleaning of the raw materials storage area - *do not exist*

1.5. Outputs (air emissions)

1.5.1. Characteristics and quantity of air emissions resulting from the unloading and transport of the raw materials inside the plant - *do not exist*

1.6. Energy balance

1.6.1. Amount of energy consumed by the loader to pile the raw materials - ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product***

1.6.2. Amount of energy consumed in the transport operations completed inside the plant: transport of raw materials, by loader, from trucks to the storage area, and from there to production area - ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product***

1.6.3. Amount of energy consumed by the loader to transport production wastes to raw materials storage area - ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product***

1.7. Transportation data

1.7.1. Description of the transport used for delivering raw materials to the plant:

Raw materials	Origin	Mode of transport	Gross weight (tons)	Return (Full / empty)
X	*30 km (on average)*	*Truck*	*15 (on average)*	*Empty*

2. PRODUCTION PROCESS

2.1. Material balance

2.1.1. Amount of raw materials consumed per functional unit:

X	*Y kg/m*^{3}

2.1.2. Amount of external fuel consumed in the boiler per functional unit:

Y	*Z m*^{3}*/m*^{3} *finished product*

2.1.3. Description of chemical products used for water treatment, including their: composition and Chemical Abstracts Service (CAS) number, type of storage at plant and amount consumed per functional unit:

Product	**Composition (and CAS)**	**Storage**	**Amount (kg/ m^3)**
Industrial salt (decalcification)	*X* *(Unknown CAS)*	*25 kg bags*	*1 ton/month (approximate consumption) = Y kg/m*^{3} *finished product*
Chemical products	*Y*	*25 l jerry cans (warnings on the jerry cans: harmful, irritants, or corrosives)*	*Sum of four products: Z kg/m*^{3} *finished product*

2.2. Water consumption (source: from borehole)

2.2.1. Volume of water consumed in the boiler per functional unit - ***APPENDIX 4.Ia - Specific consumption of water/m***^{3} ***finished product***

2.2.2. Volume of water for boiler cleaning per functional unit - *no consumption*

2.3. Outputs (solid products and wastes)

2.3.1. Characteristics, destiny, and amount of solid wastes – packaging of chemical products for water treatment and external fuel:

Packaging	**Destiny**	**Amount (kg / m^3)**
Industrial salt - *25 kg bags*	*Recycling*	***APPENDIX 4.Ia - Specific production of plastic/m***^{3} ***finished product***
Chemical products - *25 l Jerry cans*	*Reused by the supplier (production and end-of-life not considered in the modelling)*	*X (production and end-of-life not considered in the modelling)*
External fuel - *supplied in bulk, without packaging*		

2.3.2. Characteristics, origin, destiny, and amount of solid wastes from production process per functional unit:

Solid waste	Destiny	Amount (kg / m^3)
Wastes from combustion in the boiler	*Sent to licensed operator*	***APPENDIX 4.Ia - Specific production of waste in the boiler/m^3 finished product***
Wastes from water treatment	*Do not exist*	
Non-used raw materials	*Does not exist*	

2.4. Outputs (liquid products and wastes)

2.4.1. Characteristics and volume of effluents resulting from the production per functional unit, their origin and destiny: cleaning water and effluents from water treatment, etc. - *do not exist*

2.5. Outputs (air emissions)

2.5.1. Characteristics and quantity of air emissions resulting from the production process (*boiler*):

Origin	Quantity of air emissions	Characteristics
Boiler	***APPENDIX 4.Ia - Specific emissions of CO_2, CO, NOx, VOCs and Particles/m^3 finished product***	

2.6. Energy balance

2.6.1. Amount of energy consumed in the transport operations completed inside the plant: transport of salt, chemical products and external fuel - ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product*** *and* ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***

2.6.2. Amount of energy consumed in the pumping of water from the borehole - ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***

2.6.3. Amount of energy consumed in the cleaning of the water - *does not exist*

2.6.4. Amount of energy consumed in the production proces (water heating and boiler operation) - ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***

2.6.5. Amount of energy consumed in the transport operations completed inside the plant: transport of waste - ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product*** *and* ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***

2.7. Transportation data

2.7.1. Description of the transport used for carrying solid wastes to a licensed operator:

Solid waste	Destiny	Mode of transport	Gross weight (tons)	Arrival (Full / empty)
Waste	*150 km (on average)*	*Truck*	*15 (on average)*	*Empty*
Wastes from water cleaning	*Do not exist*			

2.7.2. Description of the transport used for delivering to the plant - chemical products and fuel for boiler:

Data collection concerning the production of the building product (Company - City)

Product	Origin	Mode of transport	Gross weight (tons)	Return (Full / empty)
Salt and chemical products	*250 km (on average)*	*Truck*	*3.5 (on average)*	*Empty*
External fuel	*30 km (on average)*	*Truck*	*15 (on average)*	*Empty*

3. PACKAGING AND PALLETISATION

3.1. Material balance

3.1.1. Description of each material used for packaging, palletisation and protection during transportation, including their composition and allocation (amount used in the production of the studied product compared with the total quantity delivered to the plant):

Elements for packaging, palletisation and protection during transportation	**Allocation**
PE shrink micro-perforated film	***Specific consumption of PE film (packaging)/m^3 finished product***
Cardboard	***Specific consumption of cardboard (packaging)/m^3 finished product***
Labels with technical information	***Specific consumption of paper (packaging)/m^3 finished product***
Wood pallets	***Specific consumption of pallets (packaging) /m^3 finished product***

3.2. Water consumption

3.2.1. Volume of water used for cleaning the packaging, palletisation and storage areas - *no consumption*

3.3. Outputs (solid products and wastes)

3.3.1. Characteristics, origin, destiny, and amount of solid wastes from packaging and palletisation processes per functional unit: damaged materials used for packaging, palletisation and protection during transportation (***APPENDIX 4.Ia* - *Specific production of plastic/m^3 finished product*** *or does not exist);* Non-conforming products *(used for production of granulate*); packaging of the materials used for packaging, palletisation and protection during transportation:

Data collection concerning the production of the building product
(Company - City)

Elements for packaging, palletisation and protection during transportation	**Plastic film**	**Cardboard (reels or boxes)**	**Pallets**	**Paper packages**
PE shrink micro-perforated film	***APPENDIX 4.Ia - Specific production of plastic/m^3 finished product*** *(Y kg/m^3 finished product)*	***Reel is returned to supplier*** *(in the delivery of new rolls; not considered in the modelling)*	*1 (6 or 8 rolls per pallet) - reused within the plant and burned thereafter (amount of electric energy for their transport to the boiler is already accounted for and they avoid buying other "fuel" for the boiler); a pallet for each Y kg of PE film bought - Z kg/m^3 of finished product (only the production of the pallet was considered in the modelling, the disposal was not considered)*	
Cardboard				*Not significant - not considered in the modelling*
Labels with technical information - A4 sheets (*the packaging is not significant and was not considered)*			*Not significant – not considered in the modelling*	
Wood pallets - *supplied without packaging*				

3.4. Outputs (liquid products and wastes)

3.4.1. Characteristics and volume of effluents resulting from the packaging and palletisation processes per functional unit, their origin and destiny: cleaning water, etc. - *do not exist*

3.5. Outputs (air emissions) - *no flows identified*

3.6. Energy balance

3.6.1. Amount of energy consumed in the transport of the finished product from the packaging and palletisation area to the storage area - *does not exist*

3.6.2. Amount of energy consumed in the packaging and palletisation processes - ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***

3.6.3. Amount of energy consumed in the transport operations completed inside the plant: transport of the packaging of the materials used for packaging, palletisation and protection during transportation - ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product*** *and* ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***

3.6.4. Amount of energy consumed in the transport operations completed inside the plant for the materials used for packaging, palletisation and protection during transportation***:***

Elements for packaging, palletisation and protection during transportation	Amount of energy consumed to transport to the storage area	Amount of energy consumed to transport from the storage area to the palletisation area
PE shrink micro-perforated film	*(By stacker)* ***APPENDIX 4.Ia - Specific consumption of diesel oil/m^3 finished product*** *and* ***APPENDIX 4.Ia - Specific consumption of electric energy/m^3 finished product***	
Cardboard		
Labels with technical information		
Wood pallets		

3.7. Transportation data

3.7.1. Description of the transport used for delivering the materials used for packaging, palletisation and protection during transportation to the plant:

Elements for packaging, palletisation and protection during transportation	Origin	Mode of transport	Gross weight (tons)	Return (Full / empty)
PE shrink micro-perforated film	*150 km (on average)*	*Truck*	*15 (on average)*	*Empty*
Cardboard	*110 km (on average)*	*Truck*	*15 (on average)*	*Empty*
Labels with technical information	*Not significant – not considered in the modelling*			
Wood pallets	*100 km*	*Truck*	*15*	*Empty*

3.7.2. Description of the transport used for carrying solid wastes from packaging and palletisation to a licensed operator:

Solid waste	**Destiny**	**Mode of transport**	**Gross weight (tons)**	**Arrival (Full / empty)**
APPENDIX 4.Ia - Specific production of plastic/m^3 finished product *(for recycling)*	*330 km (on average)*	*Truck*	*15 (on average)*	*Empty*

APPENDIX 4.Ia - QUANTITATIVE DATA CONSIDERED IN THE LCA STUDY

- Electric energy provider - *Spanish company*
- Flow quantification - average figures from 2008 and 2010 (2009 was not a representative year):

Type of flow	Value	Unit
Specific consumption of raw material/m^3 finished product	X	kg/m^3
Specific consumption of water/m^3 finished product (excluding social services, WC and shower rooms)	X	m^3/m^3
Specific consumption of PE film (packaging)/m^3 finished product (the total amount was considered as LDPE)	X	kg/m^3
Specific consumption of pallets (packaging)/m^3 finished product	X	kg/m^3
Specific consumption of cardboard (packaging)/m^3 finished product	X	kg/m^3
Specific consumption of paper (packaging)/m^3 finished product	X	g/m^3
Specific consumption of electric energy/m^3 finished product	X	kWh/m^3
Specific consumption of diesel oil/m^3 finished product	X	l/m^3
Specific production of waste in the boiler/m^3 finished product	X	kg/m^3
Specific production of plastic/m^3 finished product	X	kg/m^3
Specific emissions of CO_2 (boiler)/m^3 finished product	X	kg/m^3
Specific emissions of CO (boiler)/m^3 finished product	X	kg/m^3
Specific emissions of NO_x (boiler)/m^3 finished product	X	kg/m^3
Specific emissions of VOCs (boiler)/m^3 finished product	X	kg/m^3
Specific emissions of particles (boiler)/m^3 finished product	X	kg/m^3

Appendix 5.I

Environmental impacts after normalisation of construction materials and products using Ecoinvent database

(using CML 2001 v. 2.04 and West Europe - 1995 as a reference for normalisation)

Table 5.I.1 - Construction materials - Environmental impacts after normalisation

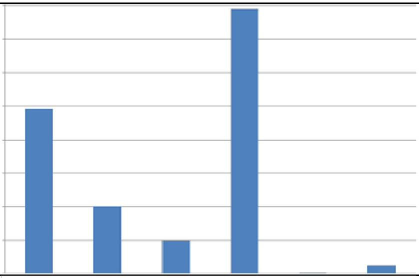
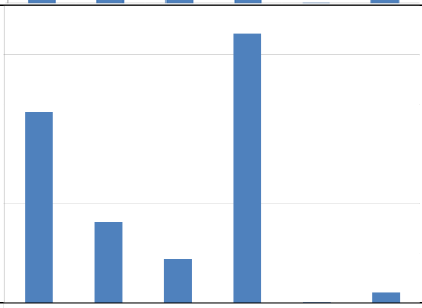
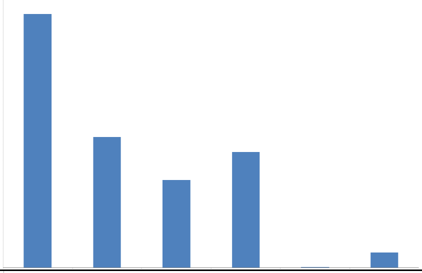
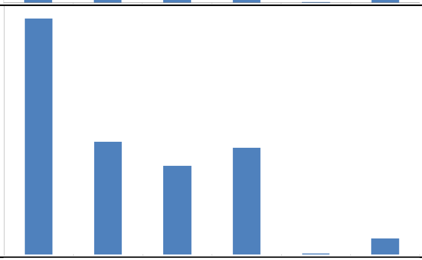
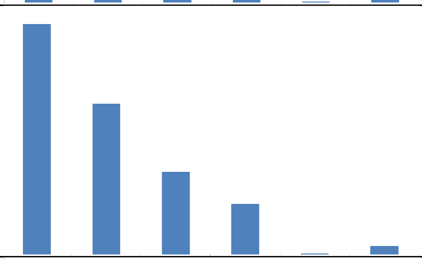
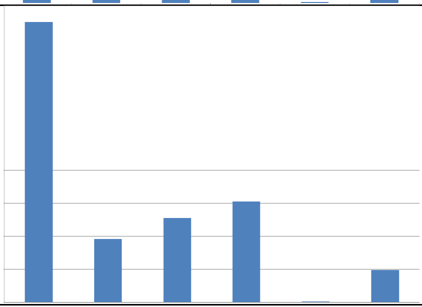
Construction materials	**Ecoinvent process**	**Method: CML 2001 V2.05 / West Europe, 1995 / Normalisation / Excluding infrastructure processes:** ADP AP EP GWP ODP POCP	**Most significant impact category**
Cement	Cement, unspecified, at plant		GWP
Concrete	Concrete, normal, at plant		GWP
Gravel and sand	Sand, at mine		ADP
	Gravel, crushed, at mine		ADP
Gypsum	Gypsum, mineral, at mine		ADP
Reinforcing steel	Reinforcing steel, at plant		ADP

Table 5.I.2 - Elements of the wall structure - Environmental impacts after normalisation

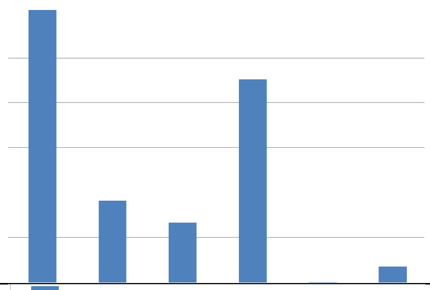
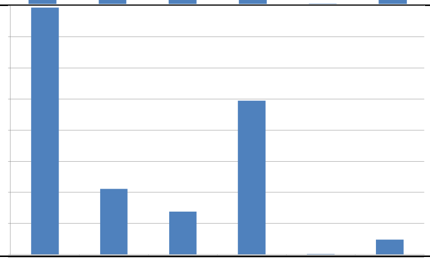
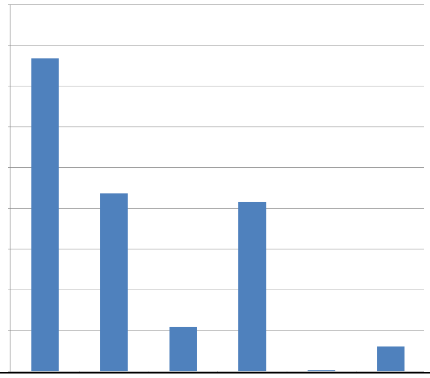
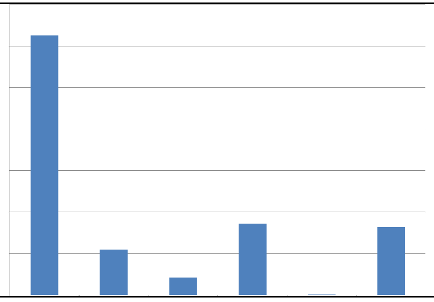
Elements of the wall structure	Ecoinvent process	Method: CML 2001 V2.05 / West Europe, 1995 / Normalisation / Excluding infrastructure processes: ADP AP EP GWP ODP POCP	Most significant impact category
Glass Fibre Reinforced Concrete (GFRC) panels	Fibre cement facing tile, at plant		ADP
Hollow fired-clay bricks	Brick, at plant		ADP
Lightweight concrete blocks	Lightweight concrete block, expanded clay, at plant		ADP

Table 5.I.3 - Insulation materials - Environmental impacts after normalisation

Insulation materials	Ecoinvent process	Method: CML 2001 V2.05 / West Europe, 1995 / Normalisation / Excluding infrastructure processes: ADP AP EP GWP ODP POCP	Most significant impact category
Expanded Polystyrene (EPS)	Polystyrene foam slab, at plant		ADP

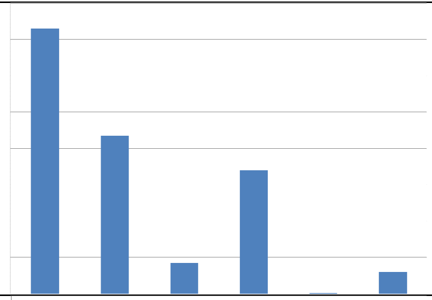
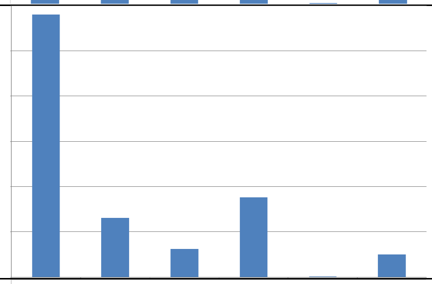
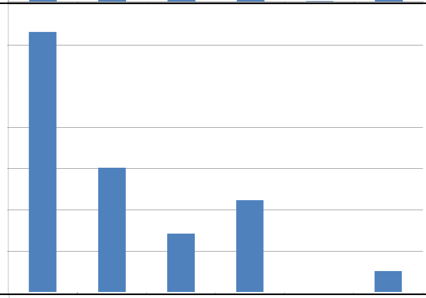
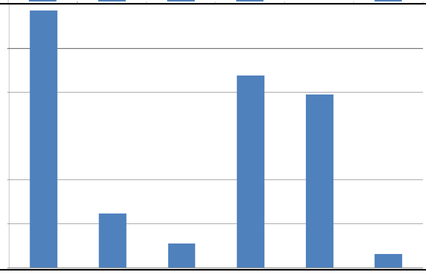
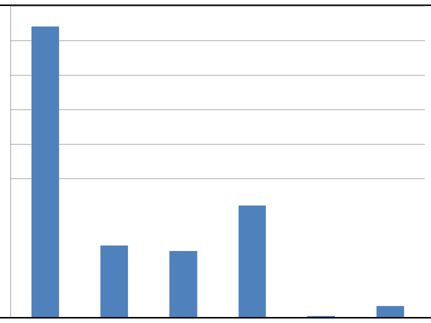
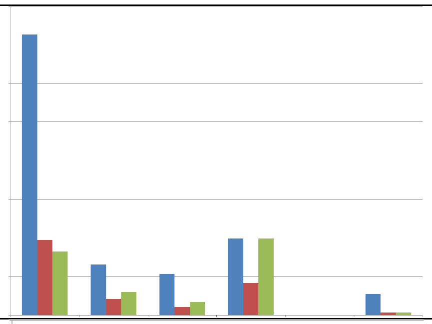
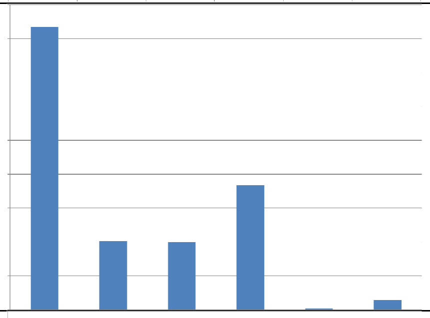
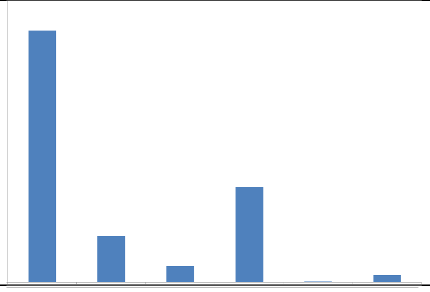
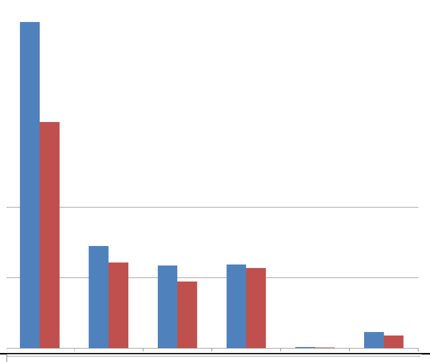
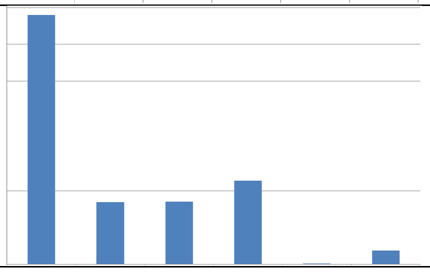
Insulation materials	Ecoinvent process	Method: CML 2001 V2.05 / West Europe, 1995 / Normalisation / Excluding infrastructure processes: ADP AP EP GWP ODP POCP	Most significant impact category
Light Expanded Clay Aggregate (LECA)	Expanded clay, at plant		ADP
Polyurethane/Polyisocyanurate (PUR/PIR)	Polyurethane, rigid foam, at plant		ADP
Stone Wool (SW)	Rock wool, at plant		ADP
Extruded Polystyrene (XPS);	Polystyrene, extruded (XPS), at plant		ADP

Table 5.I.4 - Wall coverings - Environmental impacts after normalisation

Wall coverings	Ecoinvent process	Method: CML 2001 V2.05 / West Europe, 1995 / Normalisation / Excluding infrastructure processes: ADP AP EP GWP ODP POCP	Most significant impact category
Ceramic tiles	Ceramic tiles, at regional storage		ADP

Appendix 5.I - Environmental impacts after normalisation of construction materials and products

Wall coverings	**Ecoinvent process**	**Method: CML 2001 V2.05 / West Europe, 1995 / Normalisation / Excluding infrastructure processes:** ADP AP EP GWP ODP POCP	**Most significant impact category**
Dry pre-mixed mortar	Cover coat, organic, at plant (blue)		ADP
	Cover coat, mineral, at plant (red)		ADP
	Cement mortar, at plant (green)		GWP
Gypsum plasterboards	Gypsum plaster board, at plant		ADP
Gypsum plasters	Stucco, at plant		ADP
Paint	Alkyd paint, white, 60% in solvent (blue)		ADP
	Alkyd paint, white, 60% in H2O (red)		ADP
Two-component adhesive	Adhesive mortar, at plant		ADP

Note to Tables:

- All values in the charts are dimensionless;
- Impact categories: Abiotic Depletion Potential (ADP); Acidification Potential (AP); Eutrophication Potential (EP); Global Warming Potential (GWP); Ozone Depletion Potential (ODP); Photochemical Ozone Creation Potential (POCP).

Appendix 5.II

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Comparative environmental life cycle assessment of thermal insulation materials of buildings

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Abstract: Insulation is a relevant technical solution for cutting energy consumption in buildings. The aim of this paper is to determine and evaluate the environmental impacts of the production of conventional thermal insulation materials: extruded and expanded polystyrene, polyurethane, expanded cork agglomerate and light expanded clay aggregates. These "cradle to gate" results can be considered scientifically sound since they follow the International Standards for Life Cycle Assessment and recent European standards on the environmental evaluation of buildings. They have been achieved through a consistent methodology and based on site-specific data and so provide innovative and up-to-date environmental data on insulation materials.

Keywords: buildings; cradle to gate; environmental impact; life cycle assessment; thermal insulation materials.

1 Introduction

The consumption of energy in the world today contributes to pollution, environmental degradation and global greenhouse emissions. Population growth and economic development have led to an increase in energy consumption. Hence, the foreseeable population growth and the economic development that will occur in various countries will have a critical impact on the environment [1]. The four sectors that contribute the most to energy consumption are the industrial, building (residential/commercial), transportation and agriculture sectors. A large fraction of energy consumption is accounted for by the construction and operation of buildings. In the European Union (EU), the building sector is responsible for over 40% of overall energy consumption, making a significant contribution to CO_2 emissions. Improved building energy performance can therefore alleviate the EU's dependence on energy imports, allow Member States to meet the Kyoto protocol targets and decrease CO_2 emissions [2]. Sustainability is now a relevant focus of the construction industry, and, in particular, environmental concerns related to buildings are growing among the general public and potential building buyers [3].

In Europe, the Energy certification of buildings [4] has already had positive consequences, not only in terms of buildings' thermal performance. If buildings are properly designed and operated, significant energy savings can be achieved. Hence, building designers can play a major part in solving the energy problem by making the appropriate design decisions, at an early stage, for the selection and integration of building components [5]. Thermal insulation materials have an important role and their use is a logical first step to reducing the energy required to keep a good interior temperature and therefore achieve energy efficiency [6].

With the minimization of carbon emissions resulting from the use of buildings, largely due to the progress made towards low or near-zero energy buildings, the relative importance of a building's life cycle stages is changing ([7] cited by [8]). Thus, measures to control and reduce the environmental impacts of the entire production chain of construction have become a priority, in particular the production of building materials. The increased investment in near-zero buildings is also promoting the use of passive solutions for the envelope, resulting in increased insulation thicknesses in buildings all over the world. Thus, the contribution of these materials to the life cycle environmental impact of buildings is also gaining momentum.

This paper comprises five sections, including this introduction. The scope section sets out the object of this study, including the state of the art of similar approaches. The LCA methodology used is described in detail in the third section. The resulting graphs are presented and analysed in section four. The paper ends by drawing conclusions that summarize the main findings of the work.

2 Scope

A range of thermal insulation materials are available on European markets. They can be grouped in three families according to their chemical or physical structure: mineral/inorganic; oil-derived; and so-called "organic natural". Furthermore, these materials can have a fibrous or cellular structure that will determine to a great extent both their mechanical and thermal properties (Table 1) [9].

Mineral/inorganic materials account for 60% of the market in Europe; oil-derived materials account for about 30% (particularly extruded polystyrene (XPS), expanded polystyrene (EPS) and polyurethane/polyisocyanurate (PUR/PIR)); and “organic natural” and other materials account for about 10% [10]. In this last group, expanded cork agglomerate (insulation cork board - ICB) is highlighted since Portugal is the world’s largest producer and exporter of cork-based materials. This material can be used both as insulation and as an external cladding (Figure 1). More exotic materials, such as transparent and dynamic insulation, ecological materials based on agricultural raw materials, and gas-filled and vacuum insulated panels, have found only limited acceptance in the market, mainly because of their high cost (various references cited by [10]).

Insulation materials can also be made in different shapes including loose-fill, blanket, batts or rolls, rigid, foamed-in-place, or reflective form (Table 2). The choice of the insulation materials’ type and shape depends on the intended application as well as the target’s physical, thermal and other properties [11].

Lightweight granular materials can be classed as organic (natural or synthetic), inorganic (not-transformed and transformed materials, not-transformed and transformed by-products) and mixed solutions (e.g. the so-called expanded cork - ICB - regranulate [12], or black regranulate of expanded cork, in a cement mortar matrix). These materials have several advantages: they use raw materials that do not need significant production processes to be used; they promote the recycling of scrap or waste from different industries, by shredding or other methods, and they valorise natural resources and industrial by-products. Some examples are:

- EPS granulate resulting from the pre-expansion stage of EPS board production;
- EPS or XPS regranulate resulting from shredding of waste, scrap or non-conforming boards;
- Cellulose fibres recycled from discarded journals and newspapers;
- ICB regranulate or ground raw cork.

One of the disadvantages of these materials is that their final performance strongly depends on the application quality (e.g. complete filling of the cavity). Their thermal performance can also be affected by water absorption, adsorption, and settlements (which occur more easily when the initial void index is high and when internal cohesion, dimension of the particles or dead-weight are low). Settlements can be caused by the weight of the insulation material, building vibration or hydrothermal variations. These materials can be supplied in bulk, without packaging and at lower loading costs at the plant and unloading costs on-site, but are normally sold in bags of 50, 100 or 500 litres [13].

This group of materials is of unquestionable significance in the energy, environmental and economic performance of the building envelope [14], and therefore an interdisciplinary research project was carried out to provide the environmental life cycle assessment of the main thermal insulation materials of buildings. This research included a Master’s Dissertation in Environmental Engineering [15] and a PhD Thesis in Civil Engineering [16].

The insulation materials selected for this study are those most often used in Portugal. They include XPS, EPS, PUR, ICB and LECA. A number of studies on the potential environmental impacts of producing some of these materials have already been performed (Table 3). Nevertheless, very few international studies have been published on the environmental impacts generated by the manufacture of LECA and ICB. This paper can help to fill this gap and provide a detailed environmental impact assessment of the thermal insulation materials proposed, based on real data obtained from Portuguese manufacturers. Since Portugal is a major manufacturer and exporter of cork-based products (in particular ICB boards), the environmental impact analysis of ICB should yield significant results through comparison with the alternatives.

2.1 State of the art on the environmental performance of thermal insulation materials

One of the most important properties of a thermal insulation material is thermal conductivity. Ideally, if a thermal insulation material has low thermal conductivity (W/(m.K), it is possible to obtain relatively thin building envelopes with a high thermal resistance *R-value* (m^2.K/W) and a low thermal transmittance *U-value* (W/ m^2K) [17]. Therefore, the service provided by these materials is their thermal insulation, with a specific performance level in a specific area (e.g. a square meter), and the parameters of this functional unit should be defined in order to compare different types of insulation materials.

Various life cycle assessment (LCA) studies of insulation solutions have already been performed. In most of these studies the functional unit (f.u.) was defined as the mass (kg) of insulation board that provides a thermal resistance R of 1 (m^2K/W) [18]:

$$\text{f.u.} = R\,\lambda\,\rho\,A \tag{1}$$

Where R represents the thermal resistance as 1 (m^2.K)/W, λ is the thermal conductivity measured as W/(m K), ρ corresponds to the density of the insulation product in kg/m^3 and A is the area as 1 m^2. This f.u. provides information on the volume of insulation material necessary to provide a given thermal resistance throughout the insulation life span, focusing only on the insulating and environmental properties of the material under study [18].

The main characteristics of LCA research studies of thermal insulation materials conducted worldwide are presented in Table 3, and they all compared functionally equivalent products. A detailed analysis of the results of these studies and of the information summarized in Table 3 showed that:

- The production technology, energy mix and most significant environmental impact categories differ from country to country;
- Regarding the production phase, the introduction of recycled materials into the product composition and the use of natural resins are good options to improve their environmental performance;
- The results for the transportation phase show that when choosing an insulation material it is important to consider both the energy used in manufacturing and the location of the insulation production site;
- The material with the best environmental performance is highly dependent on the environmental categories chosen in each study;
- The variety of origins of the raw materials (mineral, oil-based and organic) of thermal insulation materials results in different main environmental impact categories for each group.

Despite the differences between the LCA research studies evaluated, all of them should have a definite scope and methodological approach to compare functionally equivalent products. However, some of the studies listed in Table 3 do not follow these principles, which create limitations on the interpretation and comparison of their results [14, 15]. It was also found that only some of the studies were based on site-specific inventory data. Although some of these studies do follow LCA International Standards [19, 20], none of them reference the most recent European Standards related to the Sustainability of Construction Works (e.g. [21, 22]), which were followed in the research study presented here.

3 Research methodology

A life-cycle thinking concept should be adopted to determine the environmental impacts of insulation materials; the LCA methodology supports this concept and is a powerful tool to compare various insulation materials for their environmental performance. The technical committee (TC) 350 of the European Committee for Standardisation (CEN/TC 350 - Sustainability of Construction Works) is drafting a set of European standards for the sustainability assessment of buildings and construction products; they have been structured into three vertical columns (environmental, social and economic). Only quantifiable environmental indicators are to be considered in either building or construction material evaluations, based on these standards. They have been finishes recently and enable the assessment of the environmental performance of buildings and building products, based on a life cycle approach. In fact, the assessment of environmental performance is based on the LCA method [19, 20], and so allows LCA results from different studies of functionally equivalent building products to be compared and to be used to make meaningful choices [23, 24].
The LCA process has four phases: (1) definition of goal and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA) and (4) interpretation. These phases are briefly described below (ISO 14044, 2006):

1. The goal and scope definition phase identifies the objectives of the study, the functional unit, system boundaries, assumptions and limitations.
2. The LCI phase gathers data on the material and energy flows. The LCA study is based on input and output data from Portuguese insulation materials’ producers.
3. The LCIA phase assesses the potential environmental impacts related to the inputs and outputs from the inventory analysis phase according to different environmental impact categories.
4. The interpretation phase discusses the LCA results so as to assist decision-makers in making a final choice.

The life cycle stages of construction materials and products are already standardized (Table 4) in the European Standards [21, 22]. Therefore, the boundaries of an LCA study of a building material or assembly can be defined either from cradle to gate (including the extraction and processing of raw materials and the production), from cradle to grave (including also the transport, distribution and assembly, use, maintenance and final disposal), or from cradle to cradle (C2C), which further includes the reuse, recovery and/or recycling potential (Table 4) [25, 26]. A cradle to gate LCA approach is used in this paper, which means that the environmental impact analysis starts at the extraction of raw materials (A1 phase) and continues through their transportation (A2 phase), and finally the production (A3 phase) and packaging (A3.1 phase) of insulation material (Table 4).
In contrast with the majority of the studies listed in Table 3, this paper presents the results of LCA research studies on insulation materials that were based on the same methodological approach. This approach followed recent European standards drafted under CEN/TC 350, international standards on LCA [19, 20], and some methodological procedures described in detail in section 3.2. The LCA boundary (Product stage: A1-A3), geographical representativeness (Portugal), type of inventory data (site-specific), and environmental categories chosen are also similar for all the studies completed. Thus, it was possible to obtain and compare LCA results for functionally equivalent insulation materials.

3.1 LCA study of thermal insulation materials

The purpose of an LCA study and its field of application must be clearly defined. The goal of the current LCA study is to outline and compare the environmental profile of common thermal insulation materials. Therefore, the primary objective of the LCA study is to determine and evaluate individually the environmental impacts of five traditional thermal insulation materials manufactured in Portugal, based on a cradle to gate LCA approach. The secondary objective of the LCA study is to compare these thermal insulation materials in terms of the energy consumption during production and of their potential environmental impacts.

Ferrão [25] proposes a method to classify the quality of information used in an LCA study. This method (reproduced in Table 5) includes the most important indicators for evaluating the quality of data collected and it was applied to the classification of the information used in the LCA studies presented in this paper (Table 6). From this table it is possible to conclude that the quality of the information (site-specific data) varies in each study. Nevertheless, the quality has an average value of 1.6 in the 5 studies (on a 1 to 5 scale, where 1 = the best quality), which can be considered a good and appropriate value for the global aim of this work.

3.1.1 Functional unit

The functional unit (f.u.) of our LCA study is defined as the mass (kg) of insulation board that provides a thermal resistance R-value of 1 (m^2.K/W) and an area A of 1 m^2 [18], as defined in equation (1).

According to the above definition of f.u. and the considerations concerning functionality, the amount of insulation material that needs to be installed can be determined (Table 7). Such f.u. mainly focuses on the insulating properties of the thermal insulation materials [18]. The variables presented in Table 7, such as density, thermal conductivity and thickness, were provided by the relevant Portuguese insulation materials' producers. In the case of XPS different thicknesses correspond to different thermal conductivity values and, therefore, various f.us were calculated. Two average weights per f.u. were calculated for this material because the environmental impacts of its production depend on the final thickness of the boards: one set of blowing agents is used for thicknesses of 80 mm or less and another one is used for thicknesses of 80 mm or more (see 4.5).

3.1.2 System boundaries

The system boundaries establish the unit processes to be included in the study. The boundaries in the cradle to gate life cycle of thermal insulation materials are (Table 4):

- A1 - production/extraction of raw materials;
- A2 - transport and storage of raw materials;
- A3 - manufacturing of thermal insulation material.

For reasons of transparency and traceability, and following the recommendations of European standards [22], the environmental impacts and potential benefits quantified in the A3 stage are subdivided in this paper (namely in the presentation of LCA results - see §4) into three independent information modules which set out the manufacturing process in more detail:

- A3.1 - covering manufacturing and transportation to the factory of the packaging material that leaves the factory gate with the product;
- A3.2 - covering the gate to gate manufacturing of the product being studied, and of ancillary materials, pre-products and coproducts, all internal transportation, and the disposal of final waste (except packaging waste) generated during production;
- A3.3 - covering the production and disposal of raw materials or admixtures' packaging, and of the wrapping material of the packaging products.

The production of packaging for raw materials or admixtures (and also of the material for wrapping the packaging products) was included in the A3.3 module rather than the A3.2 (or A3.1) modules because it was impossible to isolate each of the flows from the global packaging waste streams accounted for in each plant.

Background data for modelling the production processes was taken mainly from Ecoinvent database [27] (e.g. data for the extraction/production of raw and packaging materials, electricity - see 3.1.4, and transportation of raw materials), although all data used for the inventory phase was based on questionnaires answered by manufacturers. The data sets selected to model the background processes of "production" of raw materials for the insulation materials studied are summarized in Table 8. The LCA tool chosen to model the production processes was SimaPro [28].

3.1.3 Choice of the Environmental Impact assessment method (EIAM) and categories

According to the European standard that provides the core product category rules for all construction products and services, EN 15804:2012, the impact assessment should involve seven categories (i.e. global warming, ozone depletion, acidification of soil and water, eutrophication, photochemical ozone creation, and depletion of abiotic resources (elements and fossil, separately, but the latter may be used and explained alone, if the values are known)), the characterization factors being taken from CML 2001 (developed in the Netherlands by the Institute of Environmental Sciences (CML) of Leiden University). Therefore, this EIAM was chosen for the impact assessment of the insulation products studied. The characterization models and LCIA indicators of the midpoint environmental impact categories that were used (and whose results are presented in section 4) are summarized in Table 9. These impact categories are those most used in LCA studies [29] and EPD (Environmental Product Declarations), allowing the comparison of results for similar construction products.

The results presented in section 4 include two more environmental categories calculated based on a single issue method published by Ecoinvent and expanded by PRé Consultants [30]. The cumulative energy demand (CED) method expresses the depletion of energy resources and its calculation is based on the higher heating value [31]. It provides, in fact, the calculation of six environmental categories (non-renewable, fossil; non-renewable, nuclear; non-renewable, biomass; renewable, biomass; renewable, wind, solar, geothermal; renewable, water) which were grouped and presented in a simplified form in only two categories with the same unit (megajoule - MJ):

- Consumption of primary energy, renewable (PE-Re, or renewable energy resources depletion);
- Consumption of primary energy, non-renewable (PE-NRe, or non-renewable energy resources depletion).

It is always preferable to choose a set of indicators from a robust and unified methodology (defined in this case in the CML Operational guide to the ISO standards [32]) than to choose each indicator from different methodologies. Gervásio [29] justifies this statement by noting that the interdependency of the indicators is taken into account in each methodology, e.g. considering in the development of characterization factors (for each category in CML) that a given emission can contribute simultaneously to more than one category. Two more arguments favour the choice of CML EIAM and of this set of categories for this study [29]:

the characterization models were developed based on European data, which is still more important to the categories with effects at a local scale; these categories reflect most of the present worldwide environmental concerns.

3.1.4 Energy processes

Processes included in the Ecoinvent database [27] for each energy carrier appropriately represent the reality of the Western countries, including Portugal, namely the interdependent network between countries that characterizes the international trade in electricity [33]. Therefore, these were used as a basis to model the energy supply of the production processes studied, while the corresponding quantification was carried out using site-specific data. Based on a specific composition of these energy carriers, the Ecoinvent database also includes processes that correspond to the national electricity supply for industrial (Electricity, medium voltage, at grid/PT U) consumers, based on the energetic mix of 2004. However, to accurately estimate the environmental impacts of the companies from the consumption of energy for production of the insulation products studied, these processes were updated using the latest information available concerning the Portuguese electricity mix (data from 2011) [34]. The processes themselves were not actually modified, only their share in the national electricity mix. In fact, these processes have already been thoroughly studied in several research centres worldwide, and available LCA databases include the relevant results [33]. Moreover, the modelling of energy supply systems is very complex because it involves several networks of suppliers, processing companies and distributors in a global context [33]. Table 10 presents the differences between the Portuguese electricity mix in 2004 and the updated one - of 2011, for industrial consumption. These figures show an increasing contribution from renewable energy carriers (e.g. photovoltaic) and from less harmful technologies (e.g. cogen with biogas), and a reduction in the most harmful technologies (e.g. hard coal and oil), which is leading to a mitigation of the environmental impacts of electric energy use. The use of the national electricity mix that expresses the present reality is even more important when the manufacturing (A3) is energy intensive, and, indeed, most of the environmental impacts of the life cycle of the product come from this stage.

The collection of data on the energy consumption for the manufacturing of each functional unit was easier in some of the studies presented in this paper because, in Portugal, industries that consume more than 1,000 tonnes of oil equivalent (toe) per year (plants termed intensive consumers of energy) have to undergo energy audits [25]. Each energy audit report is also a robust starting point for an LCA study [25].

3.1.5 Allocation procedure

The requirements for the allocation procedure to be considered in LCA studies are included in international and European standards [19, 20, 22]. These requirements were taken into account when modelling the products studied in this paper, to allow the artificial division of the input and output flows (and relevant environmental impacts) of the operation of each plant by the different products manufactured in order to assign a proportion to the product system under study. A summarized description of the allocation procedure followed in the completed LCA studies is presented in this section for the products for which the consequences of physical (e.g. volume or mass) and economic allocation have been compared.
The allocation procedure is most critical for products:

1. that are co-produced with other goods
2. for which manufacturing results in production waste that is recycled inside the plant and sold as a co-product.

The production of expanded polystyrene (EPS) boards includes both situations. EPS boards are produced jointly with EPS granulate until the moulding stage. All the EPS production waste is milled into regranulate and sold. Three allocation alternatives were considered for this manufacturing process: volume, mass and economic allocation (Table 11). The first option appears to be the most obvious and direct, because all production flows are measured by the company based on the final production volume of each product (boards, granulate and regranulate). However, while the final volume of the boards is directly related to their density (15 kg/m3, on average), the final volume of the other two products results from the bulk density (10.5 kg/m3 and 9 kg/m3 for granulate and regranulate, respectively). Therefore, the allocation based on the final volume does not express the physical relationship between the products during the production process. The option was to apply mass allocation (using the final production volume and the density or bulk density) between these three products in order to correctly express the physical relation between them during manufacturing.

Allocation can also be economic, especially when the difference in revenue from the co-products is not low, which can be estimated at 9% or more (1% or less is considered very low and more than 25% is regarded as high, according to European standards [22]). It was found in this case that the difference in revenue between EPS boards and regranulate is around 50%, that is, high, and the difference between EPS boards and granulate is around 15% (which is not considered to be low). Taking into account the proceeds from these revenues (based on the procedure described by Guinée et al. [35]), it was found that economic allocation can increase the share of the product system under study (EPS boards) by 5% (Table 11). This alternative was not selected, however, because it leads to final results that do not respect the underlying physical relationships between the products. Moreover, LCA results achieved using economic allocation do not express the authentic environmental impacts related to the production of each co-product. Furthermore, these results cannot be compared with available LCA results for the same products (in LCA databases or EPD) because the latter are usually achieved using allocation based on physical relations. Finally, even though this research work does not follow any specific PCR rules, it was considered more accurate to apply allocation based on physical relations in all the LCI studies completed, instead of applying different allocation procedures to each study.

The production waste from polyurethane/polyisocyanurate (PUR/PIR) board manufacturing is also milled and sold and is thus a co-product of the boards. However, its final end and selling price depends on its quality and size: regranulate can be used as a lightening element in several situations; powder is sold for different industries (e.g. plastics recycling or cosmetics). The allocation between the boards and the production waste was done, in this case, directly by the company, assuming a 10% share of all production flows for the latter. This figure derives from the comparison between the volume of blocks produced and the final volume of boards sold.

The manufacturing of ICB boards also co-produces regranulate that results from the milling of production waste. Three allocation alternatives were also considered for this manufacturing process: volume, mass and economic allocation (Table 12).The first option is again the most obvious and direct, for the same reasons as described for EPS boards. However, allocation based on the final volume again does not express the physical relationship between the products during the production process (the density of the boards is 110 kg/m3 and the bulk density of regranulate is 70 kg/m3). The option was therefore to apply mass allocation (using the final production volume and corresponding density or bulk density) between these two products.

Concerning economic allocation, it was found in this case that the difference in revenue between ICB boards and regranulate is around 27%, which is high. Taking into account the proceeds from these revenues [35], it was found that economic allocation can increase the share of ICB boards by 4% (Table 12). However, this alternative was not selected for the same reasons given for EPS boards.

4 Results of the LCA studies of thermal insulation materials

This section covers the environmental impacts of the Product stage (A1-A3) of thermal insulation materials in two phases. First, the relative percentage contribution of each sub-stage to the cradle to gate LCA results of the production of each material is presented and analysed. Then the cradle to gate LCA results of the production of the insulations materials are shown and compared for each environmental category. These results were achieved by following the LCA procedures described, and their figures are in accordance with the functional unit defined for each study.

4.1 Expanded Polystyrene (EPS)

EPS boards are suitable for application in several building assemblies. Figure 3 shows the relative percentage contribution of sub-stages (A1-A3) to the cradle to gate LCA results of the production of these boards. This figure shows a substantial influence of raw material production (A1) in the environmental impact of this product (except for ODP and POCP, but from 40% in PE-Re to 78% in PE-NRe). This impact is due to the production process of the only raw material used: the polystyrene expandable granulate. Concerning the other contributors to environmental impacts, the share of the manufacturing sub-stage (A3.2) is between 15% (in ADP) and 98% (in ODP). This sub-stage is dominated by the impact of burning naphtha in the boiler (modelled using the Ecoinvent process "Naphtha, burned in boiler 100 kW condensing, non-modulating"), by the electricity consumption and by pentane and isopentane release during manufacturing (98% of the contribution to the impact of A3.2 in POCP). Table 13 presents the relative contribution of the first two of these processes to the other impact categories in the A3.2 sub-stage.

4.2 Expanded Cork Agglomerate (ICB)

ICB boards are an insulation material that can be used in a number of building assemblies. Figure 4 shows the relative percentage contribution of sub-stages (A1-A3) to the cradle to gate LCA results of the production of these boards. Figure 4 reflects the fact that only one raw (and natural) material is used in ICB production - the "falca". Thus, the A1 sub-stage contribution is only significant for PE-Re (88.9%) and for ODP (33.9%), the former being mainly related to forests and forest roads, conservation and maintenance operations. However, the contribution of manufacturing (A3.2) is significant in many categories, such as AP, EP, GWP and POCP (more than 65%).

Figure 5 and Figure 6 provide a more detailed analysis of the individual contributors to A3.2 sub-stage impacts for EP and GWP, respectively. However, the most important contribution to EP (about 40%) is not represented in diagrams and corresponds to the impact of the direct air emissions from the boiler during the heating of water for the expansion process. Electricity consumption contributes around 10% to EP, while the disposal of the wood ash residue from the boiler for use on agricultural land is responsible for 48.2% of the impacts in this impact category. Concerning GWP, only electricity consumption presents a significant impact (95.8%) because the CO and CO_2 emissions from the boiler are biogenic and therefore not considered in this impact category by the EIAM used (CML).

4.3 Light Expanded Clay Aggregate (LECA)

LECA can be used in the insulation of several building elements but it is also used as a raw material in the production of lightweight concrete blocks. LECA is available on the market both in polyethylene (PE) (50 litres, palletized with 60 bags per wooden pallet) and polypropylene (PP) bags (open big-bags containing 1.5 m^3 or 3 m^3).

The relative percentage contribution of the sub-stages (A1-A3) to the cradle to gate LCA results of the production of LECA packaged in PE and PP bags is presented in Figure 7 (PE) and Figure 8 (PP). PP bags and raw materials do not generate packaging waste, thus the A3.3 sub-stage does not have impacts for LECA in PP bags (Figure 8). Only the cumulative impacts (A1-A3) and the packaging ones (A3.1) differ for these packaging alternatives. These figures express the environmental benefit of choosing PP bags (even if only available from a minimum order of 1.5 m^3) and the impact of the packaging in (PE bags) and palletization. In fact, the difference in environmental impact on the A3.1 sub-stage of these two alternatives varies between 1% in ODP and 77% in PE-Re, and it is also relatively significant for EP (10%) and GWP (8%).

Considering Figure 8, a more detailed analysis of the other life cycle stages can be made. Manufacturing (A3.2) is responsible for a large share of the environmental impacts (more than 78% in every category). The main individual contributors to this sub-stage are presented in Figure 9, Figure 10 and Figure 11 for three impact categories (AP, EP and GWP). These figures show that the contribution of coke production to environmental impacts varies between 20.8% (AP) and almost 57% (EP). Electricity consumption also has a share in these categories, which can vary between 5.02% (AP) and 24.7% (EP), with an intermediate value in GWP (12.9%). Environmental impacts from diesel stacker operation are around 5% in EP, while the share that is not represented (more than 70% in the AP diagram - Figure 9, and more than 60% in the GWP diagram - Figure 11) results from the impact of the direct air emissions from the kiln during the baking process.

4.4 Polyurethane (PUR)

PUR boards can be used in walls and roofs, for example. Figure 12 shows the relative percentage contribution of sub-stages (A1-A3) to the cradle to gate LCA results of the production of these boards. The importance of raw material production (A1) in PUR/PIR environmental impacts is expressed in Figure 12. The contribution of this life cycle stage is in fact significant to many categories (more than 75% for PE-NRe, ADP, AP, GWP and POCP), and is only less than 40% for PE-Re. Manufacturing (A3.2) has an impact of 27% for the former category mainly due to electricity consumption during this stage. The burdens related to packaging waste (A3.3) are mainly due to the fabrication of the metal bins (raw material packaging).

Figure 13, Figure 14 and Figure 15 provide a more detailed analysis of the individual contributors to the A1-A2 sub-stages' impacts for EP, GWP and POCP, respectively. Impact from transportation (A2) is higher on EP (13%), while raw materials (polyol and isocyanate) share the remaining parcel of impacts on this and the other two categories. Polyol has a higher impact on POCP (61.6%), with a contribution of about half this value to the other two categories (EP and GWP). Isocyanate, on the other hand, makes a lower contribution to POCP (37%), and is the main contributor to EP (53.7%) and GWP (63.2%).

4.5 Extruded Polystyrene (XPS)

Extruded polystyrene (XPS) boards are suitable for application in the building envelope, particularly in external walls (within an external thermal insulation composite system - ETICS, or internal thermal insulation, usually glued to gypsum plasterboards). Cradle to gate LCA results of the production of one cubic metre of XPS depend on the final thickness of the boards, because one set of blowing agents is used for thicknesses of 80 mm or less (dimethyl ether and carbon dioxide) and another one is used for thicknesses of 80 mm of more (difluoroethane and ethanol). Therefore, these results are presented in two parts.

Figure 16 shows the relative percentage contribution of the sub-stages (A1-A3) to the cradle to gate LCA results of the production of boards with thickness of 80 mm or less.

The importance of raw material production (A1) to XPS environmental impacts is expressed in Figure 16. The contribution of this life cycle stage is in fact significant to many categories (more than 65% for PE-NRe, ADP, AP and GWP), and is only smaller than 40% for PE-Re, ODP and POCP. Manufacturing (A3.2) has an important impact on many categories (more than 25% for AP, EP and GWP and more than 50% for PE-Re, ODP and POCP) mainly due to electricity consumption and air emissions during this stage. These air emissions are mainly generated during the internal recycling of production waste and by the release of dimethyl ether during the extrusion process.

Figure 17, Figure 18 and Figure 19 provide a more detailed analysis of the individual contributors to A1-A2 sub-stages' impacts for ADP, EP and POCP, respectively. Impact from transportation (A2) is only important to EP (8%), while raw materials (mainly polystyrene, but also dimethyl ether and flame retardant) share the remaining parcel of impacts on this and on the other two categories. Polystyrene has a higher impact on ADP and POCP (93.7% and 92.2%, respectively), and makes a lower contribution to the other category (76.3% in EP). Dimethyl ether, on the other hand, makes its highest contribution to EP (8.93%), and it is also on this category that the impact of the flame retardant is more significant (4.32%).

Figure 20 shows the relative percentage contribution of sub-stages (A1-A3) to the cradle to gate LCA results of the production of boards with thickness of 80 mm or more.

The LCA results for XPS boards with thickness $\geq$ 80 mm (Figure 16) only differ from those of the boards with thickness $\leq$ 80 mm (Figure 20) in the A1 and A2 stages, as expected. The importance of raw material production (A1) is also similar and significant for both groups of thicknesses (Figure 16 and Figure 20).

A more detailed analysis of the individual contributors to stage A1 (and A2) impacts is provided in Table 14. In fact, almost all the burden of each impact category results from polystyrene and difluoroethane production, except for ODP (with a contribution of 22.4% of the flame retardant). This table therefore presents the relative contribution of both raw materials to each impact category in the A1 and A2 sub-stages (the contribution of the latter sub-stage is lower than 8% in every category).

4.6 Comparison of LCA results per functional unit

The comparative results per f.u. for the five thermal insulation materials are presented in Table 15. In general, all insulation materials make a low contribution to ODP and PE-Re, except ICB in the last category. This impact is related to forests and forest roads, conservation and maintenance operations to allow raw material extraction (see 4.2). ICB is also the product making the most significant contribution to EP, which is mostly related to direct air emissions from the boiler during the heating of water for the expansion process (about 40%) and to the disposal of wood ash residue (from the boiler) for use on agricultural land (48.2%).

With respect to ADP, an almost linear relationship was found with PE-NRe (Figure 21), which shows the significant contribution of the consumption of fossil resources to ADP in the production process of these materials. LECA has the most significant impact on both categories, principally due to the consumption of coke and electricity during manufacturing (A3.2, see 4.3).

Figure 22 presents the cradle to gate (A1-A3) environmental impacts per f.u. of the insulation materials studied for two of the categories related to the harmful effects of air emissions (AP and POCP). LECA is the material that presents the most significant impact on AP (around four times higher than the rest). This is due to coke production (20.8%), electricity consumption (5.02%) and direct air emissions from the kiln during the baking process (more than 70%) (see 4.3). On the other hand, XPS has an impact around four times higher on POCP than the other materials. This impact results from the manufacturing stage (A3.2), mostly due to electricity consumption and air emissions generated during the internal recycling of production waste and by the release of dimethyl ether during the extrusion process (see 4.5). It was also found that PUR has the lowest environmental impacts both on AP and on POCP, of the materials studied.

Finally, the comparison of the cradle to gate (A1-A3) impacts on the categories GWP and PE-NRe for each material (Figure 23) shows that only two materials do not present an almost linear relationship between these two categories. First, XPS boards with thickness ≥ 80 mm have higher GWP than expected, mainly due to some impacts during raw materials production (i.e. polystyrene) and manufacturing (A3.2), due to air emissions generated during the internal recycling of production waste and by the release of dimethyl ether during the extrusion process), for which there is no corresponding important consumption of non-renewable resources (see 4.5). LECA, meanwhile, presents a higher impact on PE-NRe than expected, but also has the most significant GWP among the materials studied. The excessive impact on PE-NRe is due to the high consumption of coke during manufacturing (A3.2, see 4.3), which produces air emissions more prone to generate AP (Figure 22) than GWP.

5 Conclusions

Insulation materials have proved to be a good technology to reduce energy consumption and hence help achieve sustainability in buildings. This work focused on the most common thermal insulation materials available in the Portuguese market: extruded polystyrene (XPS), expanded polystyrene (EPS), polyurethane (PUR), expanded cork agglomerate (ICB) and light expanded clay aggregates (LECA). The environmental impacts of these materials were evaluated by means of a cradle to gate LCA methodological approach that enables decision-makers to understand their environmental behaviour.

The five LCA studies completed confirmed the time-intensive and iterative nature of data collection and the importance of giving permanent attention to allocation in many system processes. Data quality can vary a lot for each system process studied, as was confirmed by the characterization of the quality of the information provided by each of the companies for the LCA studies of their relevant products.

The choice of the principles to be applied in the LCA of each insulation product, following the guidelines defined in standards, were of foremost importance to guarantee the scientific validity and the innovation of the results presented in this paper.

Several LCA studies of thermal insulation materials have already been performed worldwide, but, most of these studies were limited in terms of the number of insulation materials and environmental categories considered, and some do not even follow the ISO 14040 series of international standards. Thus, the LCA results presented in this paper can be considered scientifically sound by having been achieved through a consistent methodology that also takes into consideration the most recent European standards. These results are also innovative and up-to-date LCA data on insulation products for use in buildings, in particular related to the manufacturing of LECA and ICB boards.

The cradle to gate LCA results per life cycle stage and environmental category of each insulation material have been presented and analysed, along with the identification of the processes that contribute most to each category. Some meaningful conclusions can be highlighted from these results:

- EPS makes a low contribution to all impact categories and, therefore, has a good environmental performance in comparison with the alternatives. The A1 raw material phase turns out to be very important for EPS because most of the environmental impacts are generated in this phase;
- ICB makes a low contribution to the impact categories PE-NRe, GWP and ADP, which indicates that the production of ICB involves low consumption of fossil fuels. Nevertheless, ICB has a significant bearing on EP due to the operation of the boiler. Furthermore, the environmental impacts associated with ICB production mainly come from the production phase (A3.2);

- PUR makes a relatively low contribution to all impact categories. The majority of the environmental impacts are generated in the raw materials phase (A1), due to the production of these components;
- XPS presents a similar environmental profile to PUR, except with respect to GWP and POCP. For the latter XPS presents the worst performance of all materials evaluated, but LECA has higher impact on GWP;
- LECA makes the biggest contribution to six out of eight environmental impact categories, partly due to the large consumption of fossil fuels in the production stage (A3.2) but also due to the high reference flow associated with its functional unit.

“Raw material extraction and processing and processing of secondary material input” (A1) makes a significant contribution to the cradle to gate environmental impacts of insulation materials, except for the ones based on natural raw materials (LECA and ICB). This highlights the importance of selecting the most appropriate databases and relevant processes for modelling this life cycle stage. It was also found that some life cycle stages such as transportation of raw materials (A2), packaging and packaging waste (A3.1 and A3.3, respectively), may not be discarded in a cradle to gate study because they can make a significant contribution to some environmental categories and insulation products. The results also confirm that the ODP category should continue to be considered in LCA studies (despite its relatively low importance), because some background processes are not updated and still consider the use of CFC[1] in industry and because HCFC[2] emissions can occur in current manufacturing processes. Some specificity that must be taken into account in the LCA of building products was also identified, including the diverse and significant environmental impacts of each stage of their life cycles, and the importance of giving permanent attention to allocation in many system processes. Furthermore, a sensitivity analysis was performed for two materials to evaluate the consequences of physical (e.g. volume or mass) and economic allocation in LCA results.

The use of an updated national electricity mix is essential for a cradle to gate LCA, and it is even more important when the manufacturing is energy intensive and most of the environmental impacts of the life cycle of the product come from this stage. Therefore, the latest information available about the Portuguese electricity mix was considered to be able to accurately estimate the environmental impacts of the companies arising from the consumption of energy for the production of the insulation products. The definition of appropriate and agreed weights for each environmental impact category can provide results that are essential for the building designer. Thus, a single score environmental indicator for the performance of insulation materials can be provided and used in the selection of the one with the best environmental profile for each particular use.

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TABLE CAPTIONS

Table 1

Physical structure / Chemical composition	Fibrous	Cellular	Granular
Mineral "inorganic"	Mineral wool - MW (Glass/Stone wool - GW and SW)	Foam glass (CG)	Expanded perlite; Expanded vermiculite; Light Expanded Clay Aggregate (LECA)
Oil-derived "organic synthetic"	-	EPS; PUR/PIR; XPS	EPS and XPS regranulate
Plant/animal derived "organic natural"	Cellulose; Wood wool; Cotton/Sheep wool; Duck feathers; Flax; Hemp; Straw bale; Recycled paper or denim	ICB (Figure 1); Recycled paper	ICB regranulate; Recycled paper

Table 2

Insulation material commercial form	Insulation material
Loose-fill that can be blown-in	CG and SW
Loose-fill	Expanded perlite or vermiculite; LECA; EPS, XPS and ICB regranulate; cellulose
Mineral fibre blankets, batts and rolls	MW, GW and SW
Rigid boards foamed or sprayed in-place (PUR/PIR)	ICB, EPS, XPS and PUR/PIR and GW
Other insulating solutions	Lightweight concrete blocks; precast concrete with a rigid insulation foam placed in the core (sandwich panel); insulated Concrete Forms (ICF - Figure 2); reflective materials (aluminium foil or ceramic coatings)

Table 3

Country	Research study	Material	Application	LCA study: Boundaries	Type of inventory data	LCI flows	Environmental category	Standards followed
Belgium	[9]	GW PUR SW	Cavity wall, pitched roof and ground floor	Cradle to grave	Ecoinvent database and Environmental Profiles project from members of Eurisol in the United Kingdom and PU Europe	-	Global warming, ozone layer depletion, eutrophication, photochemical ozone creation and acidification of air and water	Not documented
Canada	[38]	Cellulose, fibreboard, EPS, GW, MW, PUR, XPS	-	Cradle to gate and building operation	Based on literature	-	Embodied primary energy	Not documented
Europe	[39, 40]	SW	Roof	Cradle to grave	Site-specific	Consumption of energy and water, production of solid waste, air emissions (i.e. CO_2, NO_x and SO_x)	Global warming, acidification, nutrient enrichment, photochemical ozone creation and generation of solid waste	ISO 14040 standard series
		Flax			European average (weighted average over a period of five years)			
		Paper wool			Literature			
Greece	[3]	EPS MW PUR XPS	Load bearing walls	Cradle to grave (including board manufacture, transportation and building operation)	Site-specific	-	Embodied energy, global warming potential, acidification potential, eutrophication potential and photochemical ozone creation potential	Not documented
Greece	[41]	SW XPS	-	Cradle to gate (including transportation)	European and Greek databases	CO_2 emissions, electric and heating energy consumed, raw, auxiliary and packaging material consumption	Global warming, acidification, eutrophication, smog, solid and liquid wastes production	ISO 14040 standard series
Italy	[10]	Kenaf fibre insulation boards (and compared to SW, flax, paper wool, PUR, GW and MW)	-	Cradle to grave (including boards manufacturing, installation, maintenance, use and end-of-life)	Site-specific and based on literature (based on literature for the materials in brackets)	Consumption of energy a(renewable and fossil) and water, production of solid waste, air and water emissions	Global warming potential, global energy requirement, acidification potential, eutrophication potential, photochemical ozone creation potential, ozone layer depletion potential	ISO 14040 standard series
Spain	[42]	EPS, SW, PUR, cork, cellulose fibre-based materials and wood wool	-	Not documented		Water consumption	Embodied energy and global warming potential	Not documented
Thailand	[43]	Bagasse, coconut coir and rice hulls (and compared to cellulose, fibreglass and SW)	-	Cradle to gate	Site-specific and based on literature (based on literature for the materials in brackets)	CO_2 emissions	Embodied energy	ISO 14040 standard series

Table 4

<table>
<tr><th colspan="3">LCA boundaries</th><th>Life cycle stages / LCA information modules</th><th colspan="2">Life cycle stage designation and description</th></tr>
<tr><td rowspan="16">Cradle to cradle</td><td rowspan="15">Cradle to grave</td><td rowspan="3">Cradle to gate</td><td rowspan="3">Product stage (A1-A3)</td><td>A1</td><td>raw material extraction and processing, processing of secondary material input</td></tr>
<tr><td>A2</td><td>transport to the manufacturer</td></tr>
<tr><td>A3</td><td>manufacturing</td></tr>
<tr><td rowspan="12">Gate to grave</td><td rowspan="2">Construction process stage (A4-A5)</td><td>A4</td><td>transport to the building site</td></tr>
<tr><td>A5</td><td>installation in the building</td></tr>
<tr><td rowspan="5">Use stage - information modules related to the building fabric (B1-B5)</td><td>B1</td><td>use or application of the installed product</td></tr>
<tr><td>B2</td><td>maintenance</td></tr>
<tr><td>B3</td><td>repair</td></tr>
<tr><td>B4</td><td>replacement</td></tr>
<tr><td>B5</td><td>refurbishment</td></tr>
<tr><td rowspan="2">Use stage - information modules related to the operation of the building (B6-B7)</td><td>B6</td><td>operational energy use</td></tr>
<tr><td>B7</td><td>operational water use</td></tr>
<tr><td rowspan="4">End-of-life stage (C1-C4)</td><td>C1</td><td>de-construction, demolition</td></tr>
<tr><td>C2</td><td>transport to waste processing</td></tr>
<tr><td>C3</td><td>waste processing for reuse, recovery and/or recycling (3R)</td></tr>
<tr><td>C4</td><td>disposal</td></tr>
<tr><td colspan="2"></td><td>Benefits and loads beyond the system boundary (D)</td><td>D</td><td>reuse, recovery and/or recycling (3R) potential</td></tr>
</table>

Table 5

Scale	Confidence	Integrity	Temporal correlation	Geographic correlation	Technological correlation
1	Verified[a] data and based on measurements[b]	Data representing a sufficient[c] number of companies over a period that enables the elimination of fluctuations	Maximum difference of 3 years from the year being studied	Data from the region being studied	Data from the company being studied
2	Partially verified data and based on hypothesis[d], or not verified but based on measurements	Data representing a small number of companies, but for appropriate periods	Less than 6 years difference	Average data from a region larger than that being studied, but including it	Data from the same processes/materials but from other companies
3	Unverified data and partially based on hypothesis	Data representing a suitable number of companies, but for short periods	Maximum difference of 10 years	Data from a region with similar production conditions	Data from the same processes/materials but from a different technology
4	Verified or qualified estimations (produced by experts)	Representative data but from a small number of companies and from short periods, or incomplete data from a suitable number of companies and period durations	Difference less than 15 years	Data from a region with production conditions with some similarities	Data from similar processes/materials but analogous technology
5	Neither verified nor qualified data estimations	Unknown representativeness, or incomplete data from a small number of companies and/or short periods	Unknown age of data or difference more than 15 years	Data from an unknown region, or from a region with very different production conditions	Data from similar processes/materials but different technology

Notes to Table 5:

[a] Data can be verified by comparison with original documents, by repeating the calculations, by comparison with other sources, by material or energy balances, etc.

[b] Experimental measurement techniques must be described in the report.

[c] In order to be statistically representative data need not be complete. However, the chosen sample must be randomly chosen and be of an appropriate size to be reproducible and truly reflect the characteristics of the whole population.

[d] The considered hypothesis must also be specified in the report.

Table 6

Company that produces: (Average value - AV)	**Quality of the information used in the LCI of the building products studied (based on Table 5)**				
	Confidence (AV = 2.2)	**Integrity (AV = 3.1); market share (%)**	**Temporal correlation (AV = 1.2)**	**Geographic correlation (AV = 1)**	**Technological correlation (AV = 1)**
LECA (1.2)	1 - Verified data (internal reports and visit to the production line) and based on measurements	2 - One company and a two-year period; 33% of national production and sales	1 - 2010 and 2011	1	1
XPS boards (1.4)	2 - Unverified (but including a visit to the production line) but based on measurements	2 - One company and a two-year period; 50% of national production and 30% of sales	1 - 2010 and 2011	1	1
EPS boards (1.6)	2 - Partially verified data (internal documents and visit to the production line) and based on hypothesis	2 - One company and a three-year period	2 - 2008. 2009 and 2010	1	1
PUR boards (2.4)	5 (and not including a visit to the production line)	4 - Representative data but from only one company and from short periods (data measured from the process); 100% of national production for the construction sector	1 - 2012	1	1
ICB boards (1.6)	2 - Unverified (but including a visit to the production line) but based on measurements	2 - One company and a two-year period; most important company in the national market	2 - 2008 and 2010	1	1

Table 7

<table>
<tr><th>Insulation material</th><th>Density (kg/m³)</th><th>Thermal conductivity (W/m.K)</th><th>Thickness (mm)</th><th>Weight (per f.u.) (kg)</th><th>Average weight (per f.u.) (kg)</th></tr>
<tr><td>EPS</td><td>15</td><td>0.0396</td><td>20-100</td><td colspan="2">0.594</td></tr>
<tr><td>ICB</td><td>110</td><td>0.04</td><td>20-100</td><td colspan="2">4.4</td></tr>
<tr><td>LECA</td><td>297 (bulk density)</td><td>0.1</td><td>8-16 (size of granules)</td><td colspan="2">29.7</td></tr>
<tr><td>PUR</td><td>35</td><td>0.023</td><td>20-60</td><td colspan="2">0.81</td></tr>
<tr><td rowspan="8">XPS</td><td rowspan="8">30</td><td>0.034</td><td>30</td><td>1.02</td><td></td></tr>
<tr><td>0.035</td><td>40</td><td>1.05</td><td rowspan="4">1.05</td></tr>
<tr><td>0.035</td><td>50</td><td>1.05</td></tr>
<tr><td>0.035</td><td>60</td><td>1.05</td></tr>
<tr><td rowspan="2">0.036</td><td rowspan="2">80</td><td>1.08</td></tr>
<tr><td>1.08</td><td rowspan="3">1.12</td></tr>
<tr><td>0.038</td><td>100</td><td>1.14</td></tr>
<tr><td>0.038</td><td>120</td><td>1.14</td></tr>
</table>

Table 8

Insulation material	Raw material; process chosen (data age)	LCA databases
LECA	Clay; Clay, at mine/kg/CH (2003)	Ecoinvent [27]
	Oil; Lubricating oil, at plant/kg/RER (2003)	
XPS	Dimethyl ether; Dimethyl ether, at plant/kg/RER (2003)	Ecoinvent
	Polystyrene crystals; Polystyrene (general purpose) granulate (GPPS), production mix, at plant (2002)	Plastics Europe (ELCD) [44, 45]
	Difluoroethane; 1.1-difluoroethane, HFC-152a, at plant/kg/US (2007)	Ecoinvent
	Fire retardant; Chemicals organic, at plant/kg/GLO (2003)	
EPS	Expandable polystyrene; Polystyrene expandable granulate (EPS), production mix, at plant RER (2003)	ELCD
PUR	Polyol; Aromatic Polyester Polyols (APP) with Flame Retardant (2008)	PU Europe - Federation of European Rigid Polyurethane Foam Associations [46]
	Isocyanate; MDI E (2000-2004)	Plastics Europe
ICB	“Falca”; Raw cork, at forest road/kg/RER (2003)	Ecoinvent

Table 9

Category indicator (abbreviation)	Characterization model			LCIA indicators
	Designation	**Time span**	**Geographical scale**	
Abiotic depletion potential (ADP)	Concentration reserves and rate of depletion at a global scale	-	Global	kg antimony (Sb) equivalents (eq.)
Global warming potential (GWP)	Baseline model of the IPCC	100 years		kg carbon dioxide (CO_2) eq.
Ozone depletion potential (ODP)	Steady-state based on WMO [47] model	Infinite		kg CFC-11 eq.
Acidification potential (AP)	Adapted RAINS 10 model		Varies between local and continental	kg sulphur dioxide (SO_2) eq.
Eutrophication potential (EP)	Stoichiometric procedure [48]			kg phosphate (PO_4^{3-}) eq.
Photochemical ozone creation potential (POCP)	United Nations Economic Commission for Europe (UNECE) trajectory model (including fate)	5 days		kg ethylene (C_2H_4) eq.

Table 10

Energy carrier	Ecoinvent (2004)	Electricity mix/PT - ERSE (2011)
	Electricity mix/PT	Companies
Hard coal, at power plant	31	25
Lignite, at power plant	1	0
Oil, at power plant	12	1
Natural gas, at power plant	25	26
Hydropower	21	21
Nuclear	4	8
Production mix photovoltaic	0	1
Wind farm	3	4
Cogen with wood	3	4
Cogen with biogas	0	10

Table 11

Allocation procedure	Manufacturing share (%)		
	EPS boards	EPS granulate	EPS regranulate
Volume	39	52	9
Mass	50	43	7
Economic	55	41	4

Table 12

Allocation procedure	Manufacturing share (%)	
	ICB boards	ICB regranulate
Volume	75	25
Mass	83	17
Economic	87	13

Table 13

Category indicator	Relative contribution (%) to A3.2	
	Electricity	Naphtha, burned in boiler 100kW condensing, non-modulating
ADP	15	83
AP	37	61
EP	47	51
GWP	14	85
ODP	7	92

Table 14

Category indicator	Relative contribution (%) for A1-A2	
	Polystyrene	Difluoroethane
ADP	94	3
AP	72	26
EP	56	40
GWP	91	8
ODP	1	69
POCP	78	19

Table 15

Material	PE-NRe [MJ]	PE-Re [MJ]	ADP [kg Sb eq]	AP [kg SO_2 eq]	EP [kg PO_4 eq]	GWP [kg CO_2 eq]	ODP [kg R-11 eq]	POCP [kg C_2H_4]
EPS	73.8	0.63	0.035	0.011	1.35E-03	3.25	9.25E-08	5.83E-03
ICB	32.8	307	0.013	0.036	0.016	1.61	1.11E-07	2.55E-03
LECA (palletised PE bags)	303	24.9	0.126	0.108	7.46E-03	8.07	2.07E-06	4.95E-03
LECA (PP bags)	282	4.44	0.118	0.106	6.63E-03	7.42	2.05E-06	4.75E-03
PUR	82.6	3.37	0.035	0.013	1.56E-03	3.33	8.23E-08	1.17E-03
XPS (thickness ≤ 80 mm)	96.8	1.31	0.047	0.017	1.83E-03	5.21	4.30E-08	0.013
XPS (thickness ≥ 80 mm)	104	1.57	0.05	0.022	2.45E-03	7.08	4.54E-08	0.012

FIGURE CAPTIONS

Figure 1 - Portuguese Pavilion at the Xangai exhibition [49]
Figure 2 - Insulated Concrete Forms (ICF) [50]
Figure 3 - Relative contribution of each sub-stage of EPS production to environmental impacts
Figure 4 - Relative contribution of each sub-stage of ICB production to environmental impact
Figure 5 - Contribution of A3.2 sub-stage of ICB production to EP with 1% cut-off, generated in SimaPro
Figure 6 - Contribution of A3.2 sub-stage of ICB production to GWP with 1% cut-off, generated in SimaPro
Figure 7 - Relative contribution of each sub-stage of the production of LECA in palletized PE bags to environmental impact categories
Figure 8 - Relative contribution of each sub-stage of the production of LECA in PP bags to environmental impact categories
Figure 9 - Contribution of A3.2 sub-stage of LECA production to AP with 5% cut-off, generated in SimaPro
Figure 10 - Contribution of A3.2 sub-stage of LECA production to EP with 5% cut-off, generated in SimaPro
Figure 11 - Contribution of A3.2 sub-stage of LECA production to GWP with 5% cut-off, generated in SimaPro
Figure 12 - Relative contribution of each sub-stage of PUR/PIR production to environmental impacts
Figure 13 - Contribution of A1 plus A2 sub-stages of PUR/PIR production to EP with 1% cut-off, generated in SimaPro
Figure 14 - Contribution of A1 plus A2 sub-stages of PUR/PIR production to GWP with 1% cut-off, generated in SimaPro
Figure 15 - Contribution of A1 plus A2 sub-stages of PUR/PIR production to POCP with 1% cut-off, generated in SimaPro
Figure 16 - Relative contribution of each sub-stage of the production of XPS boards of thickness ≤ 80 mm to the environmental impact categories
Figure 17 - Contribution of A1 plus A2 sub-stages of XPS boards with thickness ≤ 80 mm production to ADP with 2% cut-off, generated in SimaPro
Figure 18 - Contribution of A1 plus A2 sub-stages of XPS boards with thickness ≤ 80 mm production to EP with 2% cut-off, generated in SimaPro
Figure 19 - Contribution of A1 plus A2 sub-stages of XPS boards with thickness ≤ 80 mm production to POCP with 2% cut-off, generated in SimaPro
Figure 20 - Relative contribution of each sub-stage of the production of XPS boards with thickness ≥ 80 mm to environmental impact categories
Figure 21 - Cradle to gate (A1-A3) environmental impacts on PE-NRe and ADP per f.u. of the insulation materials studied
Figure 22 - Cradle to gate (A1-A3) environmental impacts on AP and POCP per f.u. of the insulation materials studied
Figure 23 - Cradle to gate (A1-A3) environmental impacts on PE-NRe and GWP per f.u. of the insulation materials studied

Figure 1

Figure 2

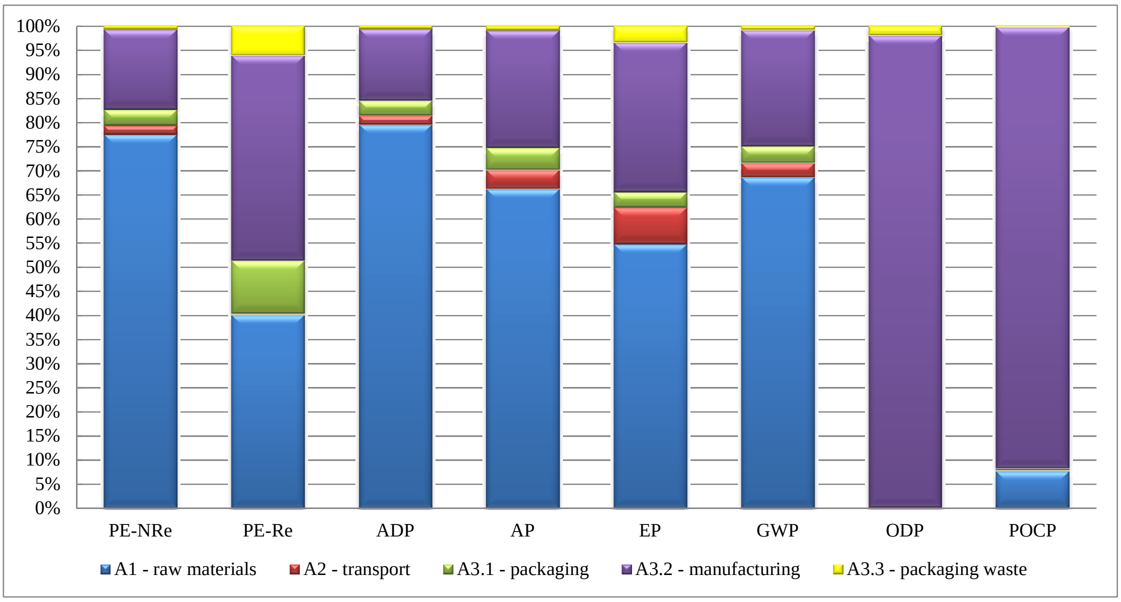


Figure 3

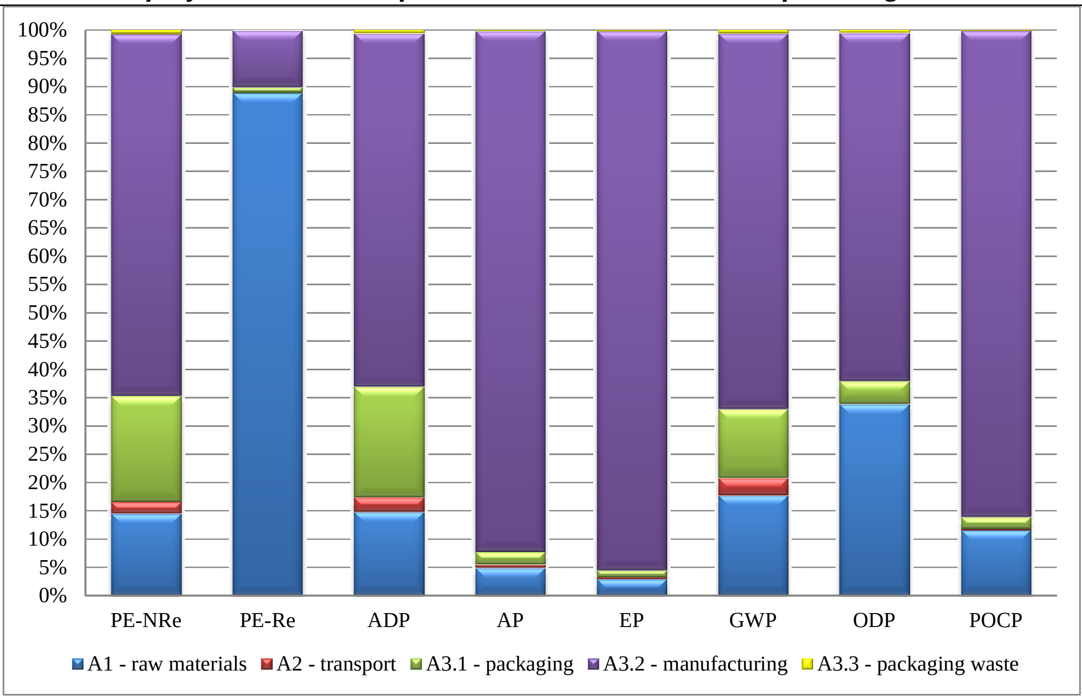


Figure 4

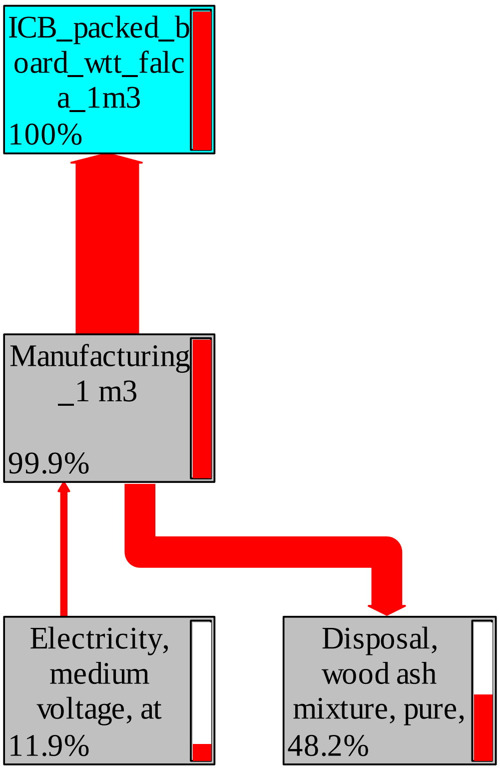


Figure 5

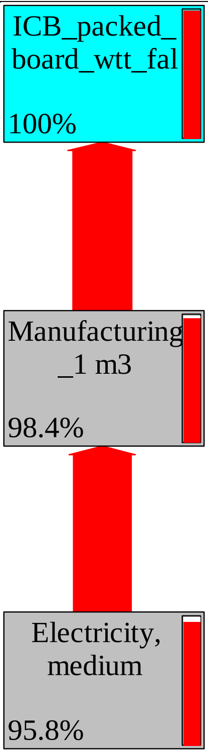


Figure 6

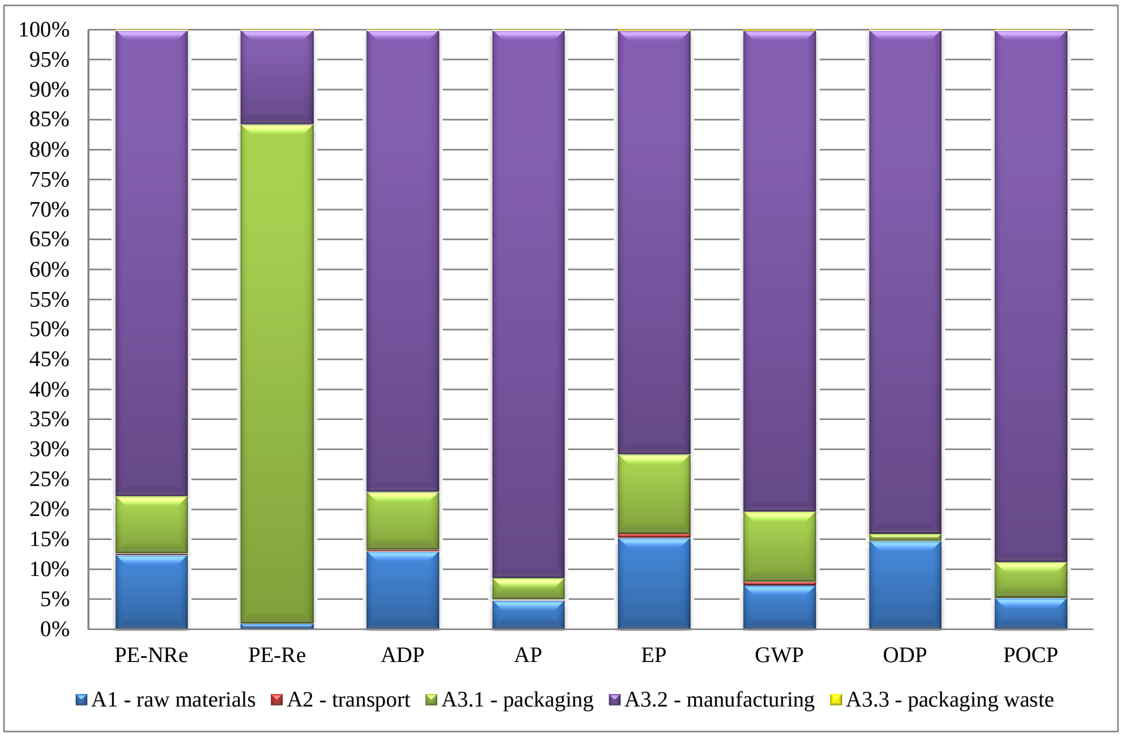


Figure 7

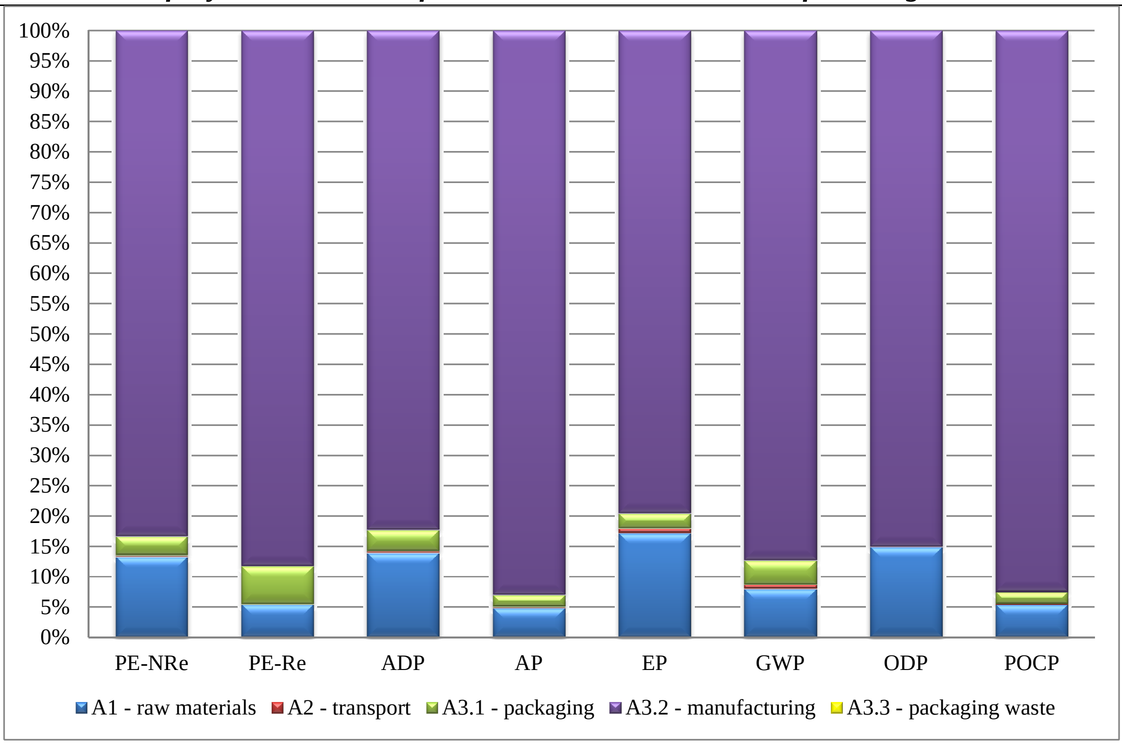


Figure 8

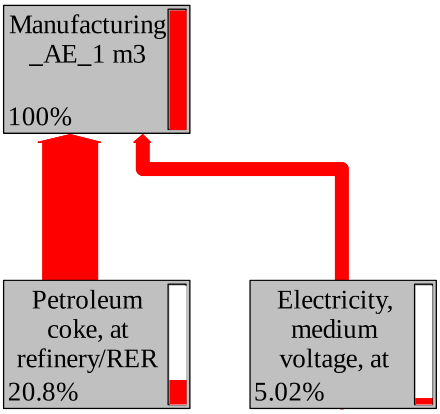


Figure 9

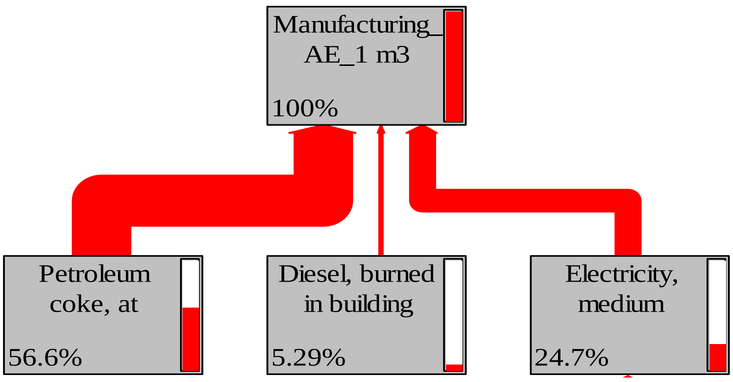
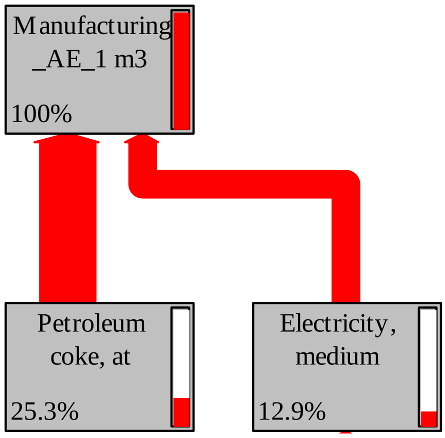


Figure 10



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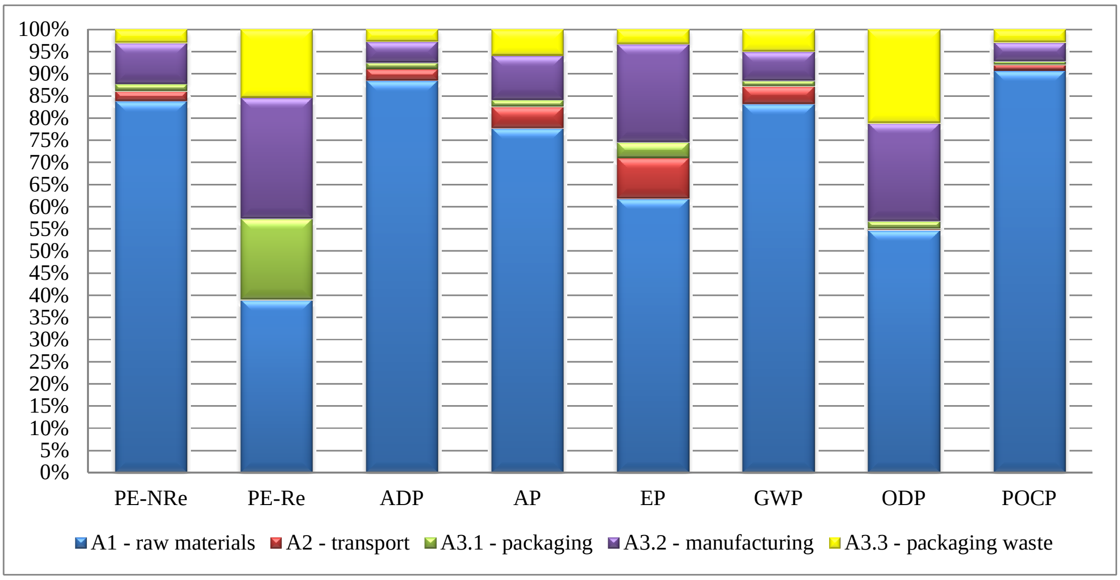

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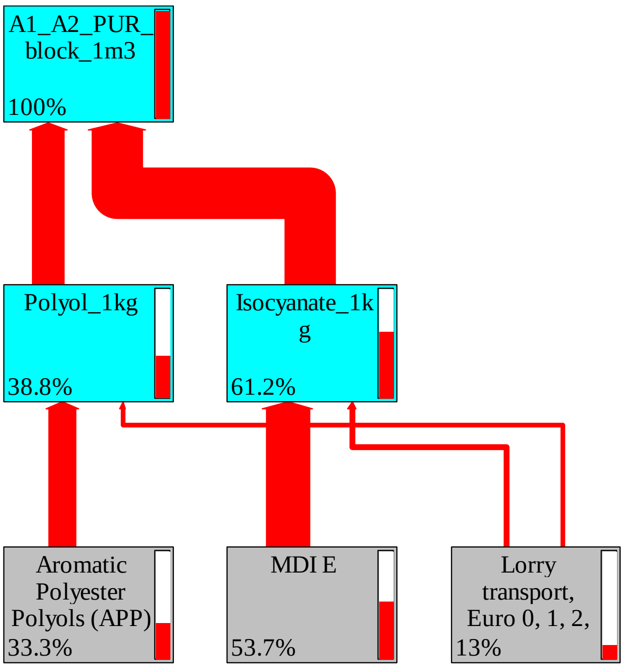

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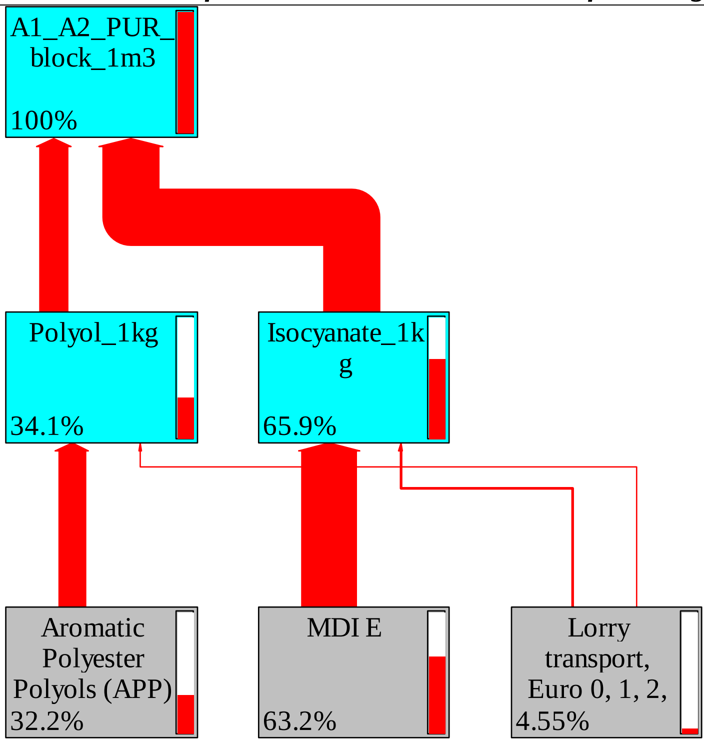

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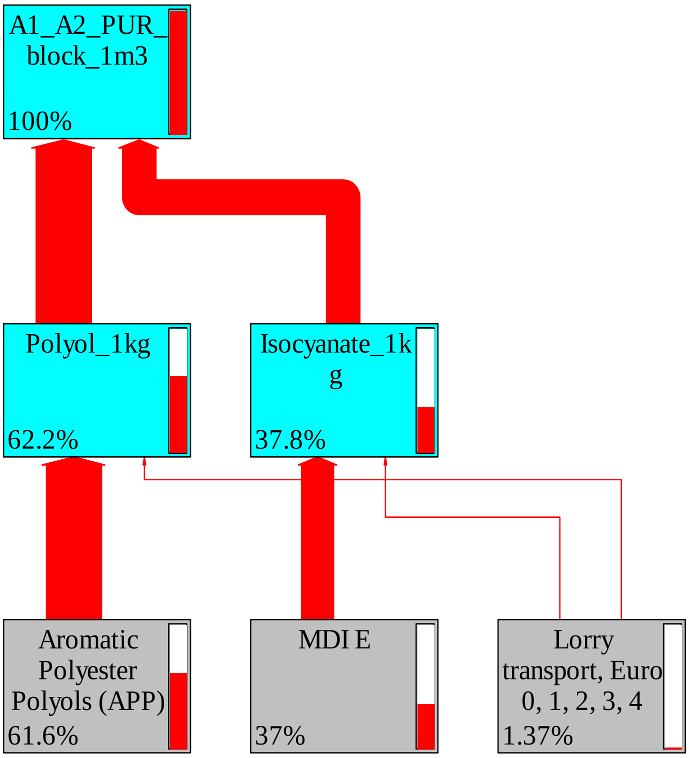

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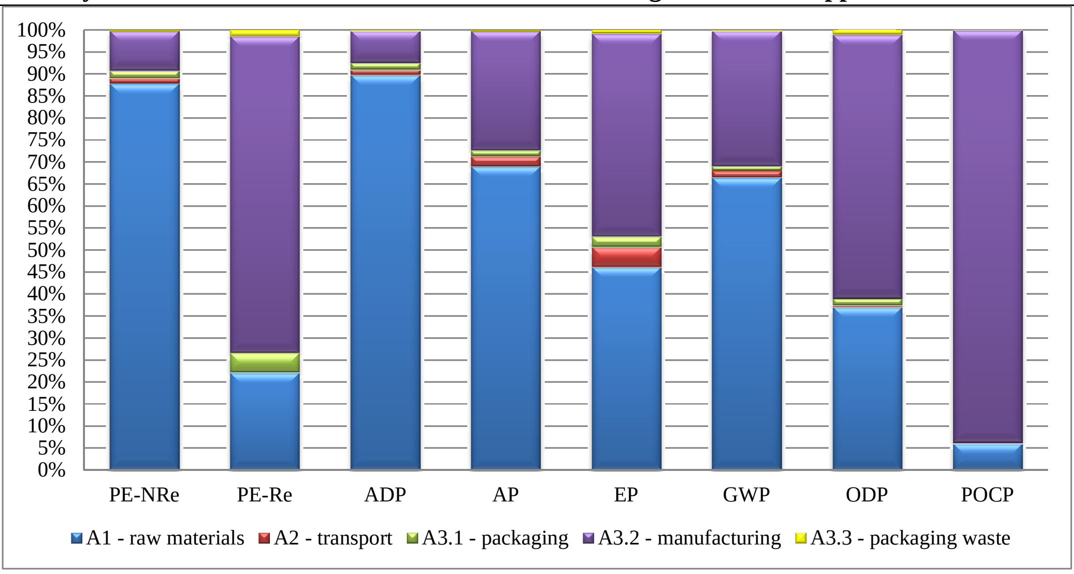

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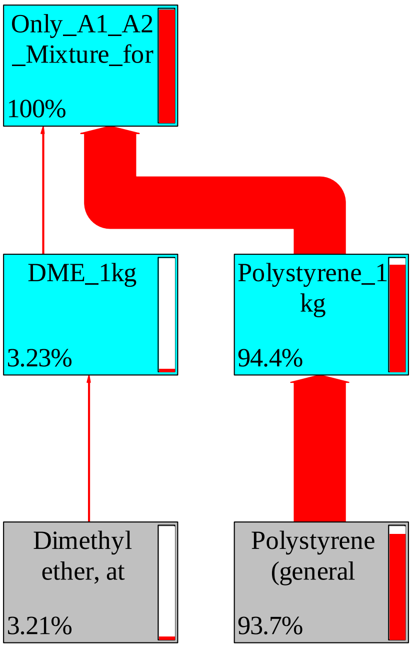
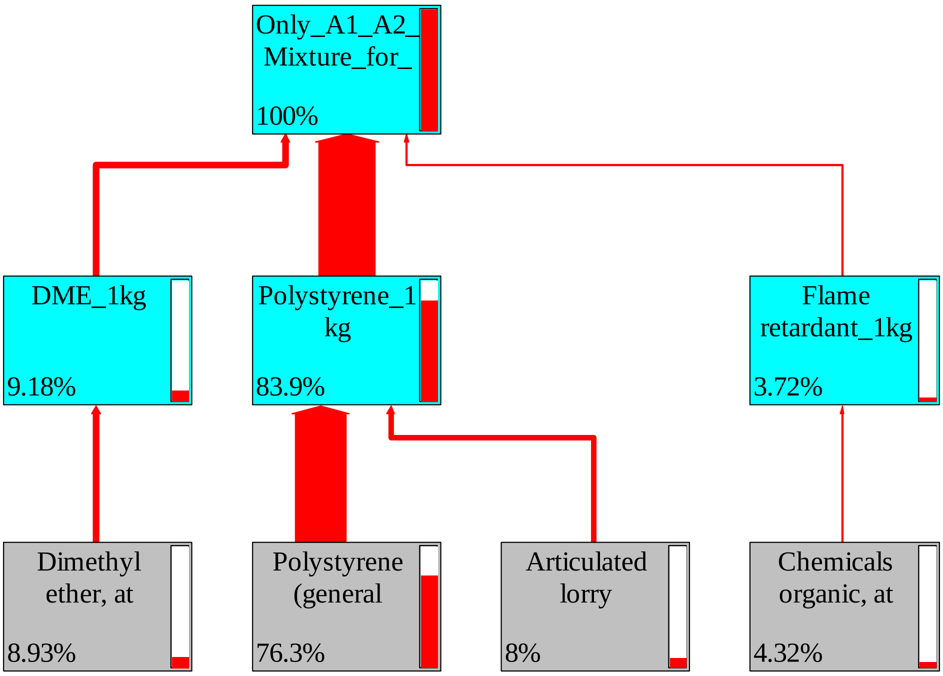


Figure 17



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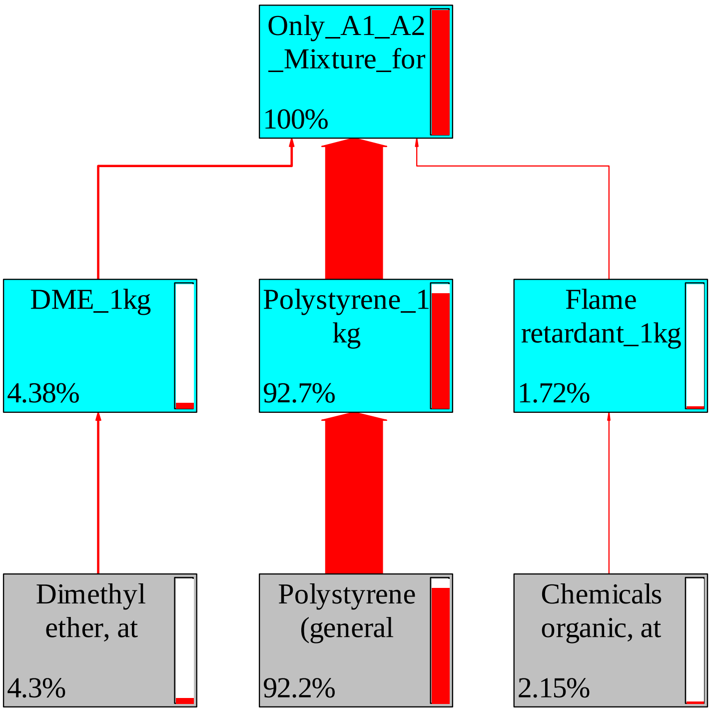

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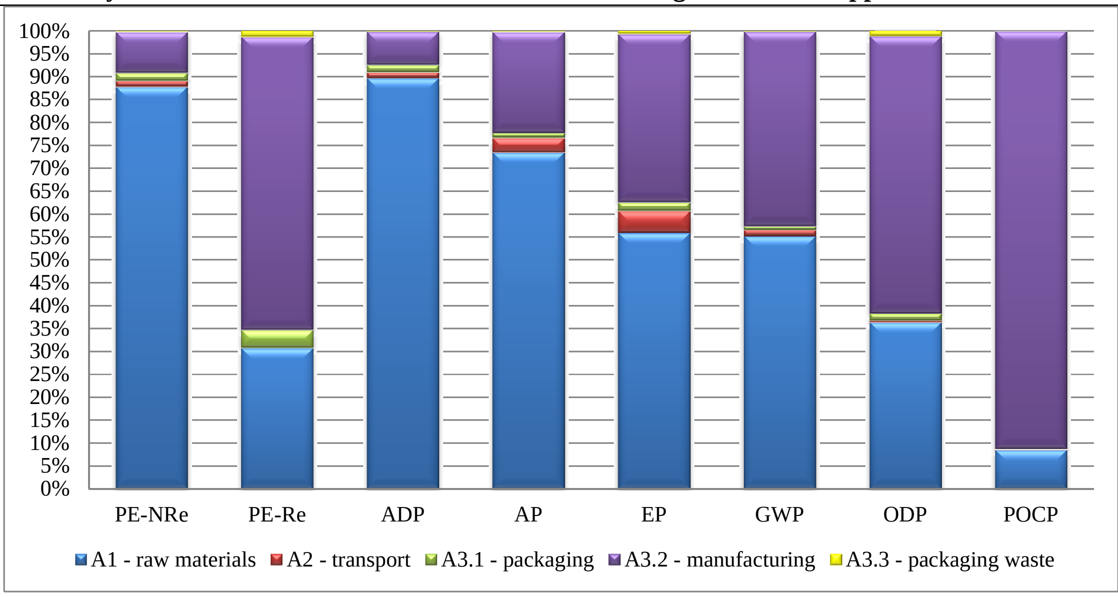

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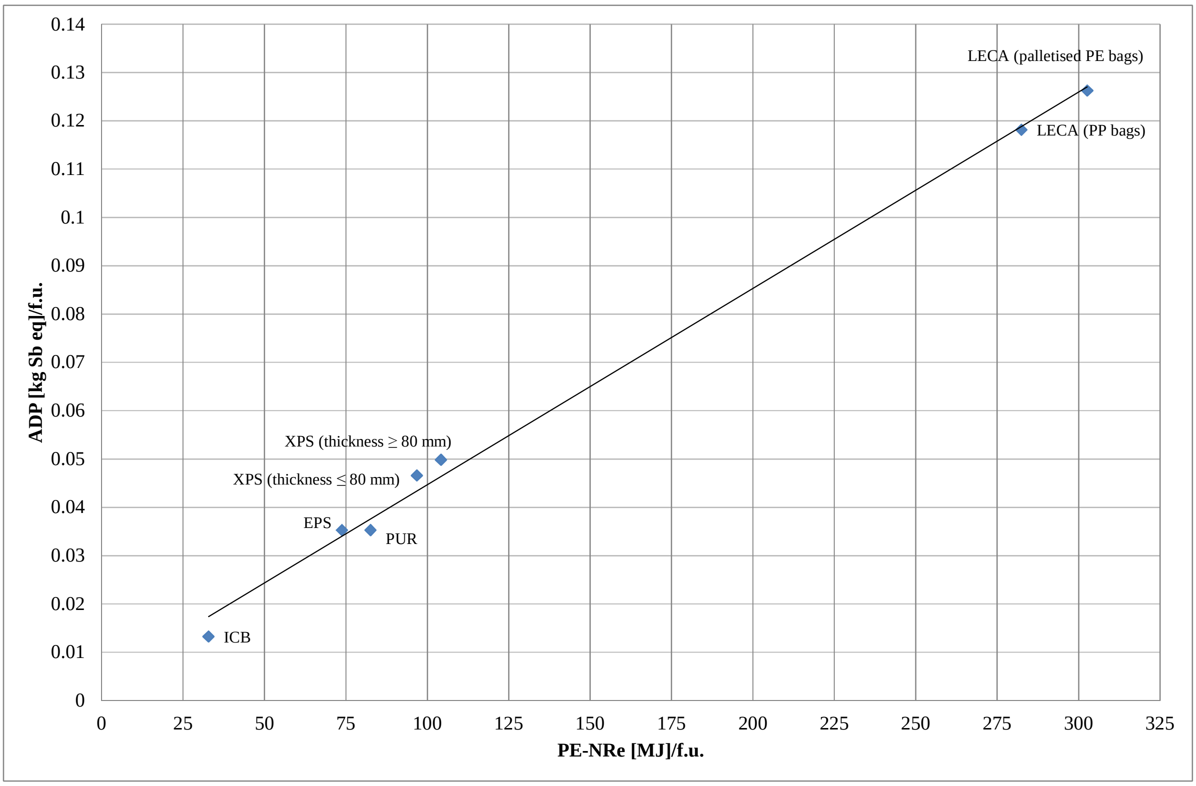

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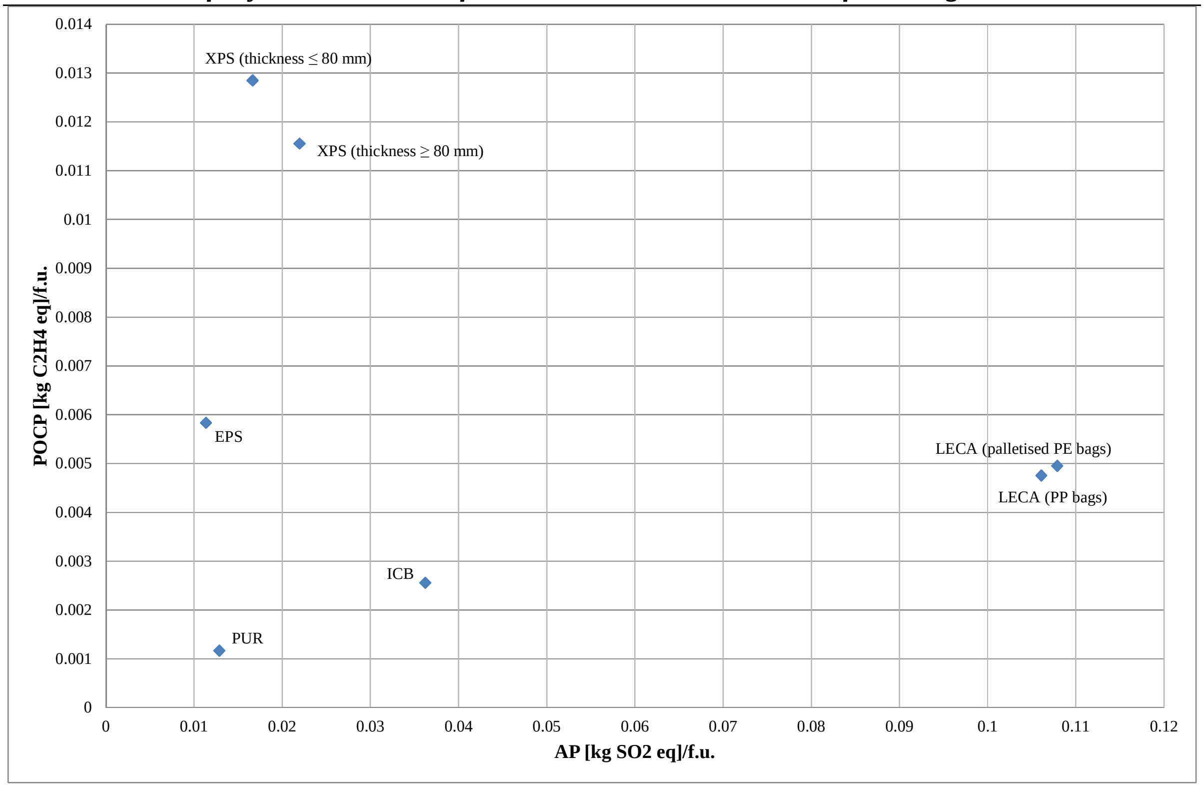

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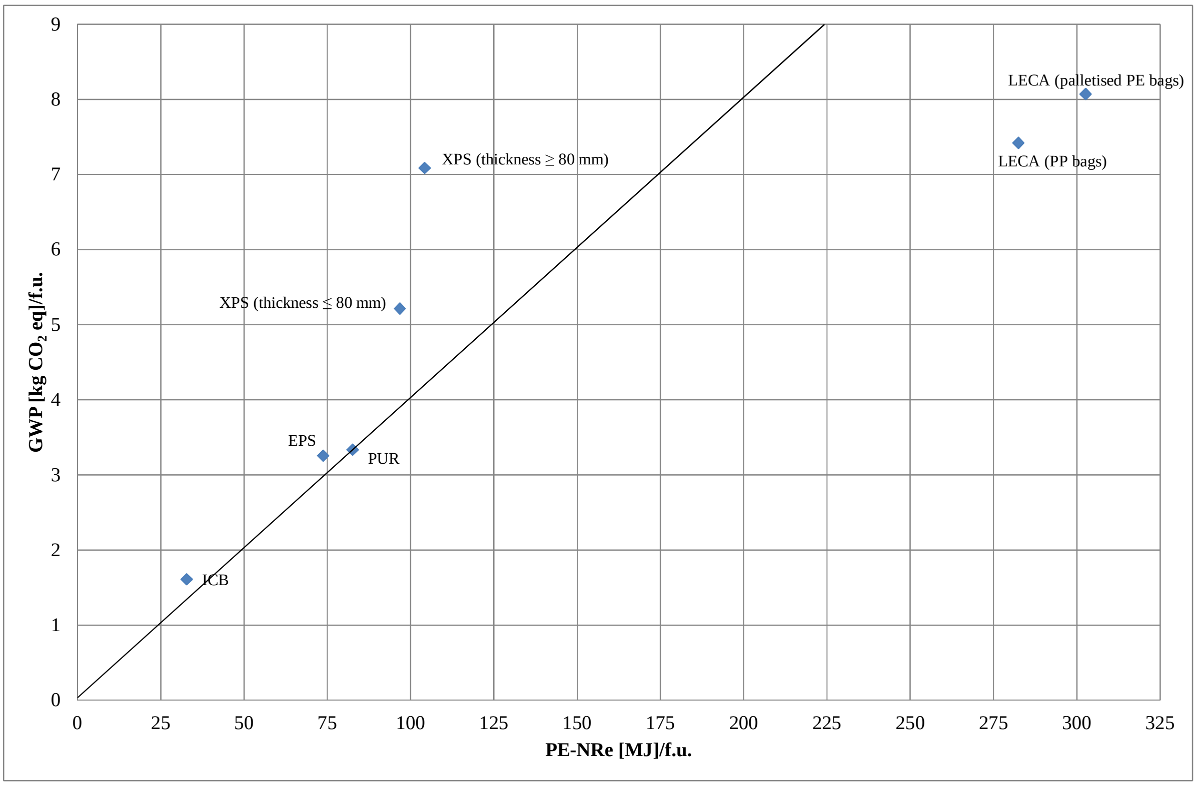

Figure 23

Appendix 6.I

LCA databases characterisation

(last access to databases on October 2012)

Table 6.I.1 - LCA databases characterisation

Characteristics	ATILH	BRE	CEMBUREAU
Designation of the database/*EPD Programme*	Inventaires de Cycle de vie	*Environmental profiles*	CEMBUREAU
Country	France	United Kingdom	European
Webpage	www.infociments.fr/developpement-durable/construction-durable/icv-ciments	www.greenbooklive.com	www.cembureau.be
Organisation responsible for the data/*Manager of the EPD Programme*	Association Technique de l’Industrie des Liants Hydrauliques (ATILH)	*Building Research Establishment*	European Cement Association
Methodology/*PCR followed*	French standard NF P01-010	Methodology for environmental profiles of construction products (2007)	Based on ISO 14020:2005, ISO 14025:2006, ISO 14040:2006, ISO 14044:2006 *PCR 2004:1 for preparing an EPD for Product Group “Cement” (Environdec)*
Availability of data (public/paid)	Public	Public	Public (available in ELCD and in Environdec)
Number of documents available	9	More than 250	1
Availability of materials in the scope of the study	Cement	PUR boards (cradle-to-grave); the majority of the profiles are of complete construction assemblies	Cement
Type of LCA data set (generic, EPD or average)	National average	Individual EPD	European average
Sampling procedure (country, Europe, producer, plant)	Country weighted mean	Plant	Aggregation of representative plant data weighted according to production
Critical review/verification	External	No	External
Market share of average LCA data (%)	85 %	-	Not documented

Table 6.I.2 - LCA databases characterisation (continuation)

Characteristics	DAPc	Ecoinvent	ELCD
Designation of the database/*EPD Programme*	*Declaración Ambiental de Produto (DAPc)*	Ecoinvent version 2.2	European Life Cycle Database version 2.0
Country	Spain	Swiss	European Union
Webpage	es.csostenible.net/dapc/ el-sistema-dapc	www.ecoinvent.ch	http://lca.jrc.ec.europa.eu/ lcainfohub/datasetArea.vm.
Organisation responsible for the data/*Manager of the EPD Programme*	*Col·legi d´Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació de Barcelona e Generalitat de Catalunya; Generalitat de Catalunya*	Swiss Centre for Life Cycle Inventories	European Platform for LCA
Methodology/ *PCR followed*	EN 15804:2012; *National-based development for each group of materials*	Ecoinvent methodology	ISO 14040:2006, ISO 14044:2006
Availability of data (public/paid)	Public	Paid	Open access database developed
Number of documents available	10	LCI of 4,000 industrial processes	LCI of 300 processes supplied by associations of producers from EU and by other sources for the most common materials, energy suppliers, transports and waste management
Availability of materials in the scope of the study	SW; ceramic tiles	All	Gravel and sand; SW; lightweight concrete blocks; gypsum plasterboards and plasters
Type of LCA data set (generic, EPD or average)	Individual EPD	Generic	Generic
Sampling procedure (country, Europe, producer, plant)	Plant	Average from industry (Swiss or European), survey or literature based	Average from European industry
Critical review / verification	External	Internal critical verification	Internal
Market share of average LCA data (%)	-	-	-

Table 6.I.3 - LCA databases characterisation (continuation)

Characteristics	**Environdec**	**IBU**	**INIES**
Designation of the database/*EPD Programme*	*International EPD System*	*Umwelt-Deklarationen (EPD)*	*Programme de Déclaration Environnementale et Sanitaire pour les produits de construction*
Country	Sweden (origin)	Germany	France
Webpage	www.environdec.com	bau-umwelt.de/ hp421/Declarations.htm	www.inies.fr
Organisation responsible for the data/*Manager of the EPD Programme*	*Swedish Environmental Management Council*	*Institut Bauen und Umwelt*	*Ten French organizations (governmental, scientific and industrial),*
Methodology/*PCR followed*	*Per group of materials*	EN 15804:2012 (most recent EPD); *National-based development for each group of materials*	*French standard NF P01-010*
Availability of data (public/paid)	Public	Public	Public
Number of documents available	8 groups of construction materials	Construction materials and products divided in 10 groups, including floor and roof coverings, masonry, wood-based and insulation materials	700 individual or average/joint EPD covering 5,000 commercial references
Availability of materials in the scope of the study	Cement; concrete; EPS; PUR/PIR; XPS; hollow fired-clay bricks; lightweight concrete blocks; ceramic tiles	EPS; SW; PUR/PIR; XPS; lightweight concrete blocks; masonry mortar; ceramic tiles; dry pre-mixed mortar	SW; PUR/PIR; XPS; hollow fired-clay bricks; lightweight concrete blocks; masonry mortar; ceramic tiles; GFRC panels; gypsum plasterboards and plasters; dry pre-mixed mortar; two-component adhesive
Type of LCA data set (generic, EPD or average)	Individual and joint EPD	Individual and joint EPD	Individual and joint EPD
Sampling procedure (country, Europe, producer, plant)	Plant	Plant, or weighted mean from company or from country	Plant, or weighted mean from company or from country
Critical review/verification	External review and approval by an accredited certification body	Advisory board	Third-party verification (only for some EPD)
Market share of average LCA data (%)	-	-	-

Table 6.I.4 - LCA databases characterisation (continuation)

Characteristics	Norwegian EPD Foundation	Plastics Europe 2005	Portuguese EPD
Designation of the database/*EPD Programme*	*Norwegian EPD Foundation*	Plastics Europe Eco-profile and *EPD Programme*	*STEPWISE EPD*
Country	Norway	European	Portugal
Webpage	www.epd-norge.no/	www.plasticseurope.org.	http://extra.ivf.se/stepwiseEPD2
Organisation responsible for the data /*Manager of the EPD Programme*	*Confederation of Norwegian Enterprise (NHO); Federation of Norwegian Building Industries (BNL)*	Plastics Europe – Association of Plastics Manufacturers	*European Research Project "STEPWISE EPD"*
Methodology/*PCR followed*	*National-based development for each group of materials*	LCI methodology; *PCR for Uncompounded Polymer resins and reactive polymer precursors*	*STEPWISE EPD guideline*
Availability of data (public/paid)	Public	Public (available in Ecoinvent and ELCD)	Public
Number of documents available	Construction materials and products divided in 10 groups, including concrete, cement, building boards and insulation materials	Eco-profiles of almost every plastic product available in the market	One
Availability of materials in the scope of the study	SW; gypsum plasterboards	PUR/PIR	Pre-mixed concrete
Type of LCA data set (generic, EPD or average)	Individual EPD	Generic	Individual EPD
Sampling procedure (country, Europe, producer, plant)	Plant	Average from European industry	Plant
Critical review/verification	Third-party verification	External	Internal critical verification
Market share of average LCA data (%)	-		-

Table 6.I.5 - LCA databases characterisation (continuation)

Characteristics	**Portuguese average LCA data set**	**PU-Europe**	**SLCA**
Designation of the database/_EPD Programme_	*EPD programme in the ceramic industrial sector*	PU Europe calculation tool	Database for “simplified” LCA - SL SLCA
Country	Portugal	European	France
Webpage	-	www.pu-europe.eu	-
Organisation responsible for the data /_Manager of the EPD Programme_	*Technological Centre for Ceramic and Glass; Portuguese Association of the Ceramic Industry*	PU Europe - European association of PU insulation manufacturers	Centre Scientifique et Technique du Bâtiment (CSTB)
Methodology/_PCR followed_	ISO 14040:2006, ISO 14044:2006; *National-based development for each group of materials*	European Standards (CEN/TC 350)	-
Availability of data (public/paid)	Public	Public	Private
Number of documents available	Four	Two	750 processes
Availability of materials in the scope of the study	Masonry units with vertical hollows and wall tiles	PUR/PIR	See INIES and Ecoinvent columns
Type of LCA data set (generic, EPD or average)	Average EPD/Generic	Generic	See INIES and Ecoinvent columns
Sampling procedure (country, Europe, producer, plant)	Average by country and use	Average from European industry	
Critical review/verification	Third-party verification	Third-party verification	-
Market share of average LCA data (%)	Not documented	Not documented	See INIES and Ecoinvent columns

Appendix 6.II

Availability of LCA data of construction materials and products depending on the sources and life cycle stages

(last access to databases on October 2012)

Table 6.II.1 - Construction materials - Product, construction and use stages

Construction materials	ATILH	CEMBUREAU	Ecoinvent	ELCD	Envirodec	Portuguese EPD
Cement	A1-A3.3	A1-A3	A1-A3		A1-A3	
Concrete			A1-A3		A1-A3	A1-A5
Gravel and sand			A1	A1		
Gypsum			A1			
Reinforcing steel			A1			

Notes to Table 6.II.1: A3 represents the manufacturing sub-stage, except the packaging material. A1-A3 represents the product stage, except the packaging material. A1-A3.3 represents the product stage, including the packaging material. * - products studied in the scope of this thesis using site-specific data.

Table 6.II.2 - Construction materials - End-of-life stage

Construction materials	ATILH	CEMBUREAU	Ecoinvent	ELCD	Envirodec	Portuguese EPD
Cement						
Concrete			C1-C2; C4			C1-C4; D
Gravel and sand			C1-C2; C4			
Gypsum						
Reinforcing steel			C1-C2; C4			

Note to Table 6.II.2: * - products studied in the scope of this thesis using site-specific data.

Table 6.II.3 - Elements of the wall structure - Product, construction and use stages

Elements of the wall structure	Ecoinvent	ELCD	Envirodec	IBU	INIES	Portuguese average LCA data set
GFRC precast panels*	A1-A3				A1-A3.1; A4-A5; B1	
Hollow fired-clay bricks	A1-A3.1		A1-A3.1; A4		A1-A3.1; A4; A5	A1-A3.1
Lightweight concrete blocks*	A1-A3.1	A1-A3.1	A1-A2; A3; A4	A1-A3.1	A1-A3.1; A4; A5; B1;	
Masonry mortar*	A1-A3			A1-A3.1; A4	A1-A5	
Reinforced concrete						

Note to Table 6.II.3: A3 represents the manufacturing sub-stage, except the packaging material. A1-A3 represents the product stage, except the packaging material. A1-A3.3 represents the product stage, including the packaging material. * - products studied in the scope of this thesis using site-specific data.

Table 6.II.4 - Elements of the wall structure - End-of-life stage

Elements of the wall structure	Ecoinvent	ELCD	Envirodec	IBU	INIES	Portuguese average LCA data set
GFRC precast panels*					C2; C4	
Hollow fired-clay bricks	C1-C2; C4				C2; C4	
Lightweight concrete blocks*					C1; C2; C4	
Masonry mortar*	C1-C4			C4; D	C2; C4	
Reinforced concrete	C1-C2; C4					

Note to Table 6.II.4: * - products studied in the scope of this thesis using site-specific data.

Table 6.II.5 - Insulation materials - Product, construction and use stages

Insulation materials	DAPc	Ecoinvent	ELCD	Envirodec	IBU	INIES	Norwegian EPD Foundation	Plastics Europe 2005	PU-Europe
EPS*		A1-A3		A1; A2-A3.1; A4+C2+C4	A1-A3.1; A4-A5				
ICB*		A1-A3							
LECA*		A1 -A3.1					A1 -A3		
PUR/PIR*		A1-A3		A1-A3.1; A4	A1-A3,1; A4	A1-A3.1; A4; A5		A1-A3	A1-A3
SW	A1-A3.1; A4; A5	A1-A3.1	A1-A3		A1-A3.1	A1-A3; A4; A5	A1- A5		
XPS*		A1-A3		A1-A3.1; A4	A1-A3.1; A4	A1-A3.1; A4; A5			

Note to Table 6.II.5: A3 represents the manufacturing sub-stage, except the packaging material. A1-A3 represents the product stage, except the packaging material. A1-A3.3 represents the product stage, including the packaging material. * - products studied in the scope of this thesis using site-specific data.

Table 6.II.6 - Insulation materials - End-of-life stage

Insulation materials	DAPc	Ecoinvent	ELCD	Envirodec	IBU	INIES	Norwegian EPD Foundation	Plastics Europe 2005	PU-Europe
EPS*		C2; C4; D			C2-C4; D				
ICB*									
LECA*							C		
PUR/PIR*		C2; C4; D		C4	C1-C3; D	C2; C4			C1-C3; D
SW	C2; C4	C1-C2; C4				C2; C4	C1- C3		
XPS*		C2; C4; D		C2; C4	C1-C4; D	C2; C4			

Note to Table 6.II.6: * - products studied in the scope of this thesis using site-specific data.

Table 6.II.7 - Claddings - Product, construction and use stages

Claddings	DAPc	Ecoinvent	ELCD	Envirodec	IBU	INIES	Norwegian EPD Foundation	Portuguese average LCA data set
Gypsum plasterboards*		A1-A3	A1-A3			A1-A3.1; A4-A5	A1-A3.1; A4-A5; B1	
One coat mortar*		A1-A3			A1-A3.1; A4; B1	A1-A5		
Paints		A1-A3				A1-A3.1; A4, A5; B		
Stabilized mortar*								
Two-component adhesive*								
Wood plastic composite boards*								

Note to Table 6.II.7: A3 represents the manufacturing sub-stage, except the packaging material. A1-A3 represents the product stage, except the packaging material. A1-A3.3 represents the product stage, including the packaging material. * - products studied in the scope of this thesis using site-specific data.

Table 6.II.8 - Claddings - End-of-life stage

Claddings	DAPc	Ecoinvent	ELCD	Envirodec	IBU	INIES	Norwegian EPD Foundation	Portuguese average LCA data set
Gypsum plasterboards*		C1;-C2; C4				C2; C4	C2; C3-C4	
One coat mortar*		C1-C2; C4			C4; D	C2; C4		
Paints						C		
Stabilized mortar*								
Two-component adhesive*								
Wood plastic composite boards*								

Note to Table 6.II.8: * - products studied in the scope of this thesis using site-specific data.

Appendix 6.III

Lasvaux, S.; Silvestre, J. D.; Hodková, J.; Chevalier, J.; de Brito, J. & Pinheiro, M.D. (2012). Towards a methodology for the selection of a coherent Life Cycle Assessment (LCA) data set of construction materials to be used as generic data for a national context – NativeLCA. *International Journal of Life Cycle Assessment (submitted for publication in 2012)*

Towards a methodology for the selection of a coherent Life Cycle Assessment (LCA) data set of construction materials to be used as generic data for a national context – NativeLCA

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Summary:

Purpose:

The main aim of the research work presented in this paper was to develop a scientifically robust methodology for the selection of a coherent Life Cycle Assessment (LCA) data set of building products to be used as generic data for a national context (e.g. the Portuguese, French or Czech contexts).

Methods:

The development of this methodology, designated as NativeLCA, begins with the state-of-the-art of the construction of generic LCA databases, the use of different LCA data sets in building's evaluation, and the existing standards that should be followed in both activities. Following, a review of available LCA data sets of construction materials and products representative of the European situation, namely existing EPD (at a national or international level) or generic LCA data sets, is presented. Then, the identification of the variability of these LCA sources is made for each material and environmental category.

Results and Conclusion:

NativeLCA methodology is based on the adaptation of existing LCA data sets on construction materials and products. This methodology is innovative mainly because of being: wide-ranging (compared with existing approaches); straightforward in its application; focused in the final output – selection of a LCA data set to be directly used by the practitioner, avoiding therefore inventory analysis and modification. The aim of achieving generic data adapted to a specific geographic context is to provide robust results that can be used by building LCA practitioner on simplified LCA or early design assessment, for example.

Keywords: building products; LCA databases; Environmental Product Declarations; European standards; life cycle assessment;

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Appendix 6.III - Lasvaux, S.; Silvestre, J. D.; Hodková, J.; Chevalier, J.; de Brito, J. & Pinheiro, M.D. (2012). Towards a methodology for the selection of a coherent Life Cycle Assessment (LCA) data set of construction materials to be used as generic data for a national context – NativeLCA.

1. Introduction

The main aim of the research work presented in this paper was to develop a scientifically robust methodology for the selection of a coherent Life Cycle Assessment (LCA) data set of building products to be used as generic data for a national context (e.g. the Portuguese, French or Czech contexts). The development of this methodology, designated as NativeLCA, begins with the state-of-the-art of the construction of generic LCA databases, the use of different LCA data sets in building's evaluation, and the existing standards that should be followed in both activities. Following, a review of available LCA data sets of construction materials and products representative of the European situation, namely existing EPD (at a national or international level) or generic LCA data sets, is presented. Then, the identification of the variability of these LCA sources is made for each material and environmental category. As several data are needed for the calculation of LCA of building assemblies according to the new European standards (CEN 2010; CEN 2011), the methodology proposed in this research work will provide two types of data, based on the review already made:

- Average LCA data for each construction material - these average data can be used as background data (LCA data of raw materials production) for different construction products in a national context, or can be used as generic LCA data for a national context;
- Average LCA data for each construction product - these data can serve as benchmark values for the LCA results that will be achieved for the same products in LCA studies at a national level, or can be used as generic LCA data for a national context.

The application of the NativeLCA methodology also allows for the comparative assessment of the quality of available European LCA data to be used in a national context.

The scope of this paper is defined by the construction materials and products being studied on the Ph.D. Thesis of the authors Silvestre (in Portugal) and Hodková (in Czech Republic), namely building materials (i.e. construction materials, insulation products, elements of the wall structure and wall internal and external claddings; only LCA data sets that include these building products were fully characterised in section 3), but the NativeLCA methodology can also be applied to other building products.

This paper comprises five sections, including this introduction. The state-of-the-art section summarize similar approaches in development worldwide. Available LCA data sets available in the European context are presented afterwards. NativeLCA methodology is then described in detail in the corresponding section. The paper ends with a final discussion and by drawing conclusions that summarise the main advantages and possible applications of this methodology.

2. State of the art

Used at the building scale, both generic and average Life Cycle Assessment (LCA) data sets and Environmental Product Declarations (EPD) enable to assess the global environmental impacts of a building using LCIA indicators. LCA software for buildings has been developed and already uses these data (Peuportier, Scarpellini et al. 2009). However, the multiplicity of LCA databases (generic, average LCA data sets and EPD scheme) leads to heterogeneity regarding the data used in the tools for buildings. When several databases are used, the parameters do not necessarily match (different LCI or LCIA indicators considered) and furthermore different results for a same parameter can be achieved depending on the database chosen

(Peuportier and Putzeys 2005). In addition, the quality of generic data sets is not equivalent and therefore it is always essential to understand how they influence the precision and validity of the results (CEN 2010). However, this type of analysis is normally impossible to be done by a typical user of software for LCA of buildings because of its schedule and lack of advanced skills on LCA. These discrepancies may let the tool users conclude that LCA approach is not sufficient robust, leading them to disregard it (Lasvaux, Chevalier et al. 2011). Therefore, the need of a LCA data set to be used as generic is high in all the countries were neither average LCA data sets nor EPD schemes already exists (e.g. Portugal and Czech Republic) in the construction sector. However, these type of data sets is also very important in all the other countries, where it can be used - at least - in the first conceptual design stage, being then possible to consider the results of individual EPD in the following design stages, when more information is available about the origin of the materials that will be used. In fact, when the number of EPD of a product (or family of products) is insufficient, its representativeness can be poor and can lead to use a unified generic database (e.g. Ecoinvent database uses data from different sources adjusted with a harmonised methodology) (Hodková and Lasvaux 2012). When quantity and/or quality of available EPD is not as good as expected, or if this kind of data is absent, more studies are needed in order to develop a proper approach to select and determine the most appropriate generic LCA data for a national context (Hodková and Lasvaux 2012).

The construction of a coherent LCA data set of building products to be used as generic data for a national context enables the use of a unified database in the environmental assessment of buildings. This paper presents a methodology that enables the construction of this kind of data set. The most recent standards and draft standards developed by the Technical Committee (TC) 350 - "Sustainable construction" - of the European Committee for Standardization (CEN/TC 350) (CEN 2010; CEN 2011) were took into account in the development of this methodology. In fact, several data sets are needed for the calculation of LCA of building assemblies according to these standards. However, and despite giving a framework for the assessment of LCA data, they do not provide consistent guidelines on the choice of existing LCA to be used in each national context ant each design stage, not even included in the CEN Technical Report TR 15941- "Sustainability of construction works - Environmental product declarations - Methodology for selection and use of generic data" (CEN 2010). The methodology proposed in this paper tries therefore to fill this gap taking also profit of the experience of the authors Silvestre, de Brito and Pinheiro (in Portugal) and the author Hodková (in Czech Republic) in being responsible for the translation of this Technical Report in their national technical committees.

2.1. Selection of LCA data sets to be used as generic in a given region

A contextualization of the Ecoinvent European LCA database is currently being made in Quebec, Canada (for "contextualization" see 4.3), which includes all type of industrial processes but do not consider other generic or EPD databases. Despite being scientifically-based, the methodology used is time and resources demanding (and therefore not prone to be applied by every practitioner) and the geographical representativeness criterion (see 4.3) is not accomplished from the beginning (Bourgault, Durme et al. 2010). The same problems affect a similar research work completed recently in New Zealand, based on European country-specific (Germany) industry data. The data sets of the 13 building materials that were adapted in order to be in accordance with New Zealand reality (and to fulfil the geographical representativeness criteria) are included in the German GaBi LCA software. The methodology used is described in detail in a report and was mainly based in the analysis of environmental hot spots and contextualization of background processes (Nebel, Alcorn et al. 2011).

At the European level, the need of a LCA data set to be used as generic had already been identified and an LCA database is being built. The European SUstainable COnstruction database (ESUCO) is however only based on the extrapolation to a European level of German EPD of construction materials, despite that production technology of core materials is based on European average industry data and background data are adapted to European average countries. This database in available only to the auditors of the German system of building energy certification (*Deutsche Gesellschaft für Nachhaltiges Bauen* - DGNB e.V.) and the methodology used for its development is not publicly available. Nevertheless, DGNB states the need of country-specific LCA data sets in order to take into account the production practices, materials diversity and electric mix of each country (DGNB 2011). This need is also highlighted in the European Project EeBGuide where the authors Lasvaux and Chevalier are presently involved (EeBGuide 2012).

Other research study was completed also in Germany to develop a systematic procedure to generate country-specific environmental profiles (complete inventories, and not only LCA results) from existing LCA data sets. This contextualization procedure can be applied to processes from any industry sector and is based on available generic and statistical data from the target country. The adaptation of a German LCI dataset for cement production for USA and Japan exemplifies this procedure (Colodel, Sedlbauer et al. 2010).

Also in Europe, a LCA database of building materials specifically adapted for Italian situation has been developed. This database included the regionalisation of existing European LCA data sets for traditional building materials. Despite being known that the choice of each data set was based on pre-defined data quality indicators, more information concerning the methodology used is not publicly available (Barozzi, Breedveld et al. 2009).

3. Background - available LCA data sets in the European context

There are two main types of LCA data sets: Environmental Product Declarations (EPD) and the “so-called” generic LCA data. The former is more suitable to be used in a detailed design stage (or at on-site assessment or building certification), while the latter meets the requirements for the early conceptual design stage (when no detailed information is available for the product). Therefore, data genericity and LCA uncertainty decreases as design detail increases. This section of the paper describes these two types of LCA data sets, along with country-specific and European average LCA ones that are also available in the European context. The amount of available data sets is growing in all the referred groups, increasing therefore the importance and the need of the methodology proposed in this paper.

3.1. Generic LCA databases

LCA generic data sets are summarized in Table 1 and include both upstream (e.g. transport and energy supply) and downstream (e.g. disposal or recycling) processes, along with data from production and processing processes, and are available in commercial LCA software (Ferrão 1998; CfD 2001; EC 2009; PRé 2009; Lasvaux, Chevalier et al. 2011).

3.2. Country-specific and European average LCA data sets

In addition to the generic LCA databases, several country-specific or European average LCA data sets have been established, which are characterised in Table 2.

Table 1 – Characterisation of LCA generic data sets

Characteristics	**Ecoinvent**	**ELCD**	**Plastics Europe 2005**
Designation of the database	Ecoinvent version 2.2	European Life Cycle Database version 2.0	*PlasticsEurope Eco-profile and EPD Program*
Country	Swiss	European Union	European
Webpage	www.ecoinvent.ch	http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm.	www.plasticseurope.org.
Organisation responsible for the data	Swiss Centre for Life Cycle Inventories	European Platform for LCA	Plastics Europe – Association of Plastics Manufacturers
PCR followed	Ecoinvent methodology	ISO 14040:2006, ISO 14044:2006	LCI methodology and PCR for Uncompounded Polymer resins and reactive polymer precursors
Availability of data (public/ paid)	Paid	Open access database developed	Public
Number of documents available	LCI of 4,000 industrial processes	LCI of 300 processes supplied by associations of producers from EU and by other sources for the most common materials, energy suppliers, transports and waste management	Eco-profiles of almost every plastic product available in the market
Type of LCA data	Generic (average from industry, survey or literature based)	Generic (average from industry)	
Critical review / verification	Internal critical verification	Internal	External

3.3. Environmental Product Declaration programs

EPD data refers to type III environmental declarations are defined in detail in the international standard "ISO 14025:2006 - Environmental labels and declarations - Type III environmental declarations - Principles and procedures" (ISO 2006) and are normally known as "Environmental product declarations" (EPD). The principles and requirements included in "ISO 21930:2007 - Sustainability in building construction - Environmental declaration of building products" (ISO 2007) work as guidelines in the development and implementation of Type III environmental declarations of construction materials and products (the ones considered in this paper are presented in Table 3), even if this standard does not include recommendations for EPD programs (Krigsvoll, Fumo et al. 2007). The Technical Committee (TC) 350 of the European Committee for Standardization (CEN/TC 350) is devoted to "Sustainable construction" and is developing, within its Workgroups (WG), some standards related to EPDs (Ekvall 2005; Krigsvoll, Fumo et al. 2007).

An EPD is voluntarily developed and presents quantified environmental information on the life cycle of a product, thus allowing comparisons between functionally equivalent products. Type III environmental declarations are based on:

- Data related to the LCA of a product, which is independently verified - internally or externally;
- Modules of information, in accordance with international standards related to LCA: ISO 14040:2006 and ISO 14044:2006 (ISO 2006; ISO 2006);

- Results of the analysis of the "Life-cycle inventory" (LCI);
- Additional environmental information, when adequate.

Table 2 – Characterisation of country-specific and European average LCA data sets

Characteristics	ATILH	CEMBUREAU	Portuguese average LCA data set	PU-Europe
Designation of the database	*Inventaires de Cycle de vie*	CEMBUREAU	*EPD program in the ceramic industrial sector*	PU Europe calculation tool
Country	France	European	Portugal	European
Webpage	www.infociments.fr.fr	www.cembureau.be	-	www.pu-europe.eu
Organisation responsible for the data	*Association Technique de l'Industrie des Liants Hydrauliques* (ATILH)	European Cement Association (CEMBUREAU)	Technological Centre for Ceramic and Glass (CTCV); Portuguese Association of the Ceramic Industry (APICER)	PU Europe - European association of PU insulation manufacturers
PCR followed	French standard	Based on ISO 14020:2005, ISO 14025:2006, ISO 14040:2006, ISO 14044:2006	National-based development for each group of materials	European Standards
Availability of data (public/ paid)	Public	Public	Public	Public
Number of documents available	Nine	One	Four	Two
Sampling procedure - generic, product-specific or average (country, Europe, producer, plant) data	Averaged (country weighted mean)	Not documented	Country average	Not documented
Critical review / verification	External	External	Third-party verification	Third-party verification
% of market share of average LCA data	85 %	Not documented	Not documented	Not documented

These declarations are developed within each EPD program (Figure 1). This kind of program has a coordinator who can be a company, a group of companies, an industrial sector, atrading association, a public agency (e.g. a standardization entity), or an independent scientific body. The coordinator manages its development and the certification process. EPDs represent a complete, robust and scientifically validated source of information of the environmental impacts of a product along the phases of its life cycle included in the study. The development of EPDs within this kind of program also makes the comparison of the results between products easier (Rocha 2010).

The production of "Product Category Rules" (PCR) for EPD design allows for harmonization of the information collected and the LCA methodology used. PCRs are developed specifically for each family of products (e.g. wood, cement-based or ceramic products) to allow for comparing results between products with similar functions or applications and achieving verifiable and consistent results (Silva, Grecea et al. 2007). PCRs can be a set of rules, requirements or guidelines to develop Type III environmental declarations for one or more product categories, which are defined in accordance with interested parties (Figure 1). It must be possible to apply the same "functional equivalent" to the products of the same category, in order to achieve a quantified performance by functional unit. PCR harmonization among EPD programs is stimulated at an international level to satisfy the comparability principle (Almeida 2010; I.EPDS. 2010). However, each EPD database has unique characteristics, namely background data, methodology and data origin that may result in significant differences in the LCA results for each construction product. The publicly available EPD documentation is also very often incomplete concerning the data origin and the methodology of calculation, increasing the risk of misunderstanding for the final user. Yet, the methodological report, that is most of the time kept confidential, should report all the hypotheses as in any LCA study. As a result, the choice of the data to be used in every national context should be cautious, chiefly if the aim is to use them as a national proxy data, by considering all the complementary information included in the EPD (metadata), (Hodková and Lasvaux 2012).

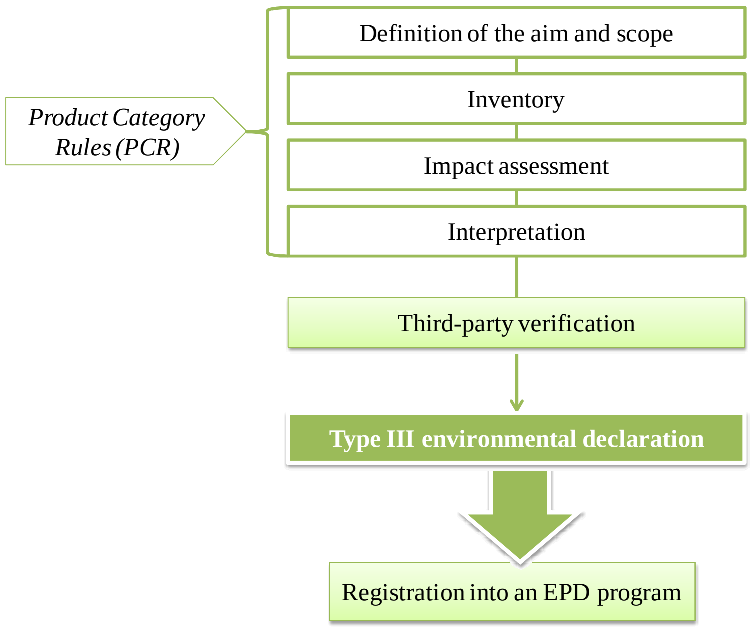

Figure 1 - Different stages of development of an EPD before registration in a official program (adapted from (Rocha 2010))

Table 4 presents a summary of the types of EPD available in the two most representative European EPD programs (the French, INIES - and the German - IBU) and compares it with the nomenclature defined in European Standards (CEN 2010). There is not yet a harmonisation of the names of each type of EPD in each national context. For example, an average data of different manufacturers is defined as:

- "Average" data in CEN Technical Report TR 15941(CEN 2010);
- "Manufacturer group declaration" in the German IBU database
- "Joint EPD" in the French INIES database

The two last ones are identical (except the English translation name). Yet, we can see on Table 4 that the "average" term, as defined in the Technical Report TR 15941, also cover the average of different production sites of the same manufacturer.

Although it is advisable to always follow standardised nomenclature, INIES nomenclature will be followed in this research work to identify each EPD document in a result of the analysis presented in Table 4.

Table 3 – Characterisation of EPD programs that include construction products

Characteristics	BRE	DAPc	Environdec	IBU	INIES	Norwegian EPD Foundation
Designation of the EPD Program	Environmental profiles	Declaración Ambiental de Produto (DAPc)	International EPD System	Umwelt-Deklarationen (EPD)	Programme de Déclaration Environnementale et Sanitaire pour les produits de construction	Norwegian EPD Foundation
Country	United Kingdom	Spain	Sweden (origin)	Germany	France	Norway
Webpage	www.greenbooklive.com	es.csostenible.net/dapc/ el-sistema-dapc	www.environdec.com	bau-umwelt.de/ hp421/Declarations.htm	www.inies.fr	www.epd-norge.no/
Manager of the EPD Program	Building Research Establishment	Col·legi d´Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació de Barcelona e Generalitat de Catalunya; Generalitat de Catalunya	Swedish Environmental Management Council	Institut Bauen und Umwelt	Ten French organizations (governmental, scientific and industrial)	Confederation of Norwegian Enterprise (NHO); Federation of Norwegian Building Industries (BNL)
PCR followed	Methodology for environmental profiles of construction products (2007)	National-based development for each group of materials	*Per* group of materials	National-based development for each group of materials	French standard	National-based development for each group of materials
Availability of data (public/ paid)	Public	Public	Public	Public	Public	Public
Number of documents available	More than 250	10	8 groups of construction materials	Construction materials and products divided in 10 groups, including floor and roof coverings, masonry, wood-based and insulation materials	700 individual or average/joint EPD covering 5,000 commercial references	Construction materials and products divided in 10 groups, including concrete, cement, building boards and insulation materials
Critical review / verification	No	External	External review and approval by an accredited certification body	Advisory board	Third-party verification	Third-party verification

Table 4 – Types of EPD documents and corresponding LCA data nomenclature (for a single product or an averaged product)

<table>
<tr><th rowspan="3">Data included in the EPD (for the same functional unit)</th><th colspan="3">LCA data nomenclature</th></tr>
<tr><th rowspan="2">TR 15941:2010 (CEN 2010)</th><th colspan="2">EPD Program</th></tr>
<tr><th>IBU</th><th>INIES</th></tr>
<tr><td>Data from one manufacturer and site</td><td>Site specific</td><td rowspan="2">Manufacturer´s declaration</td><td rowspan="2">Individual EPD</td></tr>
<tr><td>Average data of different production sites of the same manufacturer</td><td rowspan="2">Average (from different manufacturers or production sites)</td></tr>
<tr><td>Average data of different manufacturers</td><td>Manufacturer group declaration</td><td>Joint EPD</td></tr>
</table>

3.4. Other LCA and EPD databases

A research with the aim of improving the database of ELODIE (a French tool for LCA of buildings (ELODIE 2012) by calculating generic LCA data for the simplified model of this software was recently finished at the “Centre Scientifique et Technique du Bâtiment” (CSTB) in France. Generic LCA data was collected in a private database (database for “simplified” LCA - SLCA) using harmonized LCI flows and LCIA indicators, for both cradle to gate and cradle to grave data of construction materials, products, and processes. A simplified LCI database was first developed using LCI data from mainly two databases (EPD database INIES and generic LCA database Ecoinvent version 2.01) adding up to around 750 processes (600 LCI data from INIES, 130 from Ecoinvent and some more from IBU and ELCD) with the help of a homogeneous nomenclature and meta data. For the processes from both databases, 168 selected LCI flows (based on French EPD nomenclature) were inventoried in order to make possible the integration of the French EPD Life Cycle Inventory within the database. Processes imported from Ecoinvent included transport, energy, waste treatment, water and end-of-life options. Data from INIES correspond to LCI and LCIA data - cradle to grave - available in each EPD according to the French standard (AFNOR 2004; Lasvaux 2010; Lasvaux, Chevalier et al. 2011).

Based on the selected LCI flows of each of the 750 processes, 20 LCIA indicators were calculated using 15 usual Environmental Impact Assessment Methods (EIAM). Then, LCIA of each process were decomposed according to the building life cycle stages given in French and European Standards (AFNOR 2004; CEN 2012): production, transport to the building site, on-site implementation, use phase and end-of-life. Following, analyses on life cycle stages contributions were made for the production of each of construction material and product. Finally, the most documented families of products (i.e. glass wool, rock wool, concrete, steel) had been studied in detail within each environmental impact category in order to access the suitability of LCA data to the French context. This study included the comparison of the results from each database and the identification and explanation of the differences found (Lasvaux, Chevalier et al. 2011).

3.5. LCI flows and LCIA indicators available in each database

Generic LCA databases can present more than 1000 LCI flows for each process. On the other side, an EPD developed within a national program can present only a final balance of from three or four to 168 LCI flows (depending on the EPD program), plus five or more LCIA figures. Therefore, when the aim is to compare results for the same products but coming from different types of sources – e.g. generic and EPD – a first step must be completed to define the LCI and LCIA indicators to be considered in the study. Table 5 summarizes the LCI flows included in each country-specific and European average LCA data sets and EPD program (and also in SLCA database) and Table 6 includes a balance of the EIAM used in these data sets to calculate each LCIA indicator.

The most recent European Standards (FprEN 15804:2011 and prEN 15978:2011 (CEN 2011; CEN 2012)) that supports the Environmental assessment of buildings also outline the LCI and LCIA indicators that should be included in an EPD. In what refers to LCI flows, the following are referenced (CEN 2012):

- Resource use: Renewable primary energy consumption (excluding renewable primary energy resources used as raw materials), use of renewable primary energy resources used as raw materials, total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials), use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials, use of non-renewable primary energy resources used as raw materials, total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials), use of secondary material, use of renewable secondary fuels, use of non-renewable secondary fuels, use of fresh water;
- Waste categories: hazardous, non-hazardous, and radioactive waste disposed;
- Output flows: components for re-use, materials for recycling, materials for energy recovery and exported energy.

In terms of LCIA indicators, European standards determine seven to be taken into account in future European harmonised EPD (CEN 2012):

- GW - Global warming;
- ODP - Ozone depletion;
- AP - Acidification of land and water;
- EP - Eutrophication;
- POCP - Photochemical ozone creation;
- ADP - Depletion of abiotic resources (elements/non fossil resources) and depletion of abiotic resources (fossil).

European Standard FprEN 15804:2011 refers to EIAM to calculate each LCIA indicator that do not exist yet (characterisation factors applied in ELCD), except for the characterisation factor for ADP (elements and fossil) for which the CML (developed by the "Institute of Environmental Sciences" at the Faculty of Science of the University of Leiden, in the Netherlands) EIAM should take into account. CML had a first version (CML 92), and two main updates (CML 2 *baseline method 2000* and CML 2001, from which a version 2.05 is already available). This EIAM uses a midpoint approach that converts LCI flows in obtained in midpoint impacts (e.g. potential of ozone layer depletion or greenhouse effect).

3.6. Life cycle stages available in each database

The review of available LCA data sets of construction materials and products already presented in this paper included the analysis of the life-cycle stages covered by each one based on European standards nomenclature (Table 8 and Table 9). From this analysis it is possible to conclude that generic and country-specific or European average LCA data sets and EPD databases cover the product stage (cradle to gate: A1-A3 - Table 8), but only the latter include, most of the times, the impacts from the construction process stage (A4-A5) and, rarely, from the use stage (B1-B7). Several data is available in all type of databases concerning the end-of-life stage (C1-C4) and, more rarely, from the "Benefits and loads beyond the system boundary" (D). In addition, most of EPDs include aggregated data (Table 8) whether from the production to the end-of-life of the product or within a module (e.g. aggregated value for end of life). It is important to underline that one of the most significant barriers for inter-comparing all these LCA data sets (along with the methodological choices) is the different level of aggregation of the data in relation to the sub-modules defined on the European standards FprEN 15804 and FprEN 15978 (CEN 2011; CEN 2012)).

Table 5 - LCI flows included in each country-specific and European average LCA data sets and EPD program

Country-specific and European average LCA data sets / EPD program	**LCI flows**									
	Water cons.	**Waste**				**Electric energy cons.**	**CO2 emissions**			**Dust**
		Hazardous	**Non-Haz.**	**Radioactive**	**Inert**		**Land transf.**	**Biomass**	**Fossil**	
ATILH	X	X	X	X	X			X	X	X
CEMBUREAU	X	X	X			X	X			
BRE	X	Human toxicity and ecotoxicity to land and freshwater (CML 2000)		Nuclear (higher level)	Total waste disposal					
DAPc	According with European Standards									
Environdec	X	*	*			X	*			*
IBU	X	X (inc. Radioact.)	X		X					
INIES	168 (inc. water and electric energy consumption, hazardous, non-hazardous, radioactive and inert waste production, recycled waste, and emissions to the air – including dust – and water)									
Norwegian EPD Foundation	X	X	Reuse/recycling, energy production, to landfill*			X	Total			X
Portuguese average LCA data set	X*	X	X		Recycled waste	X*				
PU-Europe		X	X	X						
SLCA	X	X	X	X	X	X (Partial)		X	X	X

Note: * - Not supplied for all products

Table 6 - EIAM used in each country-specific and European average LCA data sets and EPD program to calculate each LCIA indicator

<table>
<tr><th rowspan="3">Country-specific and European average LCA data sets / EPD program</th><th colspan="8">EIAM used to calculate each LCIA indicator</th></tr>
<tr><th colspan="2">Resources with energy content</th><th rowspan="2">GWP</th><th rowspan="2">ODP</th><th rowspan="2">AP</th><th rowspan="2">ADP</th><th rowspan="2">EP</th><th rowspan="2">POCP</th></tr>
<tr><th>Renewable</th><th>Non-renewable</th></tr>
<tr><td>ATILH</td><td colspan="2">NF P01-010</td><td colspan="4">NF P01-010 (based on CML 2001 for mid-point indicators)</td><td></td><td>NF P01-010 (based on CML 2001 for mid-point indicators)</td></tr>
<tr><td>BRE</td><td></td><td></td><td colspan="3">CML 2000</td><td>Minerals Resource Extraction (ton); Fossil fuel depletion (MJ)</td><td colspan="2">CML 2000</td></tr>
<tr><td>CEMBUREAU</td><td>X</td><td>X</td><td>IPCC 2001 - 100 years</td><td>Nordic Guidelines on LCA 1992*</td><td>CML 1999</td><td>CML 2001 v. 2.05</td><td>CML 1999; Heijungs et al. 1992</td><td>Nordic Guidelines on LCA 1992; Environmental Assessment of Products - Denmark 1992; CML, 1999</td></tr>
<tr><td>DAPc</td><td colspan="8">According with European Standards</td></tr>
<tr><td>Environdec</td><td>X</td><td>X</td><td>IPCC 2001 - 100 years</td><td>Nordic Guidelines on LCA 1992*</td><td>CML 1999</td><td></td><td>CML 1999; Heijungs et al. 1992</td><td>Nordic Guidelines on LCA 1992; Environmental Assessment of Products - Denmark 1992; CML, 1999</td></tr>
<tr><td>IBU</td><td>X</td><td>X</td><td colspan="6">CML 2001</td></tr>
<tr><td>INIES[*2]</td><td colspan="2">NF P01-010</td><td colspan="4">NF P01-010 (based on CML 2001 for mid-point indicators)</td><td>NF P01-010*</td><td>NF P01-010</td></tr>
<tr><td>Norwegian EPD Foundation</td><td>Renewable energy consumption (kWh)</td><td>Non-renewable energy consumption (kWh)</td><td>IPCC (last version)</td><td colspan="2">CML 2001</td><td></td><td colspan="2">CML 2001</td></tr>
<tr><td>Portuguese average LCA data set</td><td></td><td>X</td><td colspan="3">CML 2001</td><td></td><td colspan="2">CML 2001</td></tr>
<tr><td>PU-Europe</td><td colspan="5">According with the European standard FprEN 15804:2011</td><td></td><td colspan="2">According with the European standard FprEN 15804:2011</td></tr>
<tr><td>SLCA[*2]</td><td>X</td><td>X</td><td>IPCC (last version)</td><td>-</td><td colspan="3">CML 2001</td><td>NF P01-010; CML 2001</td></tr>
</table>

Note: * - Not supplied for all products. [*2]- plus air pollution.

Table 7 - Life-cycle stages classification based on French and European standards (AFNOR 2004; CEN 2012)

Standard	**LCA boundaries**					
	Cradle-to-cradle					
	Cradle-to-grave					
	Cradle-to-gate	**Gate-to-grave**				
NF P01-010	Production	Transportation	Implementation	Utilisation	End-of-life	
FprEN 15804:2011	Product stage (A1-A3)	Construction process stage (A4-A5)		Use stage (B1-B7)	End-of-life stage (C1-C4)	Benefits and loads beyond the system boundary (D)

The information included in EPD related with all the stages after the production (B, C or D) are based on scenarios, which are mostly built and assessed using generic LCA data (similarly to the approach commonly used for modelling upstream processes, as the production of raw materials) (Table 9). Following this approach, generic data for scenarios should be “as realistic as possible and properly documented (covering the present or anticipated situation), rather than idealistic or "carefully selected"” (CEN 2010), and the assumptions made for each stage should be inter-related. For instance, construction process scenarios are important not only for the construction stage, but also for the use and end-of-life stages. On the other side, scenarios describing end-of-life stage (downstream processes – see Table 9) should reflect the existing technology, current regulations, today's average practice and a mix of different end-of-life treatments available atthe national or regional level (CEN 2010).

Table 8 – Detailed life-cycle stages classification based on European standards (CEN 2012)

Modules	**Life-cycle stage designation and description**	
Product stage (A1-A3)	A1	raw material extraction and processing, processing of secondary material input
	A2	transport to the manufacturer
	A3	manufacturing
Construction process stage (A4-A5)	A4	transport to the building site
	A5	installation into the building
Use stage - information modules related to the building fabric (B1-B5)	B1	use or application of the installed product
	B2	maintenance
	B3	Repair
	B4	Replacement
	B5	refurbishment
Use stage - information modules related to the operation of the building (B6-B7)	B6	operational energy use
	B7	operational water use
End-of-life stage (C1-C4)	C1	de-construction, demolition
	C2	transport to waste processing
	C3	waste processing for reuse, recovery and/or recycling
	C4	Disposal
Benefits and loads beyond the system boundary (D)	D	reuse, recovery and/or recycling potentials

Table 9 – Type of data - generic and site-specific - used on EPD for each life-cycle stage (CEN 2012)

<table>
<tr><th rowspan="2">Modules</th><th colspan="2">Product stage (A1-A3)</th><th rowspan="2">Construction process stage (A4-A5)</th><th rowspan="2">Use stage (B1-B7)</th><th rowspan="2">End-of-life stage (C1-C4)</th><th rowspan="2">Benefits and loads beyond the system boundary (D)</th></tr>
<tr><th>Production of raw materials</th><th>Product manufacture</th></tr>
<tr><td>Process type</td><td>Upstream processes</td><td>Processes the manufacturer has influence over</td><td colspan="4">Downstream processes</td></tr>
<tr><td>Data type</td><td>Generic data</td><td>Manufacturer´s average or site-specific data</td><td colspan="4">Generic data</td></tr>
</table>

4. NativeLCA methodology

To determine generic LCA data sets for a national context in the construction sector, the most accurate method is to accomplish a complete study for each construction material and product (Hodková and Lasvaux 2012). However, in some cases e.g. the Portuguese and Czech contexts, only a small portion of construction products have already site specific LCA data, and this quantity will not increase much in the short-term. Another option to provide a coherent approach to the LCA of buildings in a national context is to use default values for LCA of construction materials and products. However, this approach is almost an “ideal” as it requires that all the actors of the construction sector of a country agree on LCA results for default compositions of building assemblies (Peuportier, Herfray et al. 2011). A more robust approach is to select LCA data sets for each construction material and product to be used as generic data for a national context, based on a coherent methodology. Therefore, alternative approaches must be put into practice in the selection of LCA data sets to be used as generic data for a national context based on existing databases, along with a qualification method of the quality of the data available in each source accessed: generic, average or EPD data sets (Hodková and Lasvaux 2012). A methodology with this aim and characteristics is described in this paper and is called: NativeLCA. The main principles of NativeLCA methodology are (Hodková and Lasvaux 2012):

- Calculation of mean values from LCA data sets for the same declared unit, when significant documents (both individual and joint EPD and also country-specific or European average LCA data sets) are available;
- Quantification and analysis of the variability of the mean values of a given product;
- Comparison of mean values with generic data to benchmark the results and identify and analyse the differences found.

Figure 2 presents the flowchart of NativeLCA implementation and Figure 3 summarizes the information that should be collected and the decisions that must be made in each of the steps of this methodology according with the description presented in this section of the paper. Along with the description of NativeLCA methodology, there are provided some theoretical examples of the different situations that can occur, and decisions that can be made, during its application. These examples results from the experimental application already made of this methodology to determine generic data on building materials for a national context (i.e. for Czech Republic and France (Hodkova & Lasvaux, 2012 (July), and for Portugal (Silvestre and Lasvaux 2012)).

4.1. Definition of the aim and scope of the study

In spite of not corresponding to a detailed LCA study, the selection of a coherent LCA data set of construction materials and products to be used as generic data for a national context should start with the description of its aim and scope. Although the aim may be implicit, the scope definition should include:

- The functional unit of the study;
- The characterisation of each construction material and product that will be object of the study, namely their pretended composition/formula and physical and chemical characteristics;
- The LCI flows and LCIA parameters (and corresponding EIAM) that will be considered and that are considered to be relevant in a national context;
- Similarly, the life cycle stages that will be considered should also be described and justified in detail in order to define a precise life-cycle boundary (e.g. cradle-to-gate) (Hodková and Lasvaux 2012).

The detailed definition of the scope provides a harmonised basis to make the results from each database comparable and allow for the analysis of the results and differences found between them.

Concerning LCI flows, it is important to highlight that, in addition to the LCI flows included in the databases and presented in Table 5, there are other ones considered in European Standards (CEN 2012) but not provided in databases in in a disaggregated form (i.e. components for re-use, materials for energy recovery and exported energy).

European Standards (CEN 2012) also include several LCIA indicators that are not provided by available databases (e.g. use of renewable primary energy resources used as raw materials, use of secondary material and use of renewable secondary fuels) and that therefore should not be chosen in this kind of study. To identify the key LCIA to be chosen for a first application of NativeLCA, a normalization of LCIA impacts can be conducted using a specific database.

4.2. Data sets identification and description

The first step of NativeLCA methodology corresponds to the identification and quantification of available LCA data sets - data collection stage, mainly at a national and at the European level, for a chosen building product. At a national level, available data sets for a given building product can be divided on site specific data from national LCA studies, individual and joint EPD and national average LCA data sets. For the last three data sets, it is also important to note down their representativeness in terms of market share, when available.

At and international level, generic data can also be found and considered, along with individual and joint EPD and country-specific and European average LCA data sets (Hodková and Lasvaux 2012). Thereafter, a wisely choice of the meta data that should be used in the characterisation of each data set should be made, identically to Table 1 to Table 3 of this paper, and each field should be filled for each data set.

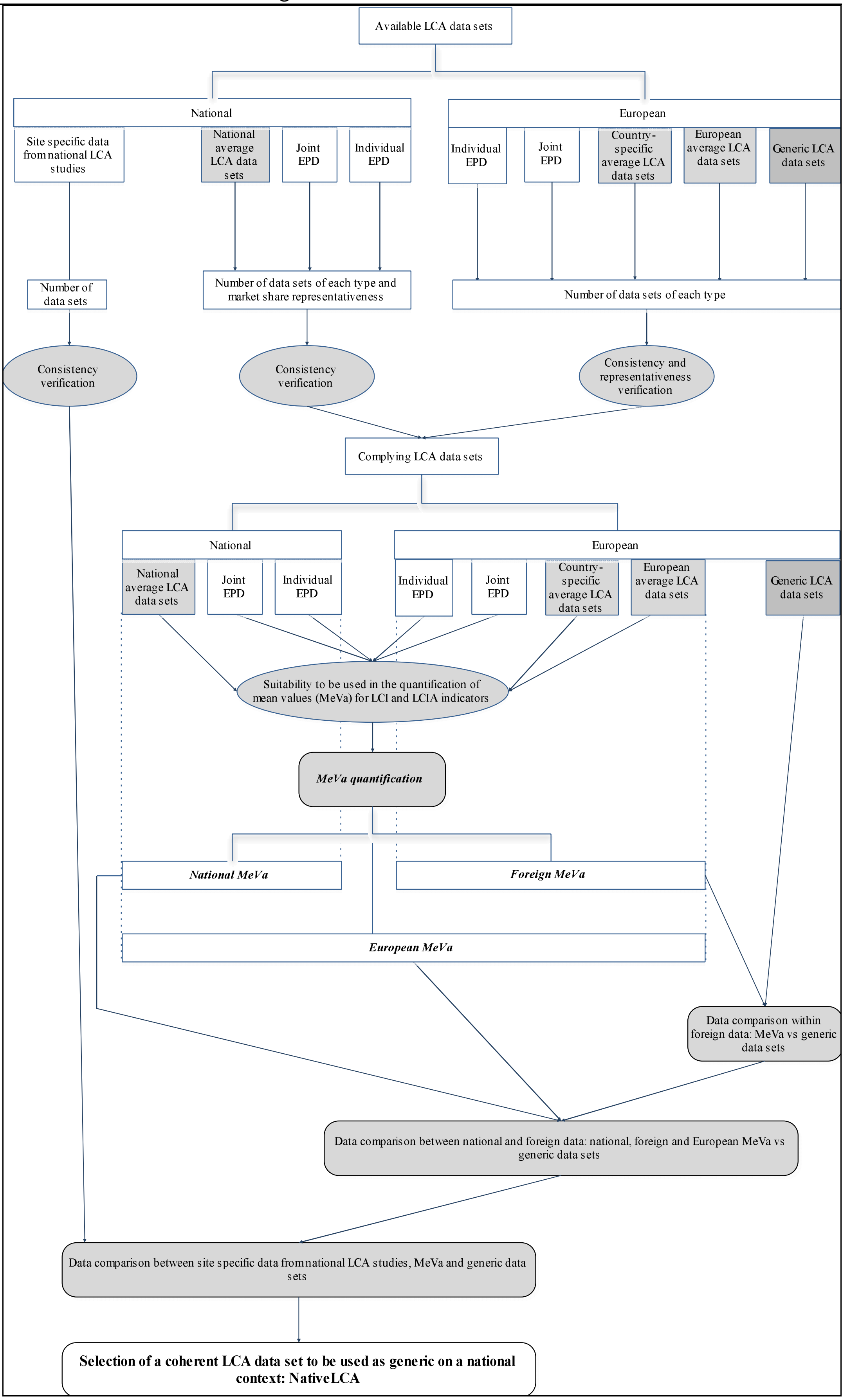

Figure 2 - NativeLCA methodology flowchart

LCA data sets							National and foreign data verification	Suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators and MeVa quantification (EPD and average data sets)	Data comparison within foreign data: MeVa vs generic data sets	Data comparison between national and foreign data: MeVa vs generic data sets	Data comparison between site specific data from national LCA studies, MeVa and generic data sets	Selection of a coherent LCA data set to be used as generic on a national context: NativeLCA
National			European									
Site specific data from national LCA studies/ ***individual EPD***	Joint EPD (* - representative of all the market share)	National average LCA data sets	Individual EPD	Joint EPD	Country-specific or European average LCA data sets	Generic LCA data set	Consistency (all data sets) and representativeness (foreign data sets)					
Yes	Joint (number)	Number of data sets	Number	Joint (number)	Country (number of data sets)	Number of data sets	Identify eliminated data sets	European MeVa	Foreign MeVa discarded	European MeVa discarded	Benchmark	Site specific data from national LCA studies
Number	Joint* (number)	Number of data sets*			European (number of data sets)			Foreign MeVa	Generic data sets discarded	Foreign MeVa discarded	Check the plausibility of site specific data from national LCA studies	National individual EPD
								National MeVa		National MeVa discarded	Site specific data from national LCA studies not available	European MeVa
										Generic data sets discarded		Foreign MeVa
												National MeVa
												Generic LCA data set (only changing background data, e.g. electricity mix, transport distances)
												A set of LCA data to be used/chosen for the early design stage and other one for the detailed design stage

Figure 3 - NativeLCA decision table

LCA meta data includes all relevant information that aids the selection of appropriate and qualified data for each context, namely the information necessary to determine the data source and for what it represents. It is fundamental that relevant meta data be kept along with each quantitative data set (related with a given database and a specific construction material or product). This way, LCA figures should be associated with the approach that leaded to their calculation, leading to a better understanding of its significance. Meta data can also be crossed between databases that present contradictory indicators in order to aid in the search for an explanation of the major differences found. According with CEN/TR 15941:2010 requirements, LCA meta data should include (CEN 2010):

- The origin of the data;
- Geographical and temporal coverage;
- A registry of the transformations that had been made to the data (e.g. averaging);
- Representativeness in all possible dimensions.

An example of a set of meta data that can be used to characterize available LCA data is presented in Table 10, following mostly the approach of SLCA construction (Lasvaux, Chevalier et al. 2011). The fields chosen do not fulfil all requirements of European Standards as the aim is only to provide sufficient information that allows for the data comparison.

4.3. Consistency and representativeness verification

The second step of NativeLCA methodology includes the verification of the consistency and representativeness of each data set in order to, respectively, confirm if they are of sufficient quality to be used in a national context. The first criteria should be verified for all data sets, while the second one is to be verified only by foreign data sets (see Figure 2).

The verification of consistency includes the checking of the following characteristics of each data set (CEN 2010):

- PCR or standard followed during LCA study and corresponding characteristics;
- LCA study hypothesis, namely system boundaries,cut-off and allocation rules;
- Consistency on the assumptions, methods, models and data, namely on the definition of parameters of the LCI and LCIA procedures, and accordance with the goal and scope of the LCA study;
- Type of internal/external/third party verification.

The verification of consistency provides a qualification of each data set using the requirements already summarized and can be made using the meta data characterization completed in the previous step (e.g. via the fields PCR followed, System boundaries, Cut-off rules, Allocation rules, Critical review / verification and % of market share of average LCA data - see Table 2, Table 3 and Table 10). A more detailed verification can always be implemented if other dimensions of LCA data sets are analysed, namely (CEN 2010): plausibility (e.g. including cross-check for selected elementary, mass and energy balances and comparison with other existing data), completeness (e.g. downstream processes should be modelled “to the elementary flows”); and uncertainty (e.g. reliability of the source, differences with other available sources and sensitivity analysis of the final results). However, considering the aim of this methodology these complementary verifications are not required.

Table 10 – Example of meta data selected to characterize LCA data sets (Lasvaux, Chevalier et al. 2011)

Type of meta data	Description	Examples
Designation	Designation included in the generic data/EPD database that describes the type of construction material or product	Concrete, steel
Function	describe the function according with SLCA	*Façades, Procede fin de vie*
Functional unit	describe the functional unit of the data	1 kg; 1m^2
Characteristics	describe physical characteristics or others	Density, use of primary and secondary raw materials
Organisation responsible for the data	describe the data provider	EMPA; French trade unions
Geographical coverage	provide the geographical validity of the data	France
Temporal representativeness	provides the year of data collection	2006; 2005-2011
Technological representativeness	provide the technological level of manufacturing processes	Usual technology (most of the cases); advanced technology
Type of LCA data and sampling procedure	describe the type of LCA data and the gate-to-gate data collection	Generic, product-specific or average (country, Europe, producer, plant) data Based on literature (partly the case of Ecoinvent); based on data collection in the manufacturer plant (always the case in French EPD)
System boundaries	describe the system boundaries of the data	Cradle to gate (A1-A3), cradle to grave (A-B-C]), cradle to cradle (A-B-C-D), etc.
Energy and transport processes LCA data	describe the energy and transport LCA data used	French FDP01-015 LCA data on electric mix and fuel; Ecoinvent ones
Cut-off rules	describes the cut-off rules	French EPD should comply with 98 % in mass whereas Ecoinvent do not provide such a rule
Allocation of by-products	describe the allocation of by-products in the plant	Mass, economic, energy
Packaging	describe the characteristics of the packaging considered in the study	Stirable thermo-retractible film, PE film, wood pallet, adhesive labels
Infrastructures	describes if the infrastructures of production (e.g. cement plant) are include within the system boundary	Included, not Included
EPD program, number and state	identify the EPD program, the number of the document and its state, including the date of expiration	INIES Expired, on line, stored, expires three year after the date of declaration
Critical review / verification	describe if a critical review / third party verification has been conducted	Internal critical review, third-party verification
Generic LCA databases	identify the Generic LCA database	Ecoinvent, ELCD
Year of release of the data	describe the year of the release of the data	2007 (Ecoinvent 2.0)

A representativeness criterion is only applied to foreign data sets in order to evaluate their suitability to be used as generic data for a national context by checking their accordance with national practices. Therefore, the features of each data set that should be observed are (CEN 2010) (see Table 10):

- Geographical coverage;
- Production technological hypothesis (technological coverage);
- Composition/formula and physical and chemical characteristics of the product represented by the data set (e.g. for cement, CEMBUREAU European average LCA data set presents the results for a median cement, but the cement that is being study can have a different composition or compressive strength);
- Background data used on LCA calculation: electric grid mix, manufacturing of raw materials, transportation modes and distances;
- Data sets used to model downstream processes: transportation modes and distances, maintenance and end-of-life practices.
- Age of the data (e.g. should have been verified within the last ten years);
- The possibility of modify background data in order to provide "contextualization".

Usually only generic data sets allow for modifications of its background data (e.g. electricity production mix, transport modelling and distances, origin of raw materials and waste treatment processes) in an approach known as "contextualization" (Peuportier, Herfray et al. 2011). If a "contextualization" is made in this step to some data set, only the corresponding "contextualized" values should be considered in the remaining steps of this methodology.

International LCA data sets were restricted in this paper to the European geographical area because data sets from out of Europe do not comply from the beginning with the representativeness criteria in terms of geographical coverage and their technological hypothesis is more liable to differ from the European practices.

At the end of this step, the pool of data sets that do not comply either with consistency and /or with representativeness criteria should be identified.

4.4. Suitability test for the quantification of mean values (MeVa) of LCI and LCIA indicators

The third step of the NativeLCA methodology includes, for the pool of data sets that comply with the consistency and representativeness criteria, the confirmation of their suitability to be used in the quantification of mean values (MeVa) for LCI and LCIA indicators.

Generic databases are not included in this verification because they normally includes only one life cycle stage represented in each process (see 3.6) and, when available through a LCA software, all LCI flows and LCIA parameters (using adequate EIAM) are liable to be calculated. Existing or on-going site-specific data from national LCA studies will also not be subjected to this checking because they will not be used in the calculus of mean values and only be compared at the end with the remaining data sets.

This step includes the assessment of the LCI flows or LCIA parameters included in the results of individual EPD, joint EPD and average LCA data sets, both nationally (e.g. Portugal, France) and from other European countries (defined as "foreign"). For the LCIA parameters, the EIAM used should also be checked, including the corresponding version and/or issue year. In this step, the level of aggregation *per* life-cycle stages and building material of LCI flows and LCIA indicators in each data set will also be analysed. As a conclusion, this step will not provide a list of data sets to be discarded but the identification of the data sets that can be used in the quantification of MeVa of each LCI and LCIA indicators and corresponding life cycle stages. In fact, as the scope of the study is prior to the data selection, only the data sets that are within the scope defined in almost one set (LCI - LCIA - EIAM - life-cycle stage - building material) will be considered.

4.5. Quantification of national, foreign and European mean values (MeVa) of LCI and LCIA indicators

A quantification of national, foreign and European mean values (MeVa) for LCI and LCIA indicators is accomplished in the fourth step of NativeLCA methodology. These values results from the combination of site-specific and/ or average data related with the manufacturing of the same product but representing different “technologies, sites, countries and/or time”. As NativeLCA will be applied mainly to building products, MeVa correspond therefore to systems averaging. MeVa calculation should however signalize (or avoid, when the goal is a given technology) averaging of processes representing two or more very different technologies for the manufacturing of the same product (EC-JRC 2011).

European Standards distinguish average (mean values) from generic data sets by referring that the former correspond to “data combined from different manufacturers or production sites for the same declared unit (which also corresponds to a joint declaration in the French EPD system (AFNOR 2004) – see Table 4)” and the latter is “surrogate data used if no system specific data are available”. Nevertheless, both types of data sets have the aim of representing a specified geographic region and time, and generic data sets can also result from site-specific or average LCA studies with the aim of representing a typical variant of a process (CEN 2010; EC-JRC 2011).

This step evolves through several sub-steps that are described next:

- Consideration of individual and joint EPDs and average data sets (national, country-specific or European) available in the country, abroad or both that have been considered suitable to be used in MeVa quantification;
- For each environmental parameter (LCI flow or LCIA indicator, in each life-cycle stage), quantification of the variability per type of material. Then, analysis of the dispersion by means of appropriate scatter plots and bars for the same declared unit. The analysis of the variability of the figures and, mainly of their mean value, allows for the explanation of the differences found and can also support the decision to maintain or exclude some data sets (EC-JRC 2011; Hodková and Lasvaux 2012). The variability is usually directly dependent of the number of data sets available for each construction material but, when a small number of data sets is available, their variability can be high but any of them should be excluded because of this problem;
- Explanation of the LCI and LCIA results’ dispersion;
- Exclusion of some data sets based on statistical criteria.

All these sub-steps precede national, foreign and European MeVa calculation. MeVA allows for the weakening of the variability that exists between all the figures considered and their quantification is accomplished by means of:

- Calculation of national, foreign and European MeVa based on the remaining data sets:
    - National MeVA should be preferably a weighted mean according with the production volumes, for each environmental indicator and for the same declared unit, of individual and joint EPD and average data sets (has recommended in European Standards (CEN 2010)), when declared, or, in alternative, according with the market shares;
    - Foreign and European MeVA should be calculated as weighted mean of declared production volumes, for each environmental indicator and for the same declared unit, of individual and joint EPD and average data sets (as recommended in European Standards (CEN 2010));
    - An arithmetic mean according to the number of companies included in each data set, for each environmental indicator and for the same declared unit, of individual and joint EPD and average data sets (at a national, foreign and European level), will be a last option for the data sets that neither declare market shares nor production volumes;
    - National average LCA data sets that do not include information concerning market shares, production volumes or number of companies considered, and foreign average LCA data sets that do not include

information concerning the two last figures, should not be treated as an individual EPD to be used in MeVA, but it should be possible to choose this data set to be used as generic in the national context;

- National and foreign (mainly European) average LCA data sets that are considered for MeVa quantification should also be considered as individual data set in the comparisons in order to be chosen to be used as generic in the national context.

MeVa calculation may include a preliminary sub-step that corresponds to the calculation of average EPD figures by producer based on its available individual EPD (Hodková and Lasvaux 2012).

4.6. Comparison within foreign data: MeVa vs. generic data sets

The goal of this step is to compare these data sets - foreign MeVa and generic - for each harmonised LCI flow and LCIA parameter, and for life-cycle stage. It has to be decided if any of these data sets should be discarded at this time. This step also allows for the verification of the likelihood of foreign MeVa when compared to generic data sets. Meta data information can be used to explain the differences found between data sets and, in the end, exclusion criteria, based on a statistical criterion, can be defined.

4.7. Comparison between national and foreign data: MeVa vs. generic data sets

Similarly to the previous step, this one intends to provide a comparison between data sets at a European level – national, foreign and European MeVa and generic - for each harmonised LCI flow and LCIA parameter, and for each life-cycle stage (Hodková and Lasvaux 2012). This step also allows for the verification of the likelihood of national MeVa when compared to foreign and European MeVa and generic data sets. Therefore, a decision can result on the exclusion of some data sets according with an adequate criterion. Meta data information can also be used to explain the differences found between data sets.

This comparison should include meta data, by using an adequate data analysis tool (Lasvaux, Chevalier et al. 2011) or data quality assessment methodologies, in order to allow for the determination of robust generic data that are consistent in terms of LCA methodology and technological, temporal and geographical representativeness (Hodková and Lasvaux 2012). For example, an EPD from INIES has often better conditions to be used in a national (i.e. French) context than Ecoinvent data sets because (EC-JRC 2011; Hodková and Lasvaux 2012): it represents a present and realistic situation; it has an appropriate time-related coverage (recent data, not older than 6 years); appropriate technologic (average national technology) and geographical representativeness; and reliable and unified data set (one unique source: EPD from INIES). In spite of that, EPD meta data do not include the % of market share or production volumes of each product or producer (for instance this information is not mandatory in the Product Category Rules - PCR - of the French EPD) and therefore its representativeness is concluded a priori or when complemented by other sources of data.

4.8. Comparison between site specific data from national LCA studies, MeVa and generic data sets

This step of NativeLCA methodology allows for the benchmark of national LCA studies (for each LCI flow and LCIA parameter, and for each life-cycle stage) with national MeVa and foreign LCA data sets (foreign and European MeVA and generic data sets). Benchmarking with foreign figures is extremely important to verify the likelihood and check the plausibility of national LCA studies when compared to national MeVa, foreign and European MeVa and generic data sets. This is especially true when national MeVa do not exist. When site specific data from national LCA studies are not available, this step is ignored.

4.9. Selection of a coherent LCA data set to be used as generic data for a national context: NativeLCA

The last step of NativeLCA methodology deals with the selection of a coherent LCA data set to be used as generic data for a national context within the ones available at this time. Available data sets can be both site specific data from national LCA studies, national foreign and European MeVA or generic. At the end of this step, one data from the pool (or, in some cases, a combination within) is chosen to be the generic data for a national context. To achieve this goal, the most adequate option is to create a Data Quality Indicator (DQI – adapted from the criteria given on European Standards (CEN 2010)) to be assessed for each of these data sets. DQI considers all the information compiled in previous steps of this methodology, mainly the results of the assessment of consistency and representativeness (CEN 2010). For example, the indication that the criteria “geographical coverage” is not fulfilled should be attached to every international data sets in order to inform the final user (Hodková and Lasvaux 2012). Using DQI, it will be possible to create a quantitative classification and corresponding ranking of available data sets in order to ease the choice of the ones that can be considered NativeLCA.

Another option can be to choose a combination of LCA data sets to be used as generic data for a national context. Using this approach, one of them can be used during early design stage (on principle, the most “generic”), and the other one (the most “specific) should be used in the detailed design stage.

When foreign data sets are chosen, mainly because lack of national data, preference should go to data sets that allow for modifications of its background data via “contextualization” (Peuportier, Herfray et al. 2011). Contextualization may include in some cases a detailed analysis and change of individual input or outputs flows of a generic data set, namely based on the differences of industrial statistical information of initial and target regions (Colodel, Sedlbauer et al. 2010). Generic data sets are usually the only ones that allows for “contextualization”, and this is an advantage for them because can improve their representativeness, being even more advantageous if technological representativeness is fulfilled. In fact, if two or more foreign data sets are considered suitable to be used as generic data for a national context, it is paramount to confirm which is more close to national practice in terms of production of the construction product being studied. This information will provide more arguments to select a coherent LCA data set to be used as generic data for a national context within the ones available. This choice should also be based in all the information compiled in previous steps of this methodology, mainly in the results of the assessment of consistency and representativeness (CEN 2010).

5. Discussion and conclusions

This paper proposes a methodology for the selection of a coherent LCA data set of building products to be used as generic in a national context - NativeLCA, based on the adaptation of existing LCA data sets on construction materials and products (generic, average, EPD or site specific). This methodology is innovative mainly because of being: wide-ranging (none of the approaches identified in the state of the art considers all types of LCA data sets); straightforward in its application (not time and resources demanding); focused in the final output – selection of a LCA data set to be directly used by the practitioner, avoiding therefore inventory analysis and modification.

The aim of achieving generic data adapted to a specific geographic context is to provide robust results that can be used by building LCA practitioner on simplified LCA or early design assessment, for example.

The methodology proposed in this paper can now be used as a research tool to answer some of the questions raised by practitioners concerning the coherency of the LCA data to be used to model a building in a national context, namely when several LCA databases are available for the same material. Thus, most of the pitfalls they find in this activity can be avoided (Lasvaux et al., 2011).

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Appendix 7.I

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Environmental, energetic and economic life-cycle assessment from "cradle to cradle" (3E-C2C) of buildings assemblies

Evaluación del ciclo de vida ambiental, energético y económico "de la cuna a la cuna" (3E-C2C) de sistemas de construcción de edificios

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Summary

This paper proposes an integrated approach for the energetic, environmental and economic (3E) life-cycle assessment from "cradle to cradle" (3E-C2C) of building assemblies and exemplifies its application in the selection of the external wall of a building.

3E-C2C approach follows the guidelines included in European standards: environmental performance is evaluated from C2C following a "Life-cycle Assessment" methodology; energetic performance corresponds to the consumption of energy for heating and cooling; and the economic module is based on the Whole-Life Costing (WLC) methodology.

The 3E *cost*-C2C approach provides a subjectivity-free tool to compare and select alternatives in the design of a building by using a prevention-based "Environmental Impact Assessment Method" that converts the results of all impact categories into an economic unit, allowing for the addition of the cost associated with the environmental impacts on the economic and energetic WLC and for the consideration of a 3E performance in all life-cycle stages.

Resumen

Este articulo propone una metodología para la evaluación del Ciclo de Vida (CV) ambiental, energético y económico (3E) "de la cuna a la cuna" (C2C) de sistemas de construcción de edificios, ilustrando su aplicación en la elección de una pared exterior.

3E-C2C sigue las directrices de las normas Europeas: la metodología de evaluación del CV para la performance ambiental C2C; el consumo de energía para calentar y resfriar para el performance energético; el modulo económico se basa en la metodología del "Coste del CV" (CCV).

3E *cost*-C2C provee una unidad sin subjetividad para comparar y elegir alternativas constructivas, usando un "método de evaluación del impacto ambiental" basado en la prevención que convierte los resultados de las categorías de impacte en una unidad económica, permitiendo la adición del coste asociado al impacto ambiental en los CCV económico y energético y la consideración del performance 3E en todas las etapas del CV.

Keywords: building, cradle-to-cradle, eco-costs, energetic performance, envelope, European standards, external walls, Life-cycle assessment, whole-life cost.

Palabras-clave: edificio, desde la cuna hasta la cuna, *eco-costos*, performance energético, envoltura, normas europeas, paredes exteriores, evaluación del ciclo de vida, coste del ciclo de vida.

1. Introduction

In Europe, the "Energetic certification of buildings" [1] has already had positive consequences, not only in terms of the thermal performance of the buildings. In Portugal, for example, it is already possible to establish a direct relationship between the energy class and the quality of construction. With the minimization of carbon emissions resulting from the exploitation of buildings, the measures to control and reduce the environmental impacts of the entire production chain of construction have become a priority. For this reason, it is time to begin determining the "carbon invoice" of the production of construction materials and construction of buildings [2]. As soon as this determination has credible and statistically significant data, the theoretical "carbon invoice" can become a real environmental tax to be applied to new constructions (and may be an incentive for rehabilitation works). Even though the European building industry has energy efficiency as its most recent priority, in a desirable future it will be possible to evaluate a building, and make its energetic certification via a balance of the environmental impacts of its materials in its whole life cycle. To fulfil the ISO 15392 general principle "holistic approach" [3], the sustainability assessment of a building must represent a part of an assessment of integrated building performance [4, 5]. In Spain, for example, a simplified "Life-Cycle Assessment" (LCA) methodology to be included in the process of energetic certification of buildings has already been proposed. This method uses the "Environmental Product Declarations" of construction materials that are already available [6]. In Italy, the need to integrate life cycle assessment quantitative indicators in the process of energy certification has also been identified [7].

The envelope is one of the main parts of the buildings. One of its parts, the external walls, directly influence the thermal and environmental performance of the building envelope because of their considerable weight in the envelope's initial embodied energy, life-cycle energy consumption, whole-life cost and users comfort. They can represent up to 15 % of the overall environmental impacts of a building over a 60-year life-cycle [8] cited by [9]. The environmental impacts of each external wall solution result directly from the attributes of the materials used, such as its initial embodied energy and thermal properties and the way the solution is designed and built. A detailed review of LCA results of more than 10 years of international research studies on the environmental impact of a building's external walls has shown that all the studies include the production of the construction materials and the majority (63%) evaluate the embodied energy of each external wall, but just a third include the end-of-life of the building assembly and no more than 42% include the construction, operation and maintenance stages [10]. Therefore, this paper proposes an approach to provide the environmental, energetic and economic life-cycle assessment from "cradle to cradle" (3E-C2C) of building assemblies and exemplifies its application in the process of selection of the external wall of a building.

2. Proposed environmental, energetic and economic life-cycle assessment from "cradle to cradle" (3E-C2C) approach

A methodology to identify optimal levels of performance of building elements that only include construction and energy costs optimization is proposed in the Recast of the "Energy Performance of Buildings Directive" of 2010 [11]. This approach is insufficient since it disregards environmental aspects of the building element in the life-cycle analysis that leads to a "cost-optimal level". Therefore, this paper proposes an approach to provide the 3E-C2C of building assemblies along the guidelines included in European draft standards under development by Technical Committee (TC) 350 of the "European Committee for Standardization" (CEN/TC 350 - "Sustainability of Construction Works"). These standards for the sustainability assessment of buildings and construction products, which have been structured into three horizontal levels (framework, building and product) and into three vertical columns (environmental, social and economic) while always taking into account technical and functional performance characteristics, will be in their final version by the beginning of 2012. This harmonized European system will allow the assessment of the environmental, social and economic performance of buildings based on a life-cycle approach.

The application of the 3E-C2C approach allows for the evaluation and comparison of building assemblies by: considering their whole life-cycle (C2C); assessing the 3E-C2C impacts and taking into account all the factors that could affect them (e.g. the performance of the assembly in the use phase of the building, service life and recycling potential).

The experimental application of the 3E-C2C approach to the process of selection of the external wall solution for a new (model) building in Portugal allowed the improvement and refinement of each of its modules and steps. Each part of the 3E-C2C of these assemblies was based on and/or compared with data included in other studies already finished in Portugal concerning the energetic, economic and/or environmental performance of solutions for the building envelope.

2.1 Scope of the study

The 3E-C2C approach was applied to a process of selection of the external walls of a model building called HEXA (developed within the LiderA, the Portuguese building environmental certification system), which has five residential floors (the ground floor is to be used for commerce) [12], represents the most common constructive and architectural practices in Portugal but has not been built yet [13]. The HEXA design drawing can be seen in Figure 1 (the building faces South), and the object of the study is the apartment on the right located on a middle floor without an adjacent building on the East façade. The location chosen for HEXA in this study was Lisbon.

Figure 1 - HEXA design drawing of a middle floor: the object of the study is the apartment on the right, without an adjacent building on the East façade [13].

The external walls under analysis are located in the North and South façades of the flat and the functional unit is a square meter of external wall (the East façade is considered to be wall W1 - see Table 1 - for all alternatives). The reference study period was defined as 50 years [12]. For the wall structure, only masonry solutions were considered (the most common solution in Portugal) and for insulation, the materials studied were Extruded Polystyrene (XPS) (inside a cavity wall) and Expanded Polystyrene (EPS) and Agglomerate of Expanded Cork (ICB) within an “External Thermal Insulation Composite System” (ETICS) (Table 1) [12].

The data of life-cycle stages of the external walls included in each module of 3E-C2C approach in the present case study are summarized in Table 2 and described in detail in sections 2.2 and 2.3.

Table 1 - Characteristics of each external wall solution (North and South façades), including maintenance actions

External wall solution	U-value ($W/m^2.K$)	External cladding (EC)	EC maintenance	Wall structure	Wall insulation	Internal coating (IC)	IC maintenance
W1	0.47	Painted cement render	Total cleaning and repainting every 5 years and repair of 35% of the area at 25 years	Cavity wall: 15+11 cm	4 cm of XPS in the air gap	Painted cement render	Total cleaning and repainting every 5 years; repair of 5% of the area each 10 years
W2	0.45	ETICS system		Brick wall: 22 cm	6 cm of EPS in ETICS		
W3	0.48	ETICS system		Brick wall: 22 cm	6 cm of ICB in ETICS		
W4	0.4	ETICS system		Brick wall: 22 cm	8 cm of ICB in ETICS		

Table 2 - Data of life-cycle stages of the external walls included in each module of 3E-C2C approach in the present case study

3E-C2C module	Production	Transport to site	Use stage - energy use for heating and cooling	Use stage - maintenance	End-of-life stage - transport and deposition
Environmental performance	x	x	x		x
Economic performance	x	x		x	x
Energetic performance			x		

2.2 Environmental performance

The environmental performance of the external wall solutions were compared from "cradle to cradle" following "Life-cycle Assessment" methodology (LCA) (based on ISO 14040:2006 and ISO 14044:2006 international standards [14, 15]). This procedure allows LCA results from different studies to be compared and to be used to make meaningful choices [16, 17].

The environmental module of the 3E-C2C approach also followed most of the principles already included in the draft standards FprEN 15643-2:2010: "Sustainability of construction works -Assessment of buildings - Part 2: Framework for the assessment of environmental performance" and prEN 15978:2010: "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation methods", as the following ones:

- The assessment of the environmental performance shall apply the LCA approach in accordance with the guidelines and requirements of ISO 14040:2006 [15];
- The results of the assessments shall be organized in three main groups: impacts specific to building fabric and site (results from the product stage and from the construction process stage), impacts and aspects specific to building in operation (maintenance, repair, replacement, water and energy use and all activities with an environmental impact) and results from the end of life stage of the building;
- The quantification of the impacts of operational energy is a direct result of the calculation of the energy used during the use stage of the building according to the "Energy Performance Building Directive" (EPBD) [1] and shall be derived from different energy carriers or LCA databases;
- The impacts and aspects related with benefits and loads beyond the building life cycle, e.g. those that result from further reuse, recycling potential and energy recovery and other recovery operations, may be included as supplementary information. They are essential to promote and allow a C2C approach in the life-cycle of the buildings and corresponding assemblies;
- The default value for the reference study period shall be the required service life of the building and the estimated service life of the assemblies shall take into account rules and guidance included in the standards ISO 15686-1,-2,-7 and -8 [18-21].

2.2.1 Product stage

The LCA from the production of each construction material (“cradle to gate” approach) was calculated using “SimaPro” software and available “Life cycle Inventory” (LCI) databases adapted to the Portuguese reality when adequate. The LCI data used was:

- Mainly “ecoinvent database system processes”, with a modification in the energy source to represent the Portuguese reality (“electricity, medium voltage, at grid PT/U”);
- The “ecoinvent system process” that corresponds to the production of ICB contains data from one major producer in Portugal;
- “CO_2 sequestration” of cork oak tree (which benefits ICB) was estimated in a “conservative" way, by simulating the incineration with energy recovering at the end of life stage and considering the corresponding negative environmental impact right in the production phase [22];
- The environmental impacts of the production of 1 ton of brick were based on the “Environmental Product Declaration” (EPD) of masonry units with vertical hollows developed in 2009 by the “Technological Centre for Ceramic and Glass”, in collaboration with the “Portuguese Association of the Ceramic Industry” (APICER), based on data collected from 11 sites and on international databases [23, 24].

2.2.2 Construction process stage

At this stage, only the environmental impacts of the transportation from factory gate to construction site were considered (brick and mortars from Leiria area - about 150 km from building site - and insulation materials from the corresponding factories - XPS from 273 km, EPS from 30 km and ICB from 85 km away).

2.2.3 Use stage - energetic performance

The energetic performance considered in the 3E-C2C approach corresponds to the estimation of consumption of energy for heating and cooling during a building’s operation, because these are the only operational costs that the façade influences (ventilation, hot water and lighting uses are similar between the external wall solutions being evaluated). These energetic needs were calculated following the national regulation related with the “Energetic and interior air quality certification in buildings” [25], which transposes the EPBD. This certification system forces the construction, sale or rental of a building or house to be followed by the corresponding certification of its energetic performance. For residential buildings, this regulation stipulates a maximum consumption of heating (winter) and cooling energy (summer), and also limits the energy for heating sanitary waters and the primary energy consumption [13].

To estimate the environmental impacts of the consumption of energy for heating and cooling, the energetic needs of the apartment (in kWh) in the study period were divided by the total area of the external wall being evaluated (40.27 m^2) in order to achieve a value related with the functional unit of the study. This value (in kWh) was introduced in “SimaPro” software and the corresponding environmental impacts were calculated considering the process which represents the Portuguese electricity supply (“electricity, medium voltage, at grid PT/U”).

2.2.4 End of life stage

At this stage selective demolition (or deconstruction) was considered to estimate environmental and economic impacts of transport and disposal of “Construction and Demolition Waste” (CDW) in adequate plants. This technique is increasingly being used in Portugal for environmental (allowing the maximization of CDW reuse/recycling potential) and economic reasons [26]. However, for ETICS solutions, it was considered that the finishing render and the insulation material are mixed after demolition and therefore have to be considered as undifferentiated CDW (waste code 17 09 04 - mixed construction and demolition wastes [27]) and sent to landfill. The environmental and economic costs of demolition works were not considered in this approach as they are similar for all the alternatives being evaluated.

The cost and the environmental impacts of the transport and disposal of the CDW generated by each external wall solution were based on Portuguese case studies which used data from waste operators and market values. Therefore, the most probable disposal place (CDW management and recycling plants of the Lisbon area) and final destiny (ex.: landfill, reuse or recycling) were considered for each type of CDW [26]. For example, to estimate the environmental performance, an operation of "rock crushing" and an avoidance of the product "crushed stone" with an output of 80% was considered for the mixture of brick and concrete from mortars (waste code 17 01 07 - mixtures of concrete, bricks, tiles and ceramics [27]) that results from the demolition. However, more studies are necessary in Portugal to evaluate the potential for improving the recycling and reuse of CDW, namely via industrial symbioses, because the end-of-life phase can have a positive contribution to the environmental performance of construction materials [28].

2.2.5 Environmental performance assessment

The LCA results C2C (without weighting or aggregation) for the external wall solutions being evaluated are presented in section 3. Single score should never be used in public comparisons of LCA results [14] and the interpretation and valuation of the results of the assessment are not within the scope of LCA international standards [14, 15]. However, in order to allow for the application of a 3E *cost*-C2C approach, an "Environmental Impact Assessment Method" (EIAM) with a weighting step (that converts the results of all impact categories into an economic unit) was used to allow the addition of the cost associated with the environmental impacts to the economic and energetic whole-life cost. 3E *cost*-C2C may become universal, when the financial implications of each environmental impact have been sufficiently assessed (ex.: the carbon market related with the cost of CO_2 emissions of the production of products). There are already examples of quantification of "natural capital", as the "Canadian Boreal Initiative" that calculated the value of the ecological services of a valley in order to "tax" industries that destroy it [29]. The invisibility of many of nature's services to the economy results in widespread neglect of natural capital, leading to decisions that degrade ecosystem services and biodiversity [30]. Only the definition of a universal economic value of natural elements and services can avoid the excessive consumption of natural resources. Nevertheless, as the value of nature starts being recognized, a global market for services from ecosystems - the natural capital - emerges at the global level [31].

Concerning the EIAM, most of the academic LCA studies use a "single indicator" which weights the results of each impact category to express them in the same unit: a "damage based" indicator (ex.: *Ecoindicator 99* whose unit is "Points"); a single issue indicator (ex.: global warming potential, corresponding to the carbon footprint with "kg CO_2 eq." as its reference unit); a "prevention based" indicator (ex.: *eco-costs 2007*, with an economic unit, the euro). All of them are suitable for different types of analysis, but for C2C calculations *eco-costs* give the most satisfactory results. *Eco-costs* define a prevention based "single indicator" for environmental burdens which is based on the concept of "marginal prevention costs" (e.g. costs required to bring the environmental burden to a sustainable level, by either "end-of-pipe" measures or by "process integrated" solutions). "Marginal prevention costs" include the *eco-costs* of toxic emissions, material depletion and energy. One substance can cause damage in different impact categories but it has only one prevention cost, so should be counted only in one impact category and e*co-costs* model considers it only in the most relevant (most expensive) impact category. This EIAM was built based on the Dutch reality by the "Delft University of Technology" but can be applied to other western European countries [22]. The weighted results of the environmental performance based on the *eco-costs* model are presented in section 4.

2.3 Economic performance

Whole-life cost (WLC) is defined as the “all significant and relevant initial and future costs and benefits of and asset, throughout its life cycle, while fulfilling the performance requirements” [32]. The economic module of 3E-C2C approach is based on the WLC methodology [32] and followed most of the principles already included in the draft standard prEN 15643-4:2010: “Sustainability of construction works - Sustainability assessment of buildings - Part 4: Framework for the assessment of economic performance”, as the following ones:

- Only the cost value was considered to express the economic performance over the life cycle, which means that the “lowest life cycle cost” building is the most economic one;
- To link the results from environmental, economic and energetic performance assessments requires that the functional equivalent is one and the same for all assessments.

The WLC from “cradle to cradle” of the solutions under analysis was estimated taking into account these principles and considering current Portuguese practices. In order to facilitate the choice between the competing alternatives, the “Net Present Value” (NPV) method was chosen. The NPV of an alternative is the summation of all costs that occur during the period of study of the life cycle of the solution under analysis, converted to their present value (using a discount rate) in order to make the NPV of all solutions comparable in year 0 - the present moment which corresponds to the design phase [12]. The NPV of the functional unit of each alternative was calculated for the study period using equation (1) considering constant prices [32] and is presented in sections 3 (economic - *Cec* - and energetic - *Ceg* - costs) and 4 (environmental cost - *Cev*):

$$NPV = \sum_{n=0}^{50} \frac{C_n}{(1+d)^n} \quad (€/m^2) \tag{1}$$

Where

C_n cost in year n (€/m^2);

d real discount rate (without considering risk) applied (3%).

2.3.1 Product and construction process stages

Economic cost in year n per square meter of external wall - Cec_n - includes, before use stage, the market acquisition cost in year 0 (which aggregates the cost of products manufacture and transport to site and the costs from the construction process), the maintenance, repair and replacement costs in the study period. These costs were mainly obtained through market surveys, contacting construction entities, as well as construction material suppliers [12].

2.3.2 Use stage - energetic cost

The energetic cost in the year n per square meter of external wall - Ceg_n - corresponds to the expense in energy use for heating and cooling calculated following the methodology described in the national regulation [25, 33]:

$$Ceg_n = 0.1 \times T \times \left(\frac{Nic}{\eta_i} + \frac{Nvc}{\eta_v}\right) \times \frac{Aap}{Aew} \quad (€/year{*}m^2 \text{ of external wall}) \tag{2}$$

Where

T cost of 1 kWh of electricity in Portugal for household consumers, with VAT but without fixed taxes (€/kWh) (0.163 €/kWh considering an installation with more than 2.3 kVA [34]);

Nic nominal annual heating needs per square meter of net floor area of the flat (kWh/m^2*year);

η_i nominal efficiency of the heating equipment (1, considering the reference value [25]);

Nvc nominal annual cooling needs per square meter of net floor area of the flat (kWh/m^2*year);
η_v nominal efficiency of the cooling equipment (3, considering the reference value [25]);
Aap net floor area of the apartment being evaluated (129.96 m^2);
Aew total area of the external wall being evaluated (40.27 m^2).

2.3.3 Use stage - maintenance cost

Economic cost in year *n* per square meter of external wall - Cec_n - includes the corresponding maintenance, repair and replacement operation costs that occur in that year. However, the environmental impacts of these operations are not considered in the environmental performance module of 3E-C2C due to their variable and unpredictable nature.

The maintenance, repair and replacement operations defined in the study for each element of the external wall are described in Table 1.

2.3.4 End-of-life stage

The economic costs in year 50, corresponding to end-of-life costs, only include those associated with transport and disposal (gate cost or tipping fee) of the building assemblies and costs and/or revenues from reuse, recycling, and energy recovery ([26]), using the approach described in section 2.2.4.

3. 3E-C2C results

Here the LCA results in five environmental categories (using an EIAM with a mid-point approach - CML 2 baseline method 2000) (Table 3) are presented along with the economic and energetic ones (Figure 2). The environmental performance results expressed in an economic single indicator, and their combination with economic and energetic performance results, are presented in section 4.

Concerning the environmental performance (LCA without energy use), W1 has a better result only in terms of "Eutrophication", mainly due to the effects of components of ETICS solutions that are sent to landfill in the other alternatives. The worst performance of W2 in the "Photochemical oxidation" category results directly from the environmental impact of EPS production. The production of XPS results in "Ozone layer depletion", making this environmental category significant only for W1. The effect on "Global Warming" of W3 and W4 is mitigated by the consideration of "CO_2 sequestration" of cork oak trees that benefit ICB.

Table 3 - LCA results - C2C of each alternative, without energy use

Environmental category	W1	Results for W2 / % of difference for W1		W3		W4	
1.1.Global Warming potential (kg CO_2 eq.)	6.64E+01	6.10E+01	-9%	5.61E+01	-18%	5.71E+01	-16%
1.2. Ozone layer depletion (kg CFC-11 eq.)	2.03E-04	4.97E-06	-3985%	4.67E-06	-4252%	4.63E-06	-4282%
1.3.Photochemical oxidation (kg C_2H_4)	1.78E-02	2.84E-02	37%	1.74E-02	-2%	1.80E-02	1%
1.4.Acidification (kg SO_2 eq.)	2.40E-01	2.29E-01	-5%	2.15E-01	-11%	2.22E-01	-8%
1.5.Eutrophication (kg PO_4^{-3} eq.)	3.91E-02	8.05E-02	51%	9.28E-02	58%	1.01E-01	61%

The LCA results of the energy use of each solution do not differ more than 2% from each other and are not significant to help in the choice of the one with the best environmental performance.

Concerning the economic and energetic performance (Figure 2), different conclusions can be drawn. The acquisition costs increase from W1 to W4 and this factor really influences the final result, making W1 the best solution in this module of 3E-C2C. However, if the building is not demolished after 50 years, the insulation material starts losing its characteristics and should be replaced. Then, W1 will be the solution for which this operation will be more complicated and expensive because of the location of XPS. W4 has the best energetic performance, which results directly from the lower U-value of this solution.

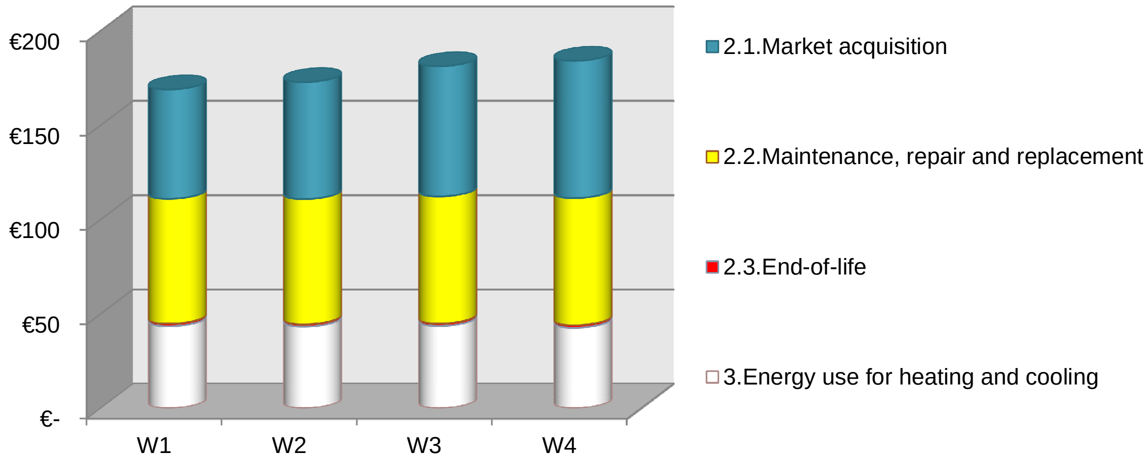

Figure 2 - NPV of the economic (*Cec* - 2.1, 2.2, 2.3) and energetic (*Ceg* - 3.) costs of each option

4. 3E *cost*-C2C results

Section 3 shows that it is important to analyze the results of each module of 3E-C2C separately. However, if it were necessary to make a sound choice of the alternatives with a justifiable criterion, what should be the weights that have to be applied for environmental, economic and energetic results? 3E *cost*-C2C provides a common subjectivity-free unit to compare different alternatives in the design of a building. For each alternative, the cost in year *n* per square meter of external wall is the sum of the environmental (*Cev*), economic (*Cec*) and energetic (*Ceg*) cost:

$$C_n = Cev_n + Cec_n + Ceg_n \text{ (€/m}^2\text{ of external wall)} \quad (3)$$

The NPV of each alternative is achieved by applying equation (1). *Cev* corresponds to the application of the EIAM *eco-costs* to the LCA results already shown in section 3.

In Figure 3 W3 and W4 show the lowest environmental cost in the production stage, mainly due to the consideration of "CO_2 sequestration" during cork oak tree grown. W1 has the greater environmental cost in the transport to site stage because XPS is produced in the more distant plant between the materials used. Costs of end-of-life environmental impacts are negative for all the alternatives because it avoids "crushed stone" due to the recycling (crushing operation) and reuse of the mixture of brick and concrete from mortars that results from the demolition of the walls and that is more significant for W1 (because it includes a higher quantity of brick and masonry mortar and is the only one that includes exterior render).

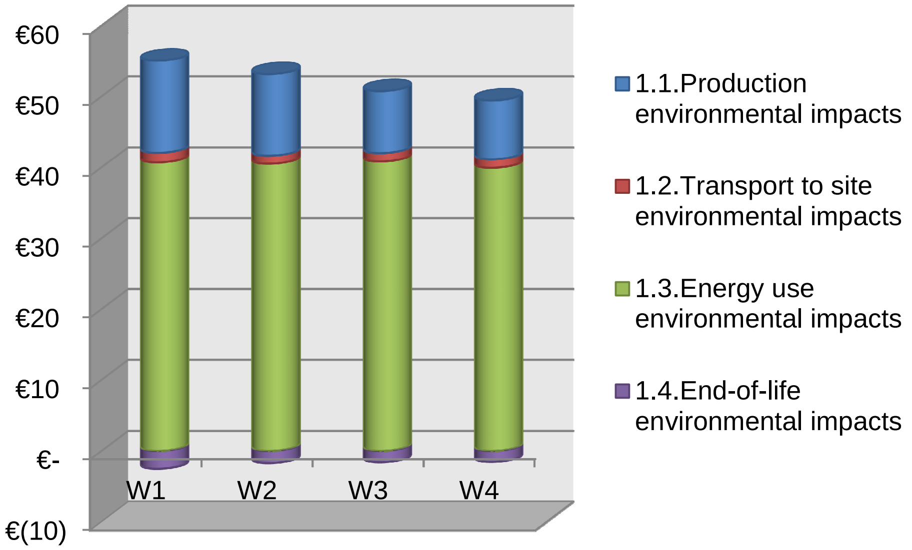

Figure 3 - NPV of the environmental (*Cev* - 1.1 to 1.4) cost

5. Discussion

3E *cost*-C2C results (Figure 4) show the importance of economic cost, which represent more than 55% of the total cost for all four alternatives. This fact, along with the small difference in the total cost between the alternatives (4% between the most and the least expensive), makes the result of this study highly dependent on the uncertainty inherent to market prices for acquisition and maintenance operations (the former are more important because they occur in year 0).

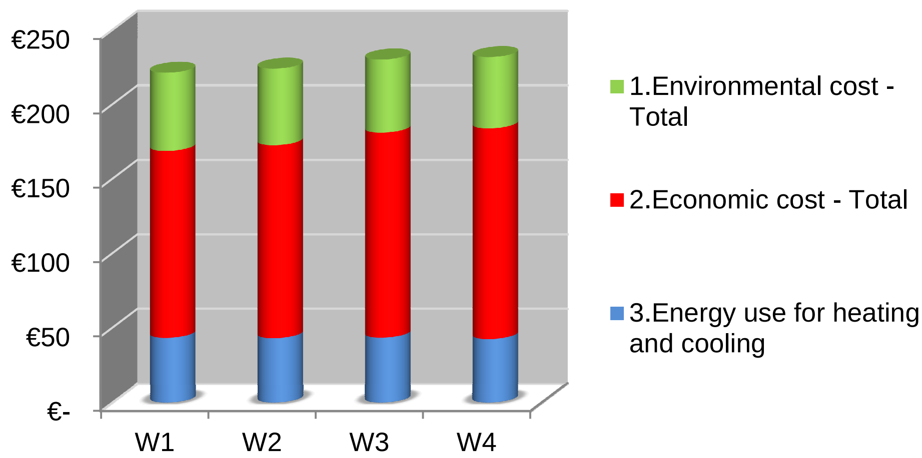

Figure 4 - NPV of the total environmental, economic and energetic cost of each alternative

Concerning the environmental costs, they decrease from W1 to W4 and are inversely proportional to the acquisition cost. Therefore, it is not clear which solution can create a maximum value to the end-user with minimum environmental burden, namely the one with the greater environmental efficiency. However, if the increase of use of ICB results in a decrease of its cost and environmental taxes in products acquisition become a reality, W3 and W4 have a high potential to become the alternatives with the best performance from a 3E *cost*-C2C point of view. The use of ICB also improves the acoustic performance of walls, but it is not yet possible to economically evaluate this positive "social impact".

Concerning the discount rate used for the calculations, a change of more or less 2% does not significantly affect the final result. However, a value higher than 5% affects mostly W3 and W4, because of their higher acquisition cost.

6. Conclusion

This paper proposes an approach which was developed following the guidelines already included in European draft standards, 3E-C2C, and that allows the comparison of two or more assemblies and to select the best alternative (even between solutions that are not functionally equivalent because of the C2C approach that also considers the use and end of life stages and the reference service life) via a multi-criteria analysis if weights are defined for environmental, economic and energetic results. This subjectivity can be eliminated with the use of 3E *cost*-C2C, which expresses all the results in the same unit and therefore allows choosing alternatives (even if they are not functionally equivalent) by considering all the relevant performance indicators in all the important life-cycle stages.

The 3E-C2C data could be also used in the management of the building to allow a permanent monitoring and update of the 3E impacts of each assembly, namely after each maintenance or refurbishment activity. In the future, this feature can be important to allow the renewal of the energetic and/or environmental efficiency certificates.

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Appendix 7.II

Silvestre, J. D.; de Brito, J. & Pinheiro, M. D. (2012a). From the new European Standards to an environmental, energy and economic assessment of building assemblies from cradle-to-cradle (3E-C2C). ***Building and Environment (submitted for publication in 2012)***

From the new European Standards to an environmental, energy and economic assessment of building assemblies from cradle-to-cradle (3E-C2C)

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Abstract

This paper proposes a method to aid in the choice of construction materials or assemblies closely related to buildings' thermal performance. The method provides an assessment of the environmental, energy and economic life cycle from cradle-to-cradle (3E-C2C) of these building elements in accordance with the most recent European standards for the environmental and economic assessment of construction works. Environmental performance is assessed from C2C following a life cycle assessment method, energy performance corresponds to consumption of energy for heating and cooling, and the economic performance is based on the whole-life costing (WLC) method.

Using 3E-C2C to help select an external wall alternative and the corresponding insulation thickness proved useful when comparing alternatives that comply with all the requirements but are not functionally equivalent, since there was no need to change their characteristics to make them comparable. It also helped to quantify different aspects of the performance of the alternatives in each stage of their life cycle, also from cradle-to-cradle.

The 3E *cost*-C2C approach supplements the 3E-C2C method by establishing weights for each aspect of the assembly's performance and for their quantification, using the same unit. This approach uses a prevention-based environmental impact assessment method that converts the results of all impact categories into an economic unit. This allows the cost of the environmental impacts to be added to the economic and energy WLC and a 3E performance C2C to be considered. The 3E *cost*-C2C approach therefore prevents contradictory conclusions that can arise from the individual analysis of each aspect.

Keywords: cradle-to-cradle; energy performance; European standards; external walls; life cycle assessment; whole-life cost.

Introduction

A building's design process is iterative and involves many decision steps. When a construction material or assembly that is closely related to a building's thermal performance has to be chosen, it is necessary to compare available alternatives by using a method that allows:

- The comparison of alternatives that comply with all the requirements (e.g. legal rules or regulations and the building's geometry) but are not functionally equivalent (e.g. that do not have the same thermal performance), without having to change their characteristics to make them comparable (e.g. changing the insulation thickness);
- The quantification of different aspects (e.g. environmental, economic and energy) of the performance of the alternatives in each stage of their life cycles, and also from cradle-to-cradle, in accordance with the life cycle assessment (LCA) international standards and with the most recent European standards related to the assessment of construction work sustainability;
- The simultaneous comparison of all these aspects of the performance of the alternatives, generally by using suitable weights for each aspect (since the designer usually cannot - or does not know how to - define them).

Such an approach has not been developed yet, and so this paper proposes a method that satisfies all these requirements and answers the needs of the building's designer. This method provides an assessment of the environmental, energy and economic life cycle of building assemblies from cradle-to-cradle (3E-C2C). Its application is exemplified in the process of selecting the external wall and corresponding insulation thickness of a new (model) building in Portugal. The 3E *cost*-C2C method enables the definition of appropriate weights for each aspect of the assembly's performance and their quantification, using the same unit.

This paper comprises five sections, including this introduction. The 3E-C2C assessment section sets out the scope and modules of the proposed method, including the state of the art of similar approaches. An example of the method's application and the results is presented afterwards, and the resulting figures are analysed in the discussion section. The paper ends by drawing conclusions that summarise the main advantages and possible applications of the 3E-C2C method.

3E-C2C assessment

Kloepffer [1] proposes a life cycle sustainability assessment (LCSA) scheme for products based on the following formula: LCSA = LCA + LCC + SLCA. For this approach the LCA should comply with ISO standards [2, 3], the LCC is an LCA-type ('environmental') life cycle costing assessment and SLCA stands for social LCA, but this paper does not draw conclusions about the weighting of the three pillars of sustainability. Although SLCAs are beyond the scope of this paper, the approach proposed by Kloepffer [1] to sum various pillars of sustainability includes some prerequisites that have been taken into account in the method proposed in this paper [1, 4], viz.:

a) The functional unit and system boundaries of the assessments should be identical, or at least consistent; one option is to use the same LCI and establish a similar goal and scope;
b) Each assessment should be life cycle-based and include the whole life cycle (i.e. cradle-to-grave) to avoid trade-offs between life cycle stages;

c) LCC should avoid any monetarisation of external costs related to potential environmental damage (which should be considered only in LCA) in order to avoid double counting.

In fact, it is important to use LCA for decision-making at the design stage, although it should be supplemented at least by a whole LCC which addresses the economic element of sustainability [4]. Decision-making that takes these two aspects into account is increasingly important in building design and public procurement [5]. Even though it is generally agreed that the third aspect of sustainability, which concerns socio-cultural issues such as welfare, health, safety and comfort, should be included so as to provide an overall assessment of a building, as yet there is no similar agreement on the assessment of these issues in construction products due to their fuzzier nature [5]; this element was therefore not included in the method proposed here.

The European standards recently compiled by the Technical Committee (TC) 350 of the European Committee for Standardisation (CEN/TC 350 - Sustainability of Construction Works) have been structured along three lines (framework, building and product) and three columns (environmental, social and economic), but always taking technical and functional performance characteristics into account. This harmonised European system allows the assessment of the environmental, economic and social performance of buildings based on a life cycle approach, and its guidelines for environmental and economic assessment were followed when developing the method proposed here. The novel nature of these standards means their applications are not yet significant, even during their development. A detailed review of the LCA results of more than 10 years of international research studies of the external walls of buildings [6] found that only 13 (21%) of the studies explicitly mention that they followed the method described in the LCA international standards, but none of them refer to the use of the approaches set out in the relevant European Standards.

State of the art of available methods for 3E assessment of building assemblies

The envelope is one of the main parts of a building. One of its components, the external walls, directly influences the thermal, economic and environmental performance of the building envelope because of these walls’ considerable weight in the envelope’s initial embodied energy, life cycle energy consumption, whole-life cost and user comfort. They can represent up to 15% of the overall environmental impact of a building over a 60-year life cycle ([7] cited by [8]). The environmental, energy and economic impacts of each external wall solution result directly from the qualities of the materials used, such as its initial embodied energy and thermal properties, and the way the solution is designed and built. Therefore, it is of paramount importance for the building’s designer to have a method to hand for comparing alternative external wall solutions of a building (or of other main building components) and for choosing the most economically and environmentally (including energy) advantageous one. Methods that partially answer this need are described next, and their main characteristics are summarised in Table 1.

In Spain, a simplified LCA method has been proposed for inclusion in the energy certification of buildings. It uses the Environmental Product Declarations (EPDs) of construction materials [12] for the product stage, and also considers the operational energy use (for heating, cooling and hot water). The final results give the total primary energy and CO_2 emissions of these two stages.

Project ‘Butterfly’ in the United Kingdom involved consulting companies and Universities in the creation of a software tool to calculate life cycle cost and maintenance, operational energy and embodied carbon cost (http://www.blpinsurance.com/sustainability/butterfly/) that will be marketed by the end of 2012. The life cycle cost method follows ISO 15686-5 [13] and energy and carbon costs are calculated as described in the CEN/TC 350 group of standards. Operational energy and embodied carbon (including the product and use stages) costs are estimated using a given carbon value. The aim is not to compare the different options in building design element by element but to arrive at conclusions about the impact of these options on the economic and energy performance of the whole building.

Table 1 - Impacts and life-cycle stages considered in methods for the environmental, economic and energetic assessment of building assemblies (economic issues are underlined)

Country	Method	Life cycle stages				
		Product stage	Transportation to the building site	Use stage: Energy use for heating and cooling	Use stage: Maintenance, repair and replacement	End-of-life
China	**[9]**	Initial economic and carbon cost		Economic and carbon costs	Economic and carbon replacement costs	-
European Union	**recast EPBD**	Construction and energy costs			-	
Lithuania	**3 E factor**	Energy consumption, environment pollution (CO_2 emissions) and expenses			Energy consumption and expenses	-
New Zealand	**NZ calculator**	LCA and initial cost		Thermal performance	LCA	-
Portugal	**[10]**	LCA				-
Spain	**Simplified LCA**	EPD (total primary energy and CO_2 emissions)	-	Total primary energy and CO_2 emissions	-	
United Kingdom	**Project 'Butterfly'**	Life cycle cost, and operational energy and embodied carbon cost				-
USA	**[11]**	Embodied energy	-	Thermal performance	-	

An optimisation method (3E - energy, economic and ecological - factor) to minimise the energy costs, environmental pollution (i.e. CO_2 emissions) and expenses during the life cycle of a single-family house was developed in Lithuania. It was used to optimise the thermal insulation, with the same weight for all three aspects. The energy used and the cost of production of the insulation material and its transportation to the construction site, the cost of building construction and renovation and heating (comparing alternative technologies) were taken into account. The ecological performance includes the CO_2 emissions during the production of the insulation material and arising from heating the building [14].

In Portugal, the LCA of a house was calculated for seven alternative exterior wall solutions with similar thermal transmittance, and seven heating systems. This study included the production phase and the heating energy and maintenance requirements for 50 years [10].

A methodology to identify optimal performance levels of building elements that only cover construction and energy cost optimisation is proposed in the Recast of the European Energy Performance of Buildings Directive (EPBD) of 2010 [15].

In the USA, a research study included the calculation of the embodied energy and thermal performance (for 30 years) of twelve external wall solutions for a building in a cold climate region [11]. In China, five façade solutions for an office building were compared in terms of their operational energy consumption (cost and carbon dioxide emissions for 50 years), life cycle environmental load (carbon cost), life cycle cost, green payback time and general payback time [9, 16].

A calculator of the thermal resistance and environmental impact of external walls (only for low-weight wood solutions) was developed in New Zealand [17, 18]. The LCA study of the walls used the Ecoinvent database, considering the same thermal resistance for a 50-year service life, but excluding the construction and the demolition of the building and the operation energy. The final user of this tool can find the environmental impact of alternative solutions for buildings' external walls, along with their initial cost.

This review shows that some of the methods only consider the environmental performance (three out of ten [9-11, 16]) and one only considers the economic performance [15]. There are three methods that only consider carbon emissions (or related costs) within the environmental impacts, along with the LCC ([12, 14] and Project Butterfly). The method developed in New Zealand [17, 18] covers both the LCA of the production and maintenance stages and the initial cost of each assembly. Therefore, none of these methods quantifies the performance of the alternatives, in all three aspects (i.e. environmental, economic and energetic), in all stages of their life cycles, either from cradle-to-cradle or from cradle-to-grave, because they do not include the end-of-life stage (see Table 1). To fill this gap, we propose the 3E-C2C approach, which is therefore innovative at an international level and allows the appraisal and comparison of construction materials and assemblies that are closely related to buildings' thermal performance (Table 2). It considers their whole life cycle (C2C) by assessing the 3Es' (environment, energy and economy) impacts and taking into account all the factors that could affect them, such as the performance of the assembly in the use phase of the building, service life and recycling potential.

Table 2 - Impacts and life-cycle stages (see section 0) of an assembly in each module of the 3E-C2C approach

3E-C2C module - assembly performance:	**Product stage (A1-A3)**	**Transport to the building site (A4)**	**Installation in the building (A5)**	**Use stage**		**End-of-life stage - transport, processing and disposal (C4-C6), and reuse, recovery and/or recycling potential (D)**
				Maintenance, repair and replacement (B2-B4)	**Energy use for heating and cooling (B6)**	
Environmental	LCA		-	LCA		
Economic	Initial cost			Costs	-	Costs
Energetic			-		Costs	-

Scope - system boundaries

The boundaries of an LCA study of a building material or assembly can be defined either from cradle-to-gate (including the extraction and processing of raw materials and the production), from cradle-to-grave (including also the transport, distribution and assembly, use, maintenance and final disposal), or from cradle-to-cradle (C2C) (also including the reuse, recovery and/or recycling - 3R - potential) (

Table 3) [19, 20]. The life cycle stages of construction materials and products are already standardised (

Table 3) in the recent European Standards referred to, including the end-of-life (C stage) and defining a supplementary LCA information module (D) - after the end-of-life of building materials - named Benefits and loads beyond the system boundary [21, 22]. The appraisal of this stage should include the net impacts and benefits related to the 3R potential of construction and demolition waste (CDW) and of other waste flows.

The detailed review of the LCA results of a building's external walls already referred to has shown that all the studies include the production of the construction materials and the majority of them (63%) evaluate the embodied energy of each external wall. However, only a third include the end-of-life of the building assembly and just 42% include the construction, operation and maintenance stages [6]. The boundaries of the 3E-C2C approach include the life cycle stages and/or processes affected by the external walls (i.e. material production and transport, heating and cooling, and maintenance operations - see

Table 3), but do not include the 3E impacts of activities during the use stage that are not affected by the exterior wall solution. In fact, the 3E impacts of electricity consumption by the technical building systems for heating and cooling are considered in the operational energy use stage (B6), but consumption by electric appliances, lighting, cooking, and domestic hot water [22] was not considered.

Table 3 - Detailed life cycle stages of building materials classification based on European standards (adapted from [22, 23])

LCA boundaries			Life cycle stages / LCA information modules		Life cycle stage designation and description
Cradle-to-cradle	Cradle-to-grave	Cradle-to-gate	Product stage (A1-A3)	A1	raw material extraction and processing, processing of secondary material input
				A2	transport to the manufacturer
				A3	manufacturing
		Gate-to-grave	Construction process stage (A4-A5)	A4	transport to the building site
				A5	installation in the building
			Use stage - information modules related to the building fabric (B1-B5)	B1	use or application of the installed product
				B2	maintenance
				B3	repair
				B4	replacement
				B5	refurbishment
			Use stage - information modules related to the operation of the building (B6-B7)	B6	operational energy use
				B7	operational water use
			End-of-life stage (C1-C4)	C1	de-construction, demolition
				C2	transport to waste processing
				C3	waste processing for reuse, recovery and/or recycling (3R)
				C4	disposal
			Benefits and loads beyond the system boundary (D)	D	reuse, recovery and/or recycling (3R) potential

Scope - declared unit

The stricter application of the LCA approach to building assemblies is difficult because of the amount of data on its processes. This makes the definition of a functional unit (which is a service as well as a product), the boundary of the assessment and the databases to be used even more important, since they lessen the sensitivity and errors of the results [24, 25].

The functional unit is usually directly linked with the functions or performance characteristics of the products and is defined such that it provides a reference that enables a construction product's LCA results to be expressed with a common basis [22]. Therefore, the functional unit for an LCA of a building's external wall can be defined as 'a square meter of external wall for 50 years'. However, a functional equivalent must be established at the design stage so that the alternatives can be compared, with particular reference to the external walls of a building. This concept is defined as "the quantified functional requirements and/or technical requirements for an assembled system for use as a basis for comparison" [22, 26]. Following this definition, LCA studies usually use "a square meter of external wall with a given heat transfer coefficient for 50 years" as the functional equivalent for the comparison of alternatives for the external walls of a building [27]. This creates a serious limitation for the designer because each solution has to be adapted to have the same heat transfer coefficient, usually by changing the thermal insulation thickness, to make them comparable. This approach also results in the rejection of innovative or less-often used alternatives such as precast concrete with rigid insulation foam placed in the core (e.g. sandwich panels), or ceramic or lightweight concrete blocks of high thickness and void content, which sometimes do not need an insulation panel in the external wall. We circumvent this limitation by means of an approach that allows the comparison of two or more assemblies with selection of the best alternative, even if they are not functionally equivalent. This is possible by just taking 'a square meter of external wall for 50 years' as the declared unit for the comparison and taking into account the use and end of life stages and the reference service life of each alternative. It is possible to compare external wall solutions with different heat transfer coefficients using this approach because the environmental impacts of their relative thermal performance for 50 years is also considered in the LCA study, along with the production impacts related to the choice of the corresponding relative thermal insulation thickness.

Environmental performance

The environmental performance quantification from the cradle-to-cradle of the 3E-C2C method follows a life cycle Assessment method (LCA) (based on ISO 14040:2006 and ISO 14044:2006 international standards [2, 3]). The environmental module of the 3E-C2C approach also follows most of the principles already included in the draft standards FprEN 15643-2:2010 [28] and FprEN 15978:2011 [21].

Construction process stage (A4-A5)

The construction stage includes the transport from the production gate to the construction site (A4), the on-site storage of products, the wastage of construction products and the processing of product packaging and product waste (A4-A5), and the installation of the product in the building (A5) [22]. At this stage, only the environmental impacts of transporting from factory gate to construction site (sub-stage A4) are considered in the 3E-C2C method.

Use stage - energy performance (B6)

The3E-C2C approach determines energy performance from the consumption of energy for heating and cooling during a building's operation. These are the only operational impacts and cost that the façade influences (electric appliances, lighting, cooking, or domestic hot water uses are similar for all the external wall solutions evaluated). These energy needs are calculated according to the national regulations for Energy and indoor air quality certification in buildings [29], which transposes the Energy Performance Building Directive (EPBD) [30].

Economic performance

Whole-life cost (WLC) is defined as 'all significant and relevant initial and future costs and benefits of an asset, throughout its life cycle, while fulfilling the performance requirements' [31]. The economic module of the 3E-C2C approach is based on the WLC method [31] and follows most of the principles in the draft standard FprEN 15643-4:2011 [32].

To facilitate the choice between the competing alternatives, the net present value (NPV) method was used. The NPV of an alternative is the sum of all costs incurred during the period of study of the life cycle of the solution under analysis, converted to their present value (using a discount rate). This makes the NPV of all solutions comparable in the year 0 - the present moment - which corresponds to the design phase [33]. The NPV of the declared unit of each alternative was calculated for the study period using equation (1), assuming constant prices [31], and is presented in sections 0 (economic - *Cec* - and energy - *Ceg* - costs) and 0 (environmental cost - *Cev*):

$$NPV = \sum_{n=0}^{50} \frac{C_n}{(1+d)^n} \quad (€/m^2) \qquad (1)$$

Where

C_n cost in year n (€/m^2);

d real discount rate (without considering risk) applied (3%).

Product and construction process stages (A1-A5)

The economic cost in year n per square meter of external wall - Cec_n - includes, before the use stage, the market acquisition cost in year 0 (which aggregates the cost of manufacturing and transporting products to the site and the cost of the construction process, without VAT), and the maintenance, repair and replacement costs in the period under analysis.

3E *cost*-C2C assessment

Companies have always been able to consume or pollute with little to no practical consequence, at costs that are normally tolerated by the general public despite being unsustainable and ethically unacceptable. The most difficult issue when dealing with this abuse is to determine the actual cost of such damage to nature [34]. However, it is only by establishing a universal economic value of natural elements and services that the excessive consumption of natural resources can be avoided [35].

The 3E *cost*-C2C approach includes an environmental impact assessment method (EIAM) with a weighting step that converts the results of all LCA impact categories into an economic unit. This enables the cost of the environmental impacts to be added to the economic and energy whole-life cost, resulting in an overall single score (3E *cost*-C2C) for each alternative being assessed. It is true that a single score should never be used in public comparisons of LCA results [2] and the interpretation and evaluation of the results of the assessment are not within the scope of LCA international standards [2, 3]. However, this has led to research studies (e.g. [27]) that only analyse the results of each alternative for each individual environmental category but cannot provide final answers about the best alternative in environmental terms. There are, however, LCA studies that use an EIAM with a single indicator which weights the results of each impact category to express them in the same unit: a damage based indicator (e.g. *Eco-indicator 99* whose unit is Points); a single issue indicator (e.g. global warming potential, corresponding to the carbon footprint, having kg CO_2 eq. as its reference unit); a prevention based indicator (e.g. *Eco-costs 2007*, whose economic unit is the euro). All of them are suitable for different types of analysis, but *Eco-costs* give the most satisfactory results for C2C calculations. *Eco-costs* express a prevention based single indicator for environmental burdens that is based on the concept of marginal prevention costs (e.g. costs required to bring the environmental burden to a sustainable level, by either end-of-pipe measures or process integrated solutions). Marginal prevention costs include the *eco-costs* of toxic emissions, material depletion and energy. One substance can cause damage in different impact categories but it has only one prevention cost. Therefore, it should be counted in only one impact category, and accordingly the e*co-costs* model considers it only in the most relevant (most expensive) impact category. This EIAM was built based on the Dutch reality by the Delft University of Technology but it can be applied to other western European countries [36].

Table 4 presents a comparison between selected environmental impact categories of CML 2 baseline method 2000 (an EIAM with a mid-point approach) and all the *Eco-costs* impact categories (the ones used in the single indicator calculus), where the related categories are placed on the same line. The selection of categories from CML 2 used the most recent European standards [21], except for abiotic depletion (which is divided in the standard into two categories - fossil and non-fossil resources, expressed in MJ and kg Sb eq., respectively).

Table 4 - Comparison between selected impact categories of CML 2 baseline method 2000 and all *Eco-costs* impact categories

CML 2 baseline method 2000 category	**Unit**	***Eco-costs* category**	**Unit**
Abiotic depletion	kg Sb eq.	Metals depletion	euro
		Oil & Gas depletion excl. energy	kg oil eq.
		Depletion of natural forests	euro
Acidification	kg SO_2 eq.	Acidification	kg SO_2 eq.
Eutrophication	kg PO_4^{-3} eq.	Eutrophication	kg PO_4^{-3} eq.
Fresh water and marine aquatic ecotoxicity	*kg 1.4-DB eq.*	Aquatic ecotoxicity	kg TEG eq.
Global Warming potential	kg CO_2 eq.	Global Warming potential - IPPC	kg CO_2 eq.
Human toxicity	*kg 1.4-DB eq.*	Fine dust (PM 2.5)	kg PM 2.5 eq.
		Carcinogens	kg C_2H_3Cl eq.
Ozone layer depletion	kg CFC-11 eq.	1.	-
Photochemical oxidation	kg C_2H_4 eq.	Summer smog	kg C_2H_4 eq.
-	-	Waste	MJ

Table 4 shows that *Eco-costs* include environmental categories that are similar to those most often used in the environmental assessment of construction materials and assemblies. The characterisation tables of *Eco-costs* for acidification, eutrophication and summer smog (photochemical oxidation) are even equal to those from CML 2. *Eco-costs* includes toxicity impact categories (i.e. aquatic ecotoxicity, fine dust (PM 2.5) and carcinogens) which, despite being also included in CML 2 and presented in italics in Table 4, are not usually used in LCA studies because of their high uncertainty and lack of scientific robustness ([37] cited by [27]). The ozone layer depletion category is not considered in *eco-costs* because HCFCs are already banned in Europe and in the USA [36]. Nevertheless, these gases are considered in the global warming potential characterisation tables of this EIAM. As for the waste produced in the system process under study, *eco-costs* gives economic credits to recyclable or combustible waste and considers the cost of disposing of inert or mixed waste (i.e. non-recyclable and non-combustible). This impact category is not considered in the 3E *cost*-C2C approach to avoid double counting. In fact, since all assemblies are modelled in detail from C2C using LCA software, an appropriate end-of-life (e.g. recycling or landfill) is ascribed to each waste flow during their life cycle, according to the Portuguese situation, and the emissions and avoided burdens of these waste flows are duly quantified.

Although it is important to analyse the results of each module of 3E-C2C separately, only the application of weights for the environmental, economic and energy results enables a sound choice to be made between alternatives, based on a justifiable criterion. Therefore, 3E *cost*-C2C provides a common subjectivity-free unit to compare different alternatives for the design of a building. For each alternative, the cost in year *n* (e.g. per square meter of external wall) is the sum of the environmental (*Cev*), economic (*Cec*) and energy (*Ceg*) cost:

$$C_n = Cev_n + Cec_n + Ceg_n \quad \text{(€/declared unit)} \qquad (3)$$

The NPV of each alternative is found by applying equation (1). *Cev* corresponds to the application of the EIAM *eco-costs* to the LCA results.

3E *cost*-C2C may become universal when the financial implications of each environmental impact have been sufficiently assessed. The use of this approach in building design allows the simultaneous comparison of different aspects of the performance of the alternatives (3E) by providing weights to each dimension that the designer usually cannot - or does not know how to - define.

Method application and results

This section illustrates the use of the 3E-C2C method in the selection of the external wall of a building in Portugal. The data on the life cycle stages of the external walls included in each module of 3E-C2C approach have already been summarised in Table 2. Their characteristics for each aspect of the 3E performance in this case study are described in detail in sections 0 and 0. The results for the external wall solutions under evaluation - 3E-C2C (without weighting or aggregation) - are then presented in section 0. Section 0 sets out the environmental performance results expressed by a single economic indicator and their combination with economic and energy performance results, based on the *Eco-costs* model.

Scope of the study

The 3E-C2C approach was applied to a process of selecting the external walls of a model building called Hexa (developed under LiderA, a Portuguese building environmental certification system). The building has five residential floors (the ground floor is to be used for commerce) [33] and represents the most common constructive and architectural practices in Portugal, but has not been built yet [38]. The Hexa design drawing can be seen in Figure 1 (the building faces south), and the subject of the study is the flat on the right located on a middle floor without building adjacent to the east façade. The location chosen for Hexa in this study was Porto, the second largest city of Portugal and the European city having the best performance in the Buildings energy efficiency category of the Green City Index [39].

The external walls studied are on the north and south façades of the flat and the declared unit is a square meter of external wall (the east façade is considered to be the same as wall R - see Table 5 - for all alternatives). The reference study period was set at 50 years [33]. Only masonry solutions were considered for the wall structure (the commonest solution in Portugal), and the insulation material studied was extruded polystyrene (XPS), inserted in a cavity wall or within an external thermal insulation composite system (ETICS). The thermal conductivity was considered for each thickness according to the data from a Portuguese producer (Table 5)).

Figure 1 - Hexa design drawing of a middle floor: the subject of the study is the flat on the right, with no adjacent building on the east façade [38]

The relevant Portuguese code [29] divides Portugal into three climatic regions depending on the winter conditions (Porto is in the I2 region) and provides maximum admissible values for the heat transfer coefficients (U) of the opaque areas of the envelope. This had the positive effect of halving the allowed U-value of these areas of the buildings in Portugal, as shown in Figure 2 for Porto. The five external walls analysed were chosen based on these figures.

Table 5 - Characteristics of each external wall solution (north and south façades), including maintenance work

<table>
<tr><th>External wall solution</th><th>U-value (W/m².K)</th><th>External cladding (EC)</th><th>EC maintenance</th><th>Wall structure</th><th>Wall insulation</th><th>Internal coating (IC)</th><th>IC maintenance</th></tr>
<tr><td>R</td><td>0.46</td><td rowspan="2">Painted cement plaster</td><td rowspan="5">Total cleaning and repainting every 5 years and repair of 35% of the area at 25 years</td><td rowspan="2">Cavity wall: 15+11 cm</td><td>4 cm of XPS in the air gap</td><td rowspan="5">Painted cement plaster</td><td rowspan="5">Total cleaning and repainting every 5 years; repair of 5% of the area each 10 years</td></tr>
<tr><td>W1</td><td>0.41</td><td>6 cm of XPS in the air gap</td></tr>
<tr><td>W2</td><td>0.55</td><td rowspan="3">ETICS system</td><td rowspan="3">Brick wall: 22 cm</td><td>4 cm of XPS in ETICS</td></tr>
<tr><td>W3</td><td>0.43</td><td>6 cm of XPS in ETICS</td></tr>
<tr><td>W4</td><td>0.3</td><td>10 cm of XPS in ETICS</td></tr>
</table>

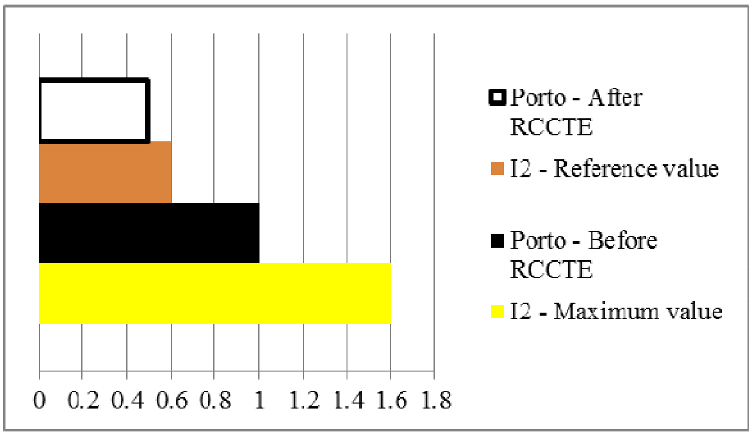

Figure 2 - Comparison between the average values of the heat transfer coefficients (U) of the opaque areas of the envelope of buildings in winter region I2, before and after the introduction of RCCTE, U [W/(m^2.ºC)] [40]

Wall R (reference) represents the average wall in Porto (U =0.46 W/(m^2.ºC)), wall W1 is an improvement on wall R by having thicker insulation, and the other walls (W2, W3, W4) represent the solution most used nowadays (ETICS), with increasing initial cost and insulation thickness, in order to assess the environmental, economic, and/or energy advantages (or weaknesses) of choosing solutions different from the traditional one (cavity wall - walls R and W1). It is therefore important to highlight some differences between the alternatives chosen for this study and wall R:

- W1 has a lower U-value due to increased insulation thickness (from 4 to 6 cm), which completely fills the air gap;
- W2 has insulation of a similar thickness as wall R, but placed within the external cladding and not into the cavity;
- W3 has insulation thicker than wall R (but the same as W1), within the external cladding;
- W4 has insulation thicker than wall R, also within the external cladding; the XPS production process for a 10 cm board differs from that for lower thicknesses;
- W2 (26 cm) and W3 (28 cm) have a lower thickness than the other solutions (without considering the claddings), and they provide the flat with a greater useful internal area, although the economic impact is beyond the scope of this paper.

These five solutions were also chosen assuming a constraint at the design stage that limited the external wall thickness (without considering the claddings) to 32 cm, to represent a realistic situation for the building designer.

Environmental performance

Product stage (A1-A3)

The LCA of the production of each construction material (cradle-to-gate approach) was calculated with SimaPro and the available life cycle inventory (LCI) databases were adapted to the Portuguese reality when appropriate. The LCI data used were:

- Mainly Ecoinvent database unit processes [41], modified by an updated Portuguese electricity mix (data from 2011 - see section 0) to model the industrial consumption for material production ([42];
- The blowing agent was chosen in the process of modelling each thickness of XPS boards according to the information provided by a Portuguese plant (i.e. the XPS production process for a 10 cm board is different from that for lower thicknesses, resulting in higher environmental impacts per mass of board);
- The environmental impacts of the production of 1 tonne of bricks were based on the Environmental Product Declaration (EPD) of masonry units with vertical holes developed in Portugal in 2009 [43, 44].

Construction process stage (A4-A5)

Only the environmental impacts of transportation from factory gate to construction site (sub-stage A4) were considered in the 3E-C2C method: bricks and mortars from Leiria area - around 185 km from the building site - and XPS insulation material from its factory, 45 km away.

Use stage - maintenance, repair and replacement (B2-B4)

This stage concerns the quantification of the environmental impacts of the materials used in maintenance, repair and replacement operations over the life cycle of the assembly (in the year that they occur, according to Table 5). However, this module does not include other impacts from these operations (i.e. water for cleaning, energy for equipment and waste flows) due to their variable and unpredictable nature, particularly in terms of frequency, waste flows and replacement materials. The frequency of the maintenance work considered in the environmental and economic module (see section 0) is identical, but there is more information about the cost of this work than there is about its environmental impacts. The default value for the reference study period was considered to be the required service life of the building and the estimated service life of the assemblies took into account the rules and guidance in ISO 15686-1,-2,-7 and -8 [45-48].

Use stage - energy performance (B6)

To estimate the environmental impacts of the consumption of energy for heating and cooling, the energy needs of the flat (in kWh, calculated as described in section 0) in each year of the study period were divided by the total area of the external wall under evaluation (40.27 m^2) to give a value related to the declared unit used. This value (in kWh) was entered into SimaPro and the environmental impacts were calculated considering a process to model the domestic consumption for heating or cooling at the use stage which represents an updated Portuguese electricity mix (data from 2011) [42]. Table 6 presents the differences between the Portuguese electricity mix in 2004 and the updated one for both industrial and domestic consumption. These figures show an increasing contribution from renewable energy sources (e.g. photovoltaic and wind power plants, the latter mainly for residential consumers) and a reduction in the most harmful technologies such as hard coal and oil. This means lower environmental impacts from electric energy use.

Table 6 - Portuguese electricity mix - differences between 2004 and 2011 for companies and residential consumers [41, 42]

Energy carrier	Electricity mix/PT - ecoinvent 2004	Electricity mix/PT for companies - ERSE 2011	Electricity mix/PT for residential consumers - ERSE 2011
Hard coal, at power plant	31	25	14
Lignite, at power plant	1	0	0
Oil, at power plant	12	1	0
Natural gas, at power plant	25	26	15
Hydropower	21	21	15
Nuclear	4	8	5
Production mix photovoltaic	0	1	4
Wind power plant	3	4	32
Cogeneration with wood	3	4	4
Cogeneration with biogas	0	10	11

End of life stage (C) and Benefits and loads beyond the system boundary (D)
At this stage selective demolition (or deconstruction) was considered to estimate the environmental and economic impacts of transporting and disposing of CDW in suitable sites. However, for the ETICS solutions, it was assumed that the finishing render and insulation material are mixed after demolition and therefore have to be considered as undifferentiated CDW (waste code 17 09 04 - mixed construction and demolition wastes [49]) and sent to landfill. The environmental and economic costs of demolition were not considered as they are similar for all the alternatives under assessment.

The cost and the environmental impacts of transporting and disposing of the CDW generated by each external wall solution were based on Portuguese case studies which used data from waste operators and market prices. Therefore, the most probable disposal site (CDW management and recycling plants in the Lisbon area) and final destination (e.g. landfill, reuse or recycling) were considered for each type of CDW [50]. For example:

- Rock crushing and avoidance of the crushed stone product with an output of 80% were considered for the mixture of brick and mortars (waste code 17 01 07 - mixtures of concrete, bricks, tiles and ceramics [49]) that results from the demolition;
- Electricity consumption from an operation of granulation and avoidance of the expandable polystyrene product were considered for the XPS boards retrieved from the demolition of cavity walls (R and W1).

Despite not yet being a common practice in Portugal to recycle insulation boards, information from a Portuguese plant confirmed that this operation is technically and economically feasible for non-contaminated boards and therefore this end-of-life scenario was considered realistic, and it offers a potential environmental advantage.

Economic performance

Product and construction process stages (A1-A5)
This cost was mainly obtained through market surveys, construction firms, and building materials suppliers [33].

Use stage - maintenance, repair and replacement cost (B2-B4)
The economic cost in year *n* per square meter of external wall - Cec_n - includes the maintenance, repair and replacement operation costs incurred in that year. The maintenance, repair and replacement operations for each element of the external wall are listed in Table 5.

Use stage - energy cost (B6)

The energy cost in year *n* per square meter of external wall - Ceg_n - corresponds to the energy use expenditure on heating and cooling, calculated by the method described in the national regulations [29, 51]:

$$Ceg_n = 0.1 \times T \times (\frac{Nic}{\eta_i} + \frac{Nvc}{\eta_v}) \times \frac{Aap}{Aew} \quad (\text{€/year*m}^2 \text{ of external wall}) \quad (3)$$

Where

T cost of 1 kWh of electricity in Portugal for household consumers, without VAT or standing charges (€/kWh) (0.139 €/kWh considering an installation of more than 2.3 kVA [52]);

Nic nominal annual heating needs per square meter of net floor area of the flat (kWh/m^2*year);

η_i nominal efficiency of the heating equipment (1, considering the reference value [29]);

Nvc nominal annual cooling needs per square meter of net floor area of the flat (kWh/m^2*year);

η_v nominal efficiency of the cooling equipment (3, considering the reference value [29]);

Aap net floor area of the flat under assessment (129.96 m^2);

Aew total area of the external wall being assessed (40.27 m^2).

End-of-life stage (C and D)

The economic costs in year 50, i.e. end-of-life costs, only include those for transport and disposal (gate cost or tipping fee) of the building assemblies and expenses and/or revenues from reuse, recycling, and energy recovery ([50]), using the approach described in section 0.

3E-C2C results

The LCA gives five environmental categories (using an EIAM with a mid-point approach - CML 2 baseline method 2000) (Table 7), which are presented along with the economic and energy ones (Figure 3).

Table 7 - LCA results - C2C of each alternative (A1-A4; B2-B4; C2-C4 and D), without energy use for heating and cooling

Environmental category	R	W1	difference from R (%)	W2		W3		W4	
Global Warming potential (kg CO_2 eq.)	1.08E+02	1.08E+02	0.4%	1.14E+02	5.5%	1.17E+02	7.7%	1.32E+02	16.8%
Ozone layer depletion (kg CFC-11 eq.)	1.19E-05	1.20E-05	0.3%	1.17E-05	-2.3%	1.19E-05	-1.8%	1.19E-05	-0.4%
Photochemical oxidation (kg C_2H_4)	3.25E-02	3.30E-02	1.8%	3.37E-02	3.6%	3.48E-02	6.8%	3.50E-02	7.2%
Acidification (kg SO_2 eq.)	5.44E-01	5.47E-01	0.5%	5.47E-01	0.6%	5.57E-01	2.4%	5.95E-01	8.6%
Eutrophication (kg PO_4^{-3} eq.)	1.51E-01	1.51E-01	0.5%	1.93E-01	22.0%	1.98E-01	23.9%	2.10E-01	28.2%
Abiotic Depletion (kg Sb eq.)	6.05E-01	6.07E-01	0.4%	6.70E-01	9.7%	7.01E-01	13.7%	7.65E-01	21.0%

Concerning the environmental performance (LCA without energy for heating and cooling), R and W1 have a better result in the majority of categories (and significantly in eutrophication and abiotic depletion). This is mainly due to the higher impacts of maintenance operations and to the effects of ETICS components that are sent to landfill in the other alternatives. The worst performance by W4 in global warming, acidification and eutrophication results directly from the environmental impact of XPS production with a different blowing agent, and not only from the use of a greater thickness of this insulation material.

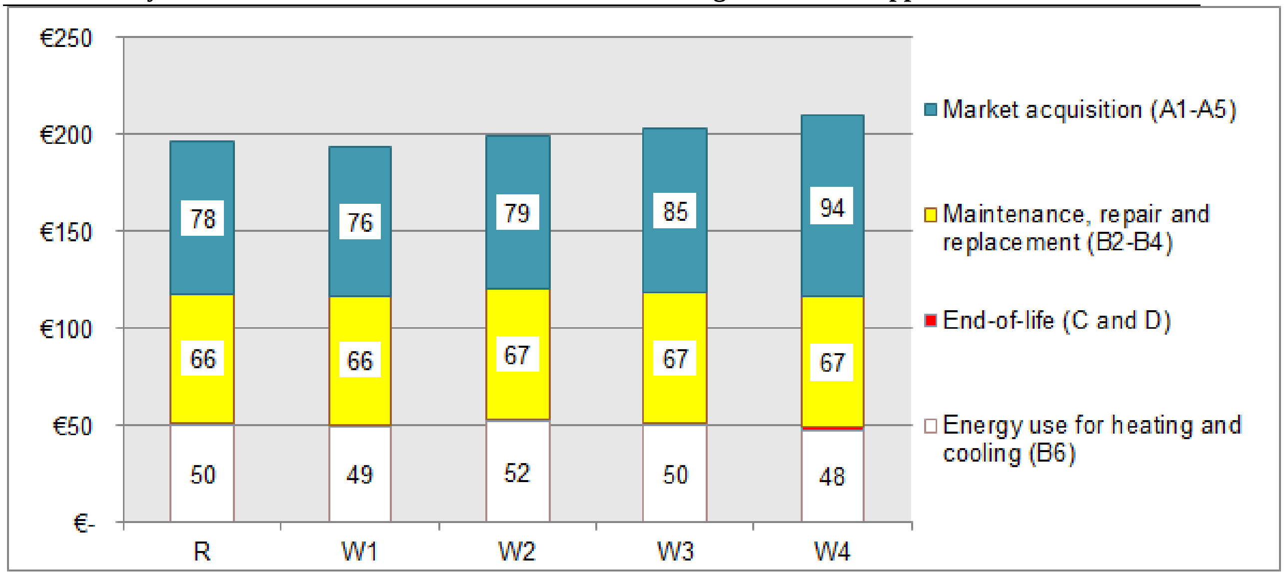

Figure 3 - NPV of the economic (*Cec*: A1-A5, B2-B4 and C and D stages) and energy (*Ceg* -B6 sub-stage) costs of each option

The LCA results of the energy use of each solution stem directly from the energy needs of the flat and do not help as a standalone criterion in the choice of the best environmental performance solution.

The economic and energy performance (Figure 3) leads to different conclusions. The acquisition costs increase from W1 to W4 and this factor really influences the final result, making W1 the best solution in this 3E-C2C module. However, if the building is not demolished after 50 years, the insulation material starts losing its characteristics and should be replaced, even in the cavity wall solutions (R and W1), which is an expensive operation because of the location of XPS. Wall R costs more than W1, despite the lower insulation thickness, because the insulation board does not completely fill the cavity in the former and therefore the inner face of the outer leaf of this wall is rendered. W4 has the best energy performance, which results directly from the lower U-value of this solution.

3E *cost*-C2C results

Figure 4 and Figure 5 present the environmental cost C2C of each alternative, but the first includes the results of the maintenance, energy use and end-of-life stages with a discount rate. W3 has the lowest environmental impact in the first case, mainly because of its greater efficiency in the balance between the environmental impacts of the product and energy use stages. W1 has the lowest environmental impacts when marginal prevention costs from life-cycle stages after stage A are considered at their present value and not discounted (Figure 5). In fact, despite not having the lowest environmental impacts, in either the product or the energy use stages, the lower maintenance and end-of-life costs of the cavity wall solutions (R and W1), when compared with the ETICS ones (W2 to W4), makes the latter less effective in environmental terms if these costs are not discounted. The cost of the end-of-life impacts is actually negative for cavity wall solutions because they do not yield a high quantity of crushed stone from the recycling (crushing operation) and reuse of the mixture of brick and mortars after demolition. Nevertheless, *Eco-costs* for future environmental impacts should be mainly based on NPV, because of its nature.

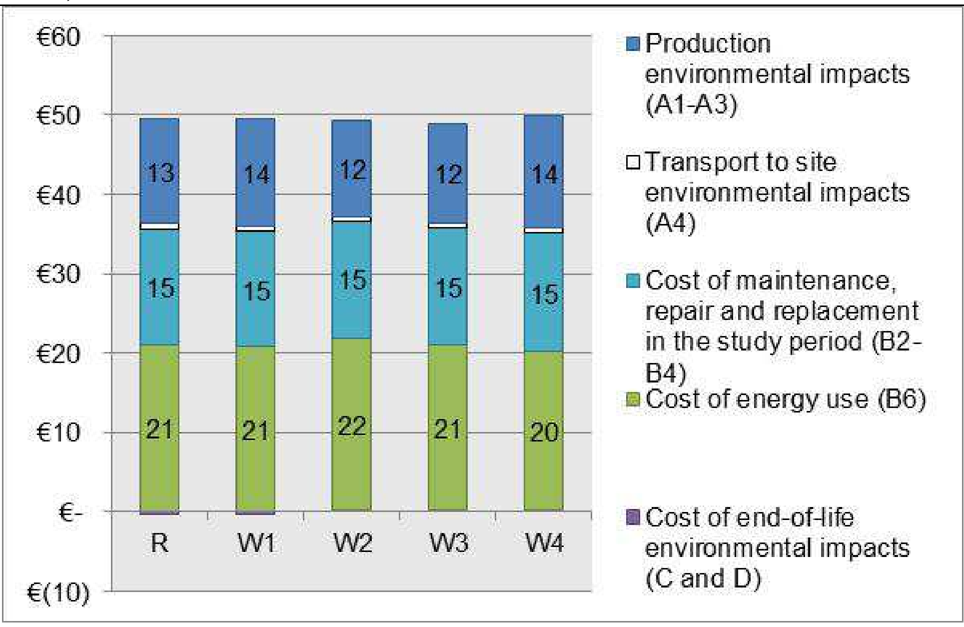

Figure 4 - NPV of the environmental (*Cev*) cost

Once the results of each 3E-C2C module have been analysed separately, the 3E *cost*-C2C approach can be used to compare the 3E performance of the alternatives, using the same economic unit. For each alternative, the cost in year *n* (per square meter of external wall) is the sum of the environmental (*Cev*), economic (*Cec*) and energy (*Ceg*) costs, as described in section 0. The weighted results of the 3E performance based on the *eco-costs* model are presented in Figure 6. The 3E *cost*-C2C results show the importance of economic cost, which accounts for between 59% and 63% of the total cost, for all alternatives. This fact, along with the small difference in the total cost between the alternatives (6% between the most and the least expensive), makes the result of this study highly dependent on the inherent uncertainty of market prices for acquisition and maintenance operations (the first is more important because it occurs in year 0). However, the best performance from a 3E *cost*-C2C point of view is achieved by wall W1.

A change of ±2% in the discount rate used for the calculations does not significantly affect the final result. However, a figure above 5% affects mostly W4, because of its higher acquisition cost.

Discussion

The results presented in section 0 provide an overview of the use of the 3E-C2C assessment method in the individual and combined quantification and comparison of various aspects (e.g. environmental, economic and energy) of the performance of building assemblies in each stage of their life cycle, and also from cradle-to-cradle. But the usefulness of the method proposed in this paper is better highlighted by summarising the design choice, depending on the method used. In particular it shows the benefits of providing the results of the 3E *cost*-C2C performance for the alternatives, using the same economic unit to aid the designer's choice. This summary is presented in Table 8 and it is concluded that alternatives can be compared that are not functionally equivalent and sound choices can be made if, and only if, an approach such as 3E *cost*-C2C is used, for the reasons given below.

- The alternative that uses least material will have the best environmental performance (wall R);

- The solution offering the best thermal performance will be the design choice in terms of energy performance (W4);
- The combined analysis of more than one performance aspect can lead to contradictory conclusions (W1 for economy and energy, or W3 or W1 for environment and energy).

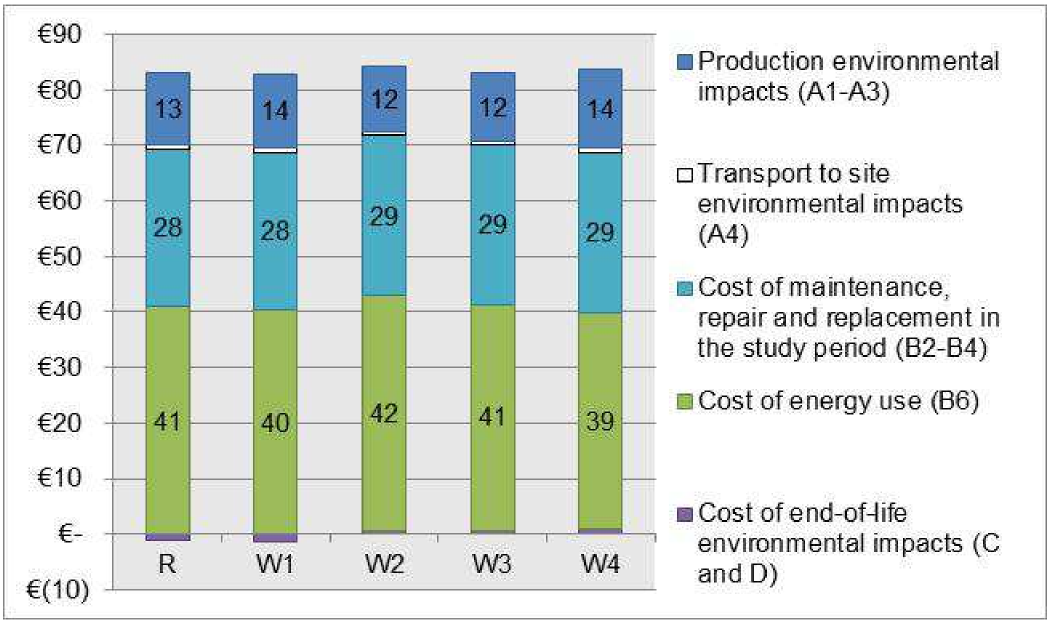

Figure 5 - Environmental (*Cev*) cost without discount rate

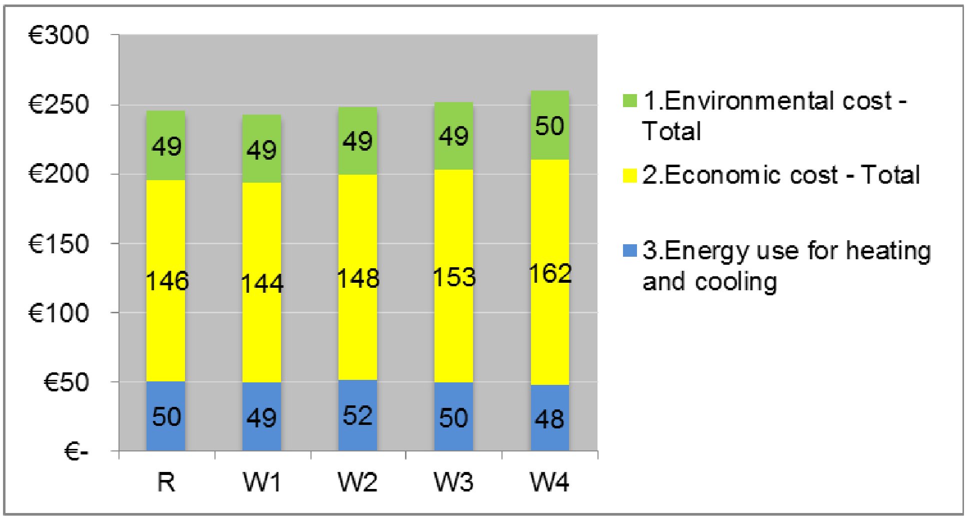

Figure 6 - NPV of the total environmental, economic and energy cost of each alternative

Conclusion

This paper proposes a method for building design that helps with the choice of construction material or assemblies closely related to thermal performance. This method provides the environmental, energy and economic life cycle assessment from cradle-to-cradle (3E-C2C) of these building elements in accordance with the latest European standards related to the environmental and economic assessment of construction works. The description of 3E-C2C provided in this paper, and its application to the process of selecting an external wall solution and the relevant insulation thickness for buildings, proved useful for: comparing alternatives that comply with all the requirements but are not functionally equivalent, without the need of changing their characteristics to make them comparable; quantifying various aspects of the performance of the alternatives in each stage of their life cycle, and also from cradle-to-cradle. There are methods with similar characteristics, but it was concluded that none of them is all-inclusive either in terms of life cycle stages or in the aspects of performance considered.

Table 8 - External wall solution that offers the best performance, depending on the method used

Approach	EIAM	Results	Life cycle stages considered	Performance aspects	Best performance/design choice	Difference to the second alternative (external wall)
LCA	CML 2 baseline method 2000	Table 7	C2C (A1-A4; B2-B4; C2-C4 and D), without energy use for heating and cooling	Environmental	R	[0.4;1.8] % (W1)
LCA		-	Energy use for heating and cooling	Energy	W4	3.7% (W1)
WLC	-	Figure 3	C2C (A1-A5; B2-B4; B6; C and D)	Economic and energy	W1	1.4% (R)
NPV of the environmental cost	*Eco-costs*	Figure 4	C2C (A1-A4; B2-B4; B6; C and D)	Environmental and energy	W3	0.7% (R)
Environmental cost without discount rate	*Eco-costs*	Figure 5	C2C (A1-A4; B2-B4; B6; C and D)	Environmental and energy	W1	0.7% (R)
3E *cost*-C2C	*Eco-costs*	Figure 6	C2C (A1-A4; B2-B4; B6; C and D)	3E	W1	1.1% (R)

The 3E *cost*-C2C approach supplements the 3E-C2C method by establishing weights for each aspect of the assembly performance and for their quantification using the same unit. This allows the simultaneous comparison of the 3E aspects of the performance without subjectivity (even if the alternatives are not functionally equivalent) by considering all the relevant performance indicators in all the important life cycle stages.

The case study presented considers typical solutions for external walls in Portugal and identifies the best alternative in each aspect of performance (using 3E-C2C) and in the overall assessment (using 3E *cost*-C2C). This example allows the discussion of the advantages of using a method that provides the combined assessment of all performance aspects in the same unit, thereby avoiding contradictory conclusions that can arise from the individual analysis of each one.

The applications already undertaken of the method proposed in this paper (i.e. in the choice of an external wall from several alternatives) confirmed that it is suitable, validated it, resulting in the improvement and refinement of each of its modules and steps. However, the 3E-C2C and 3E *cost*-C2C approaches should both be used to choose other construction materials or assemblies that are also closely related to buildings' thermal performance to aid their continuous development.

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Appendix 7.III

Silvestre, J. D.; de Brito, J. & Pinheiro, M. D. (2012). Framework for the environmental assessment of the impacts and benefits of the end-of-life of building materials. ***Journal of Cleaner Production (submitted for publication in 2012)***

Framework for environmental assessment of the impacts and benefits of the end-of-life of building materials

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ABSTRACT

The aim of this paper is to improve the contribution of the Life Cycle Assessment (LCA) methodology to setting up a Cradle to Cradle (C2C) life cycle of building materials. For this, a framework for environmental assessment of the waste flows in their life cycle is described that takes into account the most recent European Standards. The presentation of this framework starts with a summary of the information available in LCA databases related to the end-of-life and related processes and follows with the identification of the waste flows that can be generated or used throughout the life cycle of building materials. Standardized calculation rules for the evaluation of the environmental impacts and benefits of these flows are then described and analysed in detail. Finally, selected case studies are examined to provide an overview of the contribution of LCA methodology to close the loop in the life cycle of building materials.

This paper demonstrates that the application of the framework proposed can be an important source of data for decision-making at the end-of-life of building materials, especially to ascertain whether the minimization of waste flows, the maximization of their reuse or recycling operations, or the increase of the recycled content maximizes their C2C environmental performance.

Keywords: *building materials, cradle to cradle, end-of-life, environmental assessment, European Standards, Life Cycle Assessment*

1. INTRODUCTION

The boundaries of a Life Cycle Assessment (LCA) study of a building material can be defined in the following options (Table 1) (Ferrão, 2009; Ortiz et al., 2009):

- 'Cradle to gate' (including the extraction and processing of raw materials and the production of the good);
- 'Cradle to grave' (including also the transportation, distribution and assembly, the in-service stage, maintenance and final disposal);
- 'Cradle to Cradle' (C2C) (also including the reuse, recovery and/or recycling - 3R - potential).

The application of the C2C perspective in LCA of construction materials is necessary to create a cyclic metabolism (Braungart and McDonough, 2009). In fact, closing material loops can be achieved either by designing buildings for deconstruction or from developing building products that can be dismantled; both options are being increasingly addressed in the context of green buildings (IEA, 2004; Kibert, 2007). The aim of this paper is to improve the contribution of the LCA methodology to setting up a C2C life cycle of building materials, alike it was already proved to be possible for municipal solid waste (Koroneos and Nanaki, 2012). For this, a framework for environmental assessment of the waste flows in their life cycle is described that takes into account the most recent European Standards.

Applying a detailed LCA approach to building materials is a complex task because of the long life cycle of these products and the dynamics that differentiate buildings from other standard industrial products, particularly during the execution, in-service and end-of-life phases (Blok et al., 2007; Chevalier and LeTeno, 1996; Kibert, 2002). End-of-life is probably one of the most complex stages to model due to the high uncertainty of processes that will occur in buildings in the distant future (Peuportier et al., 2011).

Recent European Standards related to the evaluation of the sustainability of construction works developed by Technical Committee (TC) 350 of the European Committee for Standardization (CEN/TC 350) (Ekvall, 2005; Krigsvoll et al., 2007) include the End-of-life (C stage) but define a supplementary LCA information module (D), after the end-of-life of building materials, which is called 'Benefits and loads beyond the system boundary' (Table 1) (CEN, 2011, 2012). The evaluation of this stage should include the net impacts and benefits related to the 3R potential of construction and demolition waste (CDW) and other waste flows. This evaluation, along with the LCA of the end-of-life stage, is essential to promote and allow a C2C approach in the life cycle of the buildings and relevant assemblies. This evaluation also should clarify whether the minimization of the quantity of CDW produced, the maximization of its reuse or recycling operations, or increasing the CDW content in new materials maximizes the C2C environmental performance of building materials. This paper tries to provide a framework for this evaluation by:

1. Summarizing the information available in LCA databases on these life cycle stages;
2. Identifying the CDW (and other waste) that can be generated or used during the life cycle of building materials;
3. Describing and analysing in detail the calculation rules defined by the most recent European Standards (CEN, 2012) for this evaluation;
4. Analysing selected case studies to provide an overview of the contribution of LCA methodology to set up a C2C life cycle of building materials.

2. SCOPE

The research work presented in this paper is part of the Ph.D. thesis of the first author. The thesis focuses on the LCA of a building's external walls from C2C, including the construction materials, insulation products, elements of the wall structure and internal and external wall claddings that can be used in the construction assembly. In fact, the external walls, directly influence the thermal and environmental performance of the building envelope because of their considerable weight in its initial embodied energy, life cycle energy consumption, whole-life cost and user comfort. They can represent up to 15% of the overall environmental impacts of a building over a 60-year life cycle ((Anderson et al., 2002) cited by (Bingel et al., 2006)). A detailed review of the LCA results from more than 10 years of international research studies on the environmental impact of a building's external walls has shown that all the studies include the production of the construction materials but just a third (21 out of 63) include the end-of-life of the building assembly (Silvestre et al., 2010). Therefore, this life cycle stage must be studied in detail, with special reference to its environmental impacts and the 3R potential. Even though one cannot be sure about the impacts avoided at this stage, their quantification enables efforts to be made for 'design for dismantling' to be rewarded (Peuportier et al., 2011). These conclusions motivated the development of an innovative approach to provide the environmental, energy related and economic (3E) life cycle assessment from 'cradle to cradle' (3E-C2C) of building assemblies, exemplifying its application to the selection of the external wall of a building (Silvestre et al., 2011a).

The life cycle stages of construction materials and products are already standardized in Europe (Table 1). An extensive review was conducted to confirm whether the information available on the environmental performance of construction materials used for the external walls of buildings uniformly covers these life cycle stages (Silvestre and Lasvaux, 2012). This review included five basic construction materials, seven insulation materials, five elements of the wall structure and 14 wall coverings. Several European LCA databases were analysed, including generic (e.g. Ecoinvent) databases and those based on national or international environmental product declaration (EPD) programmes (e.g. the French INIES and the German IBU databases). It was concluded that both the generic and EPD databases cover the product stage (cradle to gate: A1-A3 - Table 1), but only the latter includes, almost always, the impacts from the construction process stage (A4-A5) and, rarely, those from the in-service stage (B1-B7). A considerable amount of data is available in both types of database about the end-of-life stage (C1-C4) and, more rarely, from the 'Benefits and loads beyond the system boundary' (D) (see Figure 1 and Figure 2).

3. FRAMEWORK

To improve the contribution of LCA methodology to setting up a C2C life cycle of building materials that takes into account the latest European Standards related to the evaluation of the sustainability of construction works it is important to identify the waste flows that may occur during this life cycle, and describe and analyse in detail the rules for calculating their environmental assessment, included in the relevant standards.

3.1. Construction and demolition waste (CDW) flows

Construction and demolition waste (CDW) flows can be divided into three groups (Table 1 and Figure 3):

- Secondary material input (recycled content) at product stage (A1 and A3), either from the construction industry (PCODW - see next points) or from other industries (industrial symbiosis - IS);
- Production waste (PW), also at the product stage;
- CDW outputs - at the construction stage (CW, corresponding to construction products waste), in service stage (UW, namely due to maintenance operations), and end-of-life stage (DW), which correspond to the A5, B2-B5 and (C1, C3 and C4) sub-stages, respectively.

The evaluation of the environmental impacts of these waste flows, in conjunction with the 'Benefits and loads beyond the system boundary' (module D), can answer the following question: Does the minimization of the quantity of PCODW produced, the maximization of their reuse or recycling operations, or the increase of recycled content in new materials (from IS and PCODW) maximize the C2C environmental performance of building materials?

3.2. LCA of the end-of-life stage (C1-C4)

When a construction product is replaced, dismantled or deconstructed from a building it reaches the end-of-life stage. All outputs of this stage are at first considered to be waste, but they can cease to be waste and attain the status of product (or of a secondary raw material) if they reach the 'end-of-waste state' (CEN, 2012). According to the European Waste Framework Directive (EP, 2008), the latter state is achieved when all the following conditions are met:

- It is commonly used for specific purposes;
- A market or demand exists for such material;
- It fulfils the technical requirements for the specific purposes and meets existing legislation and standards;
- The use of the substance or object will not lead to overall adverse environmental or human health impacts.

To clarify this concept, the European Commission is preparing a set of end-of-waste criteria for priority waste streams, in particular for CDW (EC, 2012; EP, 2008). However, these criteria are only available for certain types of scrap metal (iron, steel and aluminium scrap). This type of waste only reaches the 'end-of-waste state' after a sequence of treatment processes (e.g. cutting or shredding) that prepares it for use as a direct input into the next product system (EU, 2011). Thus, no waste processing after the 'end-of-waste state' is reached has yet been defined for any waste type. As a result, there are no environmental loads to be quantified beyond the system boundary and assigned to module D (and therefore system boundary 2, in the common practice and in the alternative in Figure 4, has to be followed - see Figure 5) (CEN, 2012).

The LCA of the end-of-life stage can include the following optional sub-stages (CEN, 2012):

- C1 - 'deconstruction, including dismantling or demolition, of the product from the building, including initial on-site sorting of the materials';
- C2 - transportation of the discarded product as part of the waste processing (e.g. to a recycling site) and transportation of waste (e.g. to final disposal);
- C3 - waste processing (e.g. collection of waste fractions from the deconstruction and waste processing of material flows intended for reuse, recycling and energy recovery);
- C4 - waste disposal, including physical pre-treatment and management of the disposal site.

3.3. LCA of the benefits and loads beyond the system boundary (module D)

The net impacts and benefits related to the 3R potential of CDW to be considered in module D are particularly important for reusable and recyclable construction materials. These potential benefits and loads derive from net flows leaving the product system that have not been allocated as co-products at the product stage (sub-stages A1-A3, in which avoided impacts from allocated co-products should be included) and that have passed the end-of-waste state (CEN, 2012).

3.4. Stage C and module D - LCA calculation rules

The LCA of the phases after the product stage (A1-A3, the only stage that is mandatory in an EPD - see Table 1) should be supported by realistic and representative scenarios (CEN, 2012). A precautionary approach leads to the consideration of the same waste treatment processes as today (or, at least, the current average technology or practice (CEN, 2012)) and an alternative could be to use a probabilistic range of scenarios (Peuportier et al., 2011). When this information is available in an EPD or in generic LCA databases, especially for stage C and module D, it can be a crucial source of data to enable the decision-maker to compare different alternatives for the end-of-life of construction products.

The C3 sub-stage is usually within the product system under study. Processes (e.g. collection and transport) before the end-of-waste state for materials leaving the system as secondary materials are, as a rule, part of the C3 sub-stage (system boundary 2 in the common practice and in the alternative in Figure 4). Any further processing necessary (e.g. in order to replace primary material input in another product system) after reaching the 'end-of-waste state' is considered to be beyond the system boundary and has to be included in module D (system boundary 1 of the alternative in Figure 4) (CEN, 2012).

It should be noted that waste processing (e.g. collection and transport, but sometimes also recovery or recycling) during any stage of the product system up to the system boundary (i.e. production, construction, use, or end-of-life stages) is included in the relevant stage. Only waste processing after reaching the end-of-waste state (during any stage of the product system, i.e. during A, B or C stages) is part of module D, as in the approach described for the C3 sub-stage and represented in Figure 4 (CEN, 2012). Thus, not all environmental impacts from waste processing operations are included in stage C and module D because they can be accounted for in the remaining life cycle stages when they occur before the ‘end-of-waste state’.

Figure 5 shows the assignment of the environmental impacts and benefits to the end-of-life stage (C) and to module D, taking only system boundary 2 into account. Potential benefits from use in the next product system of energy (i.e. heat and power - I_e in Figure 5) generated at sub-stage C4 (waste disposal) from waste incineration or landfill should be considered in module D, while the loads (e.g. emissions - I_w in Figure 5) from waste disposal in this sub-stage are part of the product system under study, according to the ‘polluter pays’ principle, and should be considered at sub-stage C4 (CEN, 2012).

European Standards define a specific ‘allocation procedure of reuse, recycling and recovery’ - 3R. In fact, LCA information module D can award the ‘design for 3R’ of buildings and building products by considering the potential benefits of avoiding the use of primary materials, and also the loads from the recycling and recovery processes (CEN, 2012). The calculation of the net impacts from this stage includes the following steps (CEN, 2012):

- Calculation of the net output flows of secondary material from the product system: adding all output flows and subtracting all input flows of this type from each sub-stage (e.g. B1-B5, C1-C4, etc.), and then from the stages (e.g. B, C), and finally from the total product system;
- Calculation of the potential impacts and benefits of processing the net output flows calculated in the previous step: adding the impacts from recycling and recovery processes from beyond the system boundary (after the end-of-waste state) up to the point of functional equivalent (‘where the secondary material or energy substitutes primary production’), and subtracting the impacts from ‘the substituted production of the product or substituted generation of energy from primary sources’;
- Application of a justified value-correction factor (to reflect the difference in functional equivalence when the output flow ‘does not reach the functional equivalence of the substituting process’).

With respect to these calculation rules, it is important to highlight that the substitution effects are calculated only in module D for the net output flows, while the amount of secondary material output ‘that is able to replace one to one the input of secondary material as closed loop’ is allocated to the product system under study (sub-stage A1 - see Table 1) (CEN, 2012).

The environmental impact from waste recycling (and from the eventual transport) can be represented as: I_r+I_t (and assigned to the C2 and C3 sub-stages, respectively - see Figure 5). This operation avoids the impacts from the production of a similar new product (potential benefit of I_n in module D, see alternative in Figure 5) and the impacts from waste treatment (I_w - common practice in Figure 5). Therefore, recycling should be promoted only if $(I_r+I_t) < (I_n+I_w)$, because it will avoid an impact that corresponds to: $(I_n+I_w–I_r–I_t)$ (Peuportier et al., 2011). The environmental impacts represented by I_r and I_t should be included in module D only if they occur after the ‘end-of-waste state’ (system boundary 1 of the alternative in Figure 4); otherwise they should be considered in the stage of the product system where the flow occurs - see alternative in Figure 5. If the option is not to recycle, I_w should be included in sub-stage C4 (common practice in Figure 5). The methodology used for this calculation should avoid double counting of the benefit of recycling (Peuportier et al., 2011).

If recycling rates are defined as r_p and r_e, respectively at production and end-of-life stages, and net output flows are represented by N_f, the ‘allocation procedure of 3R’ defined in the European Standard (CEN, 2012) can amount to an environmental impact reduction. This reduction can be represented by three individual amounts (this is an approach similar to the stock flow method, for the first amount, and to the one proposed by the steel industry for all amounts (adapted from (Peuportier et al., 2011)):

- $[r_p.(I_n–I_r)]$ at sub-stage A1 (that includes processing of secondary material input, such as recycling processes - see Table 1 and common practice in Figure 6), where only the impact from I_r is considered for the amount of secondary material used;
- $[r_e.(I_w-I_t)]$ expressed by a reduced environmental impact ($r_e.I_t$ instead of $r_e.I_w$) at the stage of the product system where the waste flow occurs;
- $[(I_n-I_r)$ for $N_f]$, this impact reduction being entirely considered as impacts and benefits in module D when recycling occurs after the ‘end-of-waste’ state; when recycling occurs before the ‘end-of-waste state’, the benefit is considered in module D (I_n for N_f) and the impact from I_r is considered at the stage of the product system where recycling occurs, but for the entire end-of-life flow (r_e), not only for net output flows (N_f); this results in double counting of the impacts of the recycling process for the output flows that are used as input of secondary material in the same system process (sub-stage A1) as closed loop (as represented in the alternative in Figure 6).

In conclusion, it was found that three important criteria defined in the literature (Peuportier, Herfray et al. 2011) were considered in the LCA calculation rules described:

- Reward of the use of recycled products at the construction phase (by considering only the recycling process, instead of the production of a new product, at stage A1; this can benefit e.g. the use of recycled aggregates instead of natural ones (Blengini et al., 2012));
- Reward of the sorting of waste and recycling at the end-of-life (by considering: disposal scenarios with fewer impacts or higher benefits from sorted CDW; the potential benefits of avoiding the use of primary materials; the loads from the recycling and recovery processes);
- Avoid double counting of the benefit of recycling (by calculating substitution effects in module D only for the net output flows).

However, it was also found that standardised LCA calculation rules (CEN, 2012) result in double counting of the impacts of the recycling process for the output flows that are used as input of secondary material in the same system process as closed loop, but only when recycling occurs before the 'end-of-waste state' (as represented in the alternative in Figure 6).

4. RESULTS

The extensive review of the information available on the environmental performance of construction materials for external walls of buildings already described (Silvestre and Lasvaux, 2012) led to some results being collected on the contribution of LCA methodology to setting up a C2C life cycle of building materials. In the first place, it is important to say that no generic LCA database calculated in accordance with the most recent European Standards is available yet, and only two European EPD programmes exclusively devoted to materials and products for the construction industry (the Spanish and the German ones) have followed these standards, but only for a limited number of documents (Silvestre and Lasvaux, 2012):

- The 'Declaración Ambiental de Producto' (DAPc or EPD), is managed in Spain by the Collegi d´Aparelladors, Arquitectes Tècnics i Enginyers d'Edificació of Barcelona and by the 'Generalitat de Catalunya', (DAPc, 2010);
- The 'Umwelt-Deklarationen' (EPD), developed by the Institute of Construction and Environment (Institut Bauen und Umwelt - IBU) in Germany whose EPDs are based on several PCRs and are available on the IBU website (IBU, 2010; UNEP, 2008).

Therefore, the results analysed in this paper were selected from the EPDs of these two European programmes and relate only to insulation and wall cladding materials due to paper length restrictions.

4.1. Insulation materials

The analysis starts with three oil-derived insulation boards: extruded polystyrene (XPS), expanded polystyrene (EPS) and polyurethane/polyisocyanurate (PUR/PIR). These EPDs are available from the German EPD programme.

The EPS declaration (for white boards with a density of 25 kg/m^3) shows that:

- Two end-of-life scenarios were considered: 100% incineration, with the impacts of this process included in sub-stage C3 and the resulting energy in module D (scenario A); 100% to landfill, with the corresponding impacts declared at C4 sub-stage (scenario B);
- Disposal of packaging was considered at sub-stage A5, including the impacts resulting from incineration, but the energy gains in this process are declared in module D and are the only impact at this stage in the second scenario.

Considering two of the most important environmental indicators, non-renewable primary energy consumption (PE non-renewable - NRe) and global warming potential (GWP), Table 2 summarizes the results for 1 m^3 of EPS for product stage and also for end-of-life and module D, for both scenarios. From this table it is possible to conclude that:

- The incineration process can be very rewarding from an energy recovery perspective, particularly if it is equally economically worthwhile; however, the economic factor can be decisive if there is an environmental tax for the high level of CO_2 emissions (which are 8% higher than the ones from the production process);
- Landfilling seems to be a better option when the impacts from this process are compared with the ones from the product stage.

It would be interesting to have a third scenario for recycling of the boards. However, the EPD did not contemplate this, despite the assumption that this operation is 'technically and economically feasible'.

The XPS declaration (for boards with an average density of 34.5 kg/m^3) shows that only one end-of-life scenario was considered. This scenario amounts to 50% of waste used for thermal recovery via incineration and 50% sent to landfill, with the impacts of these processes included in sub-stage C4 and the benefits in module D.

Again considering only the results of PE-NRe and GWP (Table 3), it is concluded that these figures can be associated with a weighted scenario between the two considered for EPS. Therefore, despite being informative in terms of the environmental performance of this construction product, the presentation of joint results for two end-of-life scenarios does not provide enough information to the person who has to choose the best destination for CDW.

The PUR declaration (for boards without facings with an average density of 30 kg/m^3) again shows that only one end-of-life scenario was considered. This scenario involves the thermal treatment (incineration) of the product with energy recovery, with the impacts and benefits of this process included in an LCA information module that encompasses both stage C and module D.

The results of PE-NRe and GWP (Table 3) are similar to scenario A for EPS (Table 2). Again, it would be more informative to have another end-of-life scenario, namely board recycling.

This analysis now looks at a mineral 'inorganic' insulation board made of stone wool (SW), using an EPD from the Spanish EPD programme. In this declaration (for boards without facings with a density of 30 kg/m^3), once again only one end-of-life scenario was considered. This scenario covers the disposal of the product in an inert material landfill, with the relevant impacts included in sub-stage C4. This is the only scenario considered even though this declaration states that this product is recyclable. This last scenario was not chosen because it is not yet a common practice to recycle this type of product in Spain.

The results of PE-NRe and GWP (Table 3) are similar to those of scenario B for EPS (Table 2). Even though the relationship between the impacts of the product stage and the end-of-life is similar for both products for PE-NRe (close to 80 times higher), it is different for GWP (44 for EPS and 88 times higher for SW). The latter difference may be due to the higher level of CO_2 emissions in SW production and the higher impact of EPS landfill.

4.2. Ceramic tiles

The German EPD programme has only one solution with ceramic tiles, but within a ventilated rain screen façade system. This document is not analysed in detail in this paper because the end-of-life impacts and benefits are jointly presented for tiles and aluminium profiles for some environmental categories.

Two different producers have developed EPDs for ceramic tiles under the Spanish EPD programme. These declarations (one for products - EPD1 - with an average density of 24 kg/m^2, and the other one whose average density is not declared) contain similar end-of-life scenarios:

- 17% of the product is considered to be recycled (the benefits and burdens are considered in module D), while the rest is sent to landfill (with the impacts considered in the C4 sub-stage);
- Module D also includes the benefits and impacts from recycling all types of packaging in the preceding stages of the life cycle of ceramic tiles.

Again considering only the results of PE-NRe and GWP (Table 4), it is concluded that the scenario considered can be informative in terms of the environmental performance of this construction product. However, the presentation of joint results for two end-of-life scenarios does not help the decision-maker to choose an option unless additional calculations are performed to convert the two options (recycling and landfill) into an equivalent unit. Moreover, from an environmental and economic point of view, a detailed study of the influence of the recycling rate of the tiles and waste packaging on the environmental performance of this product can lead to interesting results. In fact, selective demolition (or deconstruction) should be increasingly considered when estimating the environmental and economic impacts of transporting and disposing of CDW in appropriate plants because this technique is being used more and more in Portugal for environmental (allowing the maximization of CDW reuse/recycling potential) and economic reasons (Coelho and de Brito, 2013a, b).

5. CONCLUSION

The environmental impacts of the end-of-life of building materials have to be studied in detail, including the reuse, recovery and/or recycling potential, in order to set up a 'cradle to cradle' life cycle of these products. The assessment of the net impacts and benefits related to that potential is particularly important when these products are reusable and recyclable. Therefore, this paper proposes a framework for such assessment, having concluded that the information available in the literature, LCA databases and EPD programmes is limited in terms of this life cycle stage, with particular reference to the materials used in the external walls of buildings.

This framework is based on the identification of waste flows that may be generated during the life cycle of building materials and on the rules for calculating their environmental assessment contained in the most recent European Standards concerned with assessing the sustainability of construction works, along with the analysis and visual presentation and interpretation of these waste flows. Input, but more especially output, of waste can occur in the production, construction, use, and end-of-life stages, and it is important to understand the influence of their variation on the maximization of the C2C environmental performance of building materials. The description and analysis of the calculation rules and their correlation with the European Waste Framework Directive are important to encouraging the dissemination and facilitation of their use by LCA practitioners, and to enabling decision-makers to interpret any available results (in particular in EPD or generic LCA databases developed using these methods) and compare them with real data.

This analysis included a simplified comparison with other allocation procedures of reuse, recycling and recovery. This comparison led to the conclusion that these calculation rules result in double counting of the impacts of the recycling process for the output flows that are used as input of secondary material in the same system process as closed loop, but only when recycling occurs before the 'end-of-waste state'. It was also found that three important criteria are followed by these LCA calculation rules: rewarding the use of recycled products at the construction phase and the sorting of waste and recycling at the end-of-life, and the prevention of double counting of the benefit of recycling.

It was considered important not only to provide a framework but also to analyse selected case studies that can give a clearer overview of the contribution of LCA methodology to setting up a C2C life cycle of building materials. Therefore, the EPD documents (whose LCA studies follow the latest European Standards) of five construction materials from two European programmes were chosen and their results partially analysed. Despite the lack of adequate results (achieved following the most recent European Standards) to arrive at meaningful conclusions, some individual conclusions could be drawn. First, the majority of EPDs analysed only provide one end-of-life scenario that, despite being informative, should be complemented by at least one more scenario, preferably concerned with recycling. One EPD from the Spanish programme (for stone wool) even states that the product is recyclable, but the only scenario presented involves the disposal of the product in an inert material landfill because it was considered that recycling this type of product is not yet common practice in Spain. Some EPDs provide joint results for two end-of-life scenarios, which, despite being realistic, either do not provide the people responsible for choosing the best destination for CDW with enough information, or else they require additional calculations to convert two options (e.g. recycling and landfill) into an equivalent unit if scenarios are to be tested with a sensitivity analysis (Nebel, 2006).

This paper demonstrates that the application of the framework proposed can be an important source of data for decision-making based on choosing between alternatives to 'close the loop' in the life cycle of building materials by identifying the ones that help to improve the environmental performance of these products from a C2C perspective. Nevertheless, more studies are necessary to explore the obstacles (especially in terms of laws, cost and scale) that hinder the choice of the best end-of-life options in environmental terms. More research is also essential to evaluate the potential for improving the recycling and reuse of CDW, particularly through industrial symbiosis, because the end-of-life phase can make a positive contribution to the environmental performance of construction materials (Silvestre et al., 2011b).

6. ACKNOWLEDGEMENTS

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TABLE CAPTIONS

Table 1 - Detailed life cycle stages of building materials classification based on European Standards (adapted from (CEN, 2012; Silvestre and Lasvaux, 2012))

Table 2 - Summary of the environmental impacts of 1 m^3 of EPS from an EPD in the German programme (IBU, 2010)

Table 3 - Summary of the environmental impacts of 1 m^3 of XPS (adapted from an EPD in the German programme), 1 m^3 of PUR (from an EPD in the German programme) and 1 m^3 of SW (adapted from an EPD in the Spanish programme) (DAPc, 2010; IBU, 2010)

Table 4 - Summary of the environmental impacts of 1 m^2 of ceramic tiles from EPDs in the Spanish programme (DAPc, 2010)

Table 1 - Detailed life cycle stages of building materials classification based on European Standards (adapted from (CEN, 2012; Silvestre and Lasvaux, 2012))

LCA boundaries	Life cycle stages / LCA information modules	Life cycle stage designation and description	
Cradle to cradle / Cradle to grave / Cradle to gate	Product stage (A1-A3)	A1	raw material extraction and processing, processing of secondary material input
		A2	transport to the manufacturer
		A3	manufacturing
Cradle to cradle / Cradle to grave / Gate to grave	Construction process stage (A4-A5)	A4	transport to the building site
		A5	installation into the building
	Use stage - information modules related to the building fabric (B1-B5)	B1	use or application of the installed product
		B2	maintenance
		B3	repair
		B4	replacement
		B5	refurbishment
	Use stage - information modules related to the operation of the building (B6-B7)	B6	operational energy use
		B7	operational water use
	End-of-life stage (C1-C4)	C1	de-construction, demolition
		C2	transport to waste processing
		C3	waste processing for reuse, recovery and/or recycling (3R)
		C4	disposal
	Benefits and loads beyond the system boundary (D)	D	reuse, recovery and/or recycling (3R) potentials

Table 2 - Summary of the environmental impacts of 1 m^3 of EPS from an EPD in the German programme (IBU, 2010)

Environmental category	Unit	Life cycle stages/ LCA information modules						
		A1-A3	Scenario A - Incineration			Scenario B -Landfill		
			C2-C4	*D*	*C2-C4 plus D*	*C2-C4*	*D*	*C2-C4 plus D*
PE-NRe	MJ	2378.7	27.7	-832.3	-804.6	29.7	-6.5	23.2
GWP	kg CO_2 eq.	78.7	85.1	-48.1	37	1.8	-0.4	1.4

Table 3 - Summary of the environmental impacts of 1 m^3 of XPS (adapted from an EPD in the German programme), 1 m^3 of PUR (from an EPD in the German programme) and 1 m^3 of SW (adapted from an EPD in the Spanish programme) (DAPc, 2010; IBU, 2010)

Insulation material	Environmental category	Unit	Life cycle stages/ LCA information modules				
			A1-A3	*C4*	*D*	*C4 plus D*	*C plus D*
XPS	PE-NRe	MJ	3205	20	-619	-599	
	GWP	kg CO_2 eq.	142	60	-36	24	
PUR	PE-NRe	MJ	2768				-499
	GWP	kg CO_2 eq.	134				57.5
SW	PE-NRe	MJ	376	4.8			
	GWP	kg CO_2 eq.	53.4	0.6			

Table 4 - Summary of the environmental impacts of 1 m^2 of ceramic tiles from EPDs in the Spanish programme (DAPc, 2010)

Environmental category	Unit	Life cycle stages/ LCA information modules							
		Ceramic tiles - EPD1				Ceramic tiles - EPD2			
		A1-A3	*C4*	*D*	*C4 plus D*	*A1-A3*	*C4*	*D*	*C4 plus D*
PE-NRe	MJ	251	3.8	-17.7	-13.9	204	3.3	-9.49	-6.19
GWP	kg CO_2 eq.	16.2	0.5	-0.9	-0.4	13.3	0.4	-0.7	-0.3

FIGURE CAPTIONS

Figure 1 - Percentage of products for which data is available in generic LCA databases and EPD programmes concerning the end-of-life stage (C1-C4) (Silvestre et al., 2012)

Figure 2 - Percentage of products for which data is available in generic LCA databases and EPD programmes concerning module D (Benefits and loads beyond the system boundary) (Silvestre et al., 2012)

Figure 3 - Construction and demolition waste input and output flows (Silvestre et al., 2012)

Figure 4 - Comparison between common practice in construction materials production (use of primary raw materials), with its alternative (use of recycled materials), including the two possible ways to define the LCA system boundary in accordance with European Standards (CEN, 2012)

Figure 5 - Assignment of the environmental impacts and benefits to end-of-life stage (C) and to module D, taking only system boundary 2 into account (based on (CEN, 2012))

Figure 6 - Assignment of the environmental impacts from recycling operations before the 'end-of-waste' state: secondary material input from other system processes (common practice) and output flows that are used as input of secondary material in the same system process as closed loop (alternative) (based on (CEN, 2012))

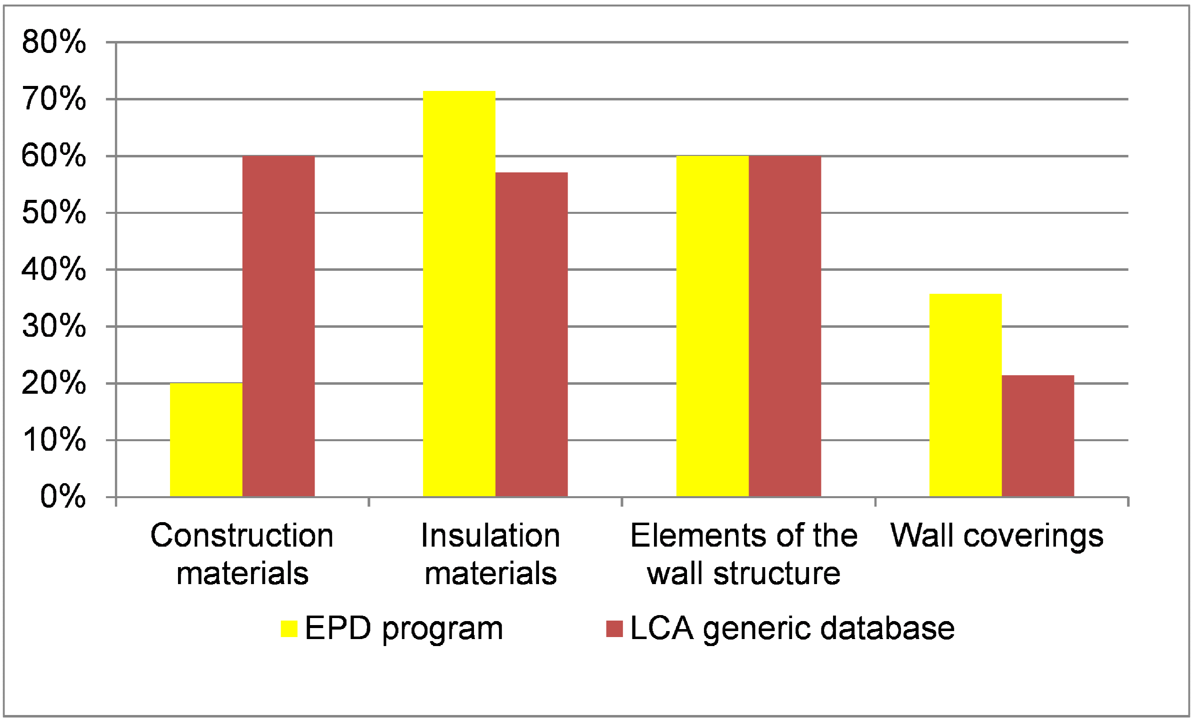

Figure 1

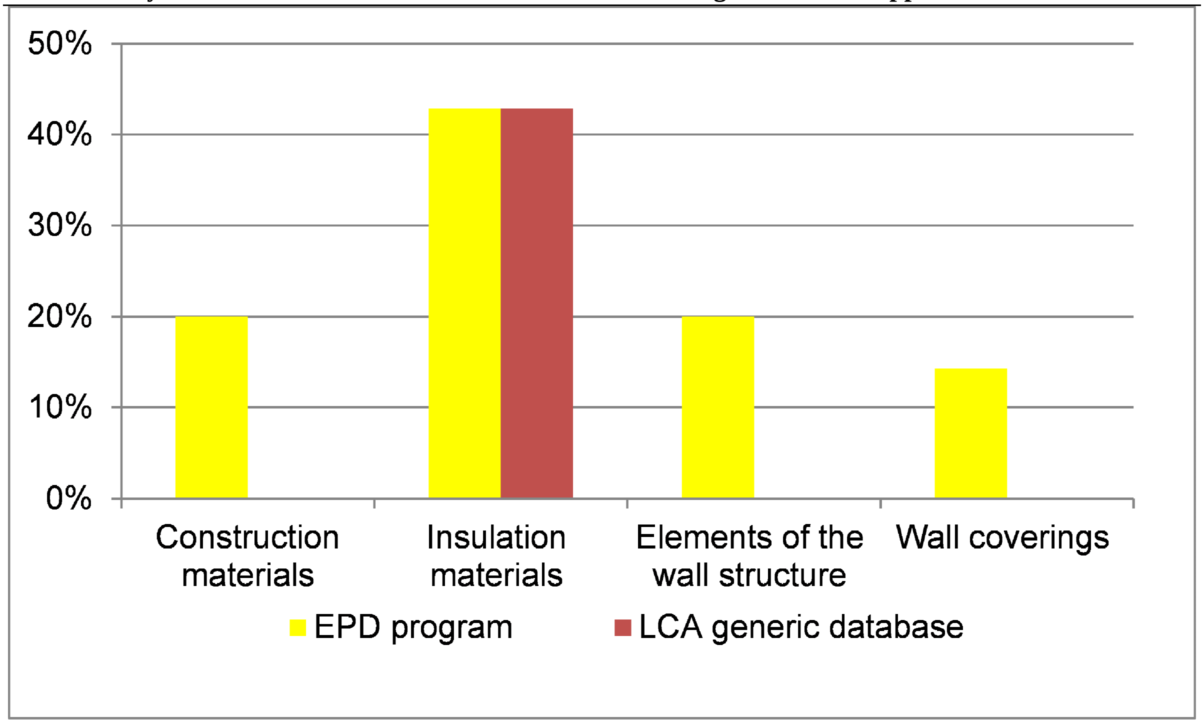

Figure 2

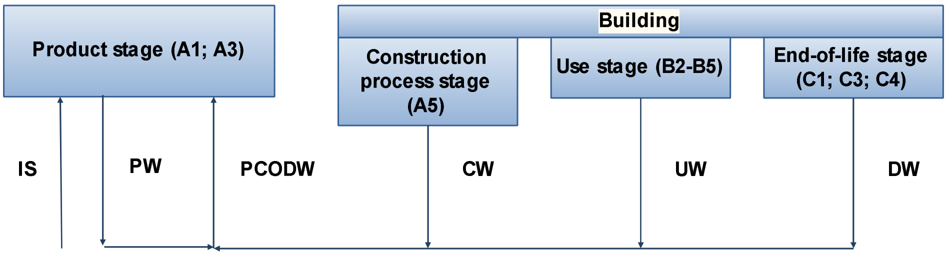

Figure 3

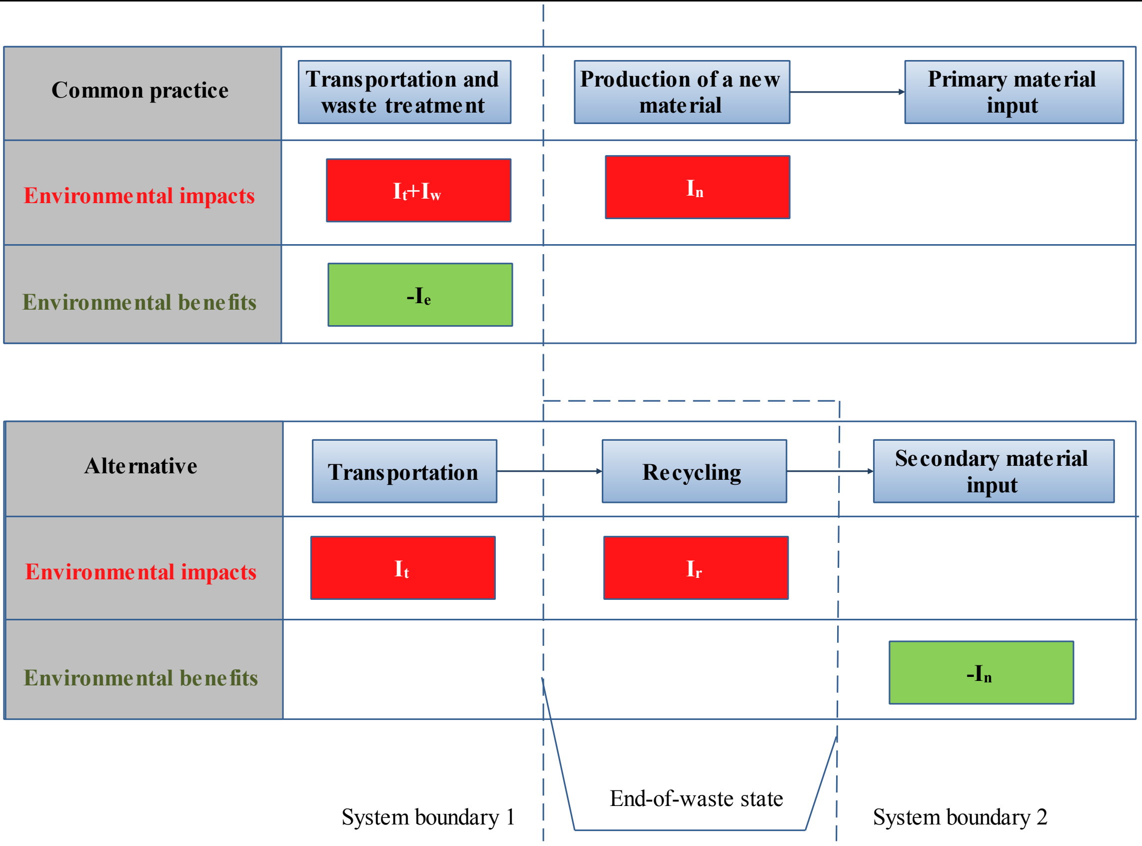

Figure 4

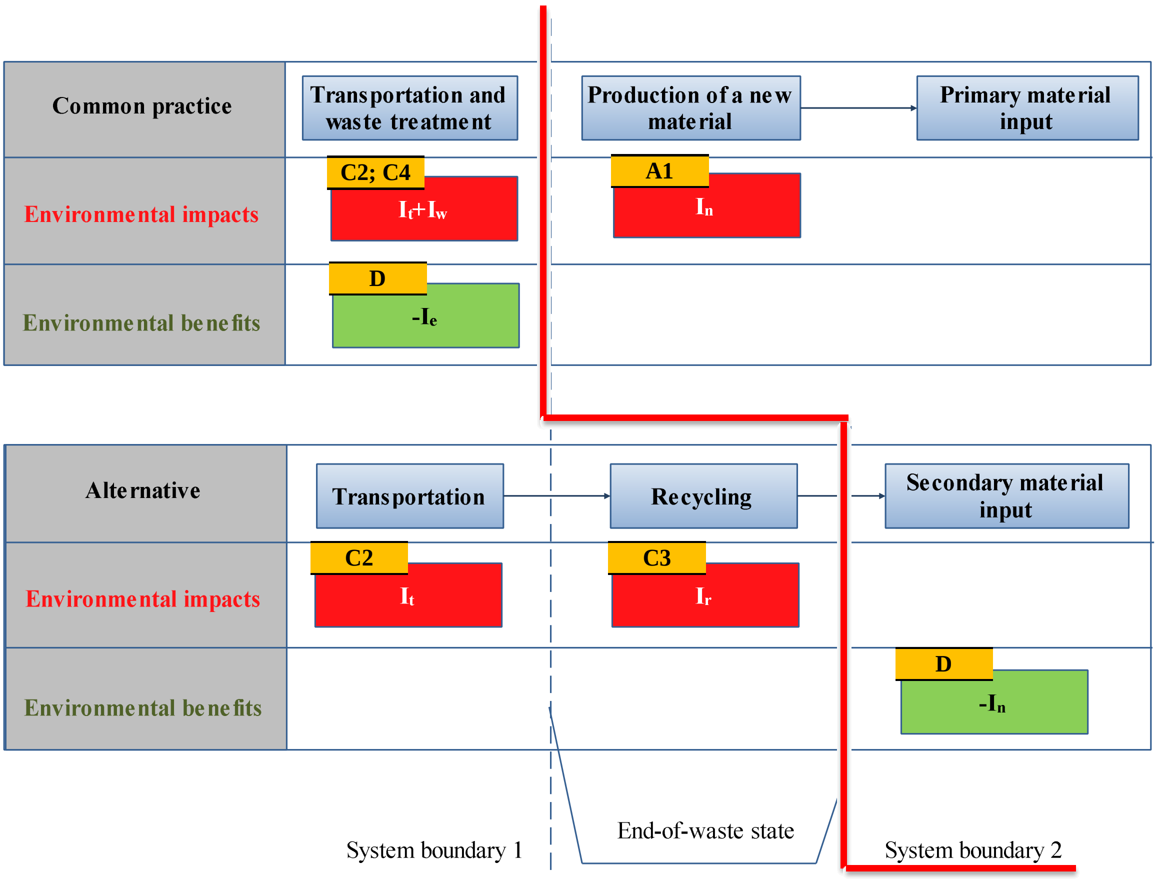

Figure 5

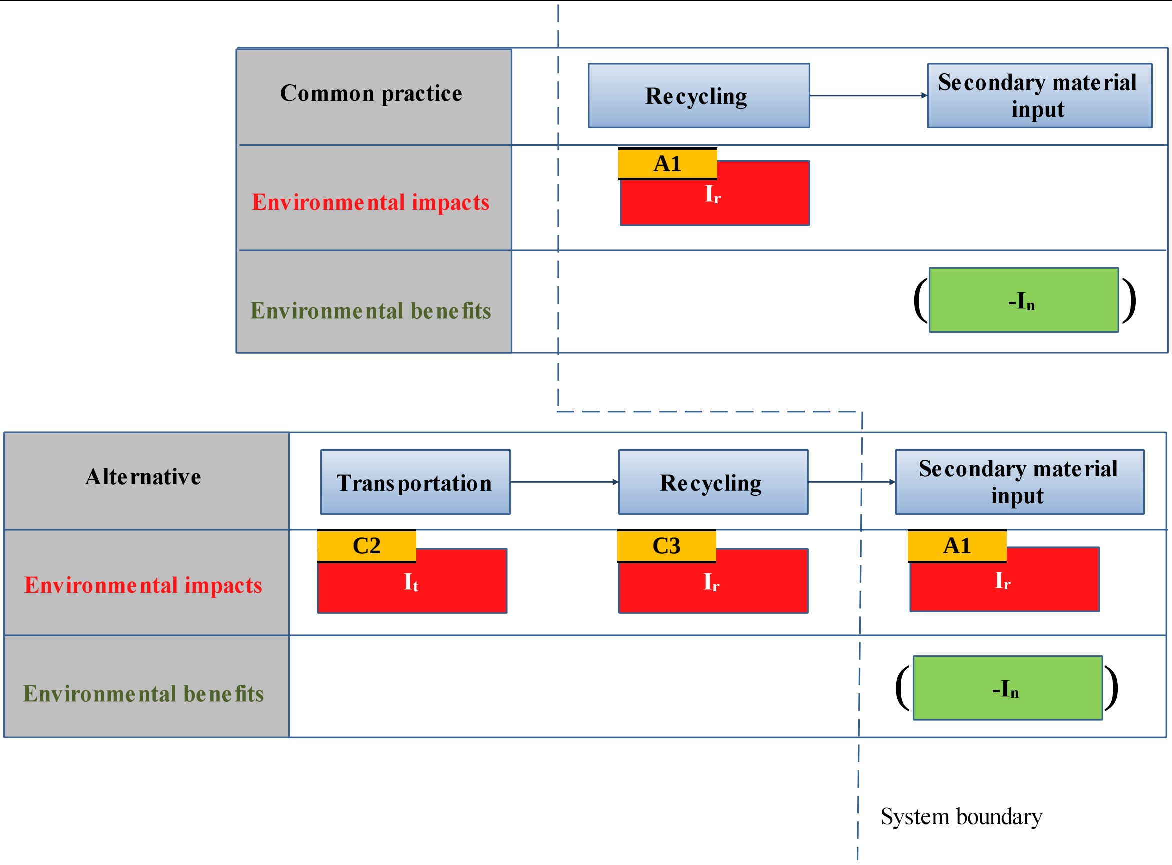
Common practice
Recycling
Secondary material input
Environmental impacts
A1
I_r
Environmental benefits
($-I_n$)
Alternative
Transportation
Recycling
Secondary material input
Environmental impacts
C2
I_t
C3
I_r
A1
I_r
Environmental benefits
($-I_n$)
System boundary

Figure 6

Appendix 7.IV

Composition, dimensions, thermal performance and maintenance, repair and replacement operations of the external wall solutions evaluated in Chapter 7

Table 7.IV.1 - Single-leaf walls - External insulation

External wall	External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]	Thickness (m)
			Material [Density (kg/m^3)]	λ [W/(m.ºC)]	Thickness (mm)			
W1	ECS3 - Adherent [0.02 m render, adhesive, (insulation), glass fiber mesh, 0.01 m render and water-based paint] within an ETICS	ICS1 - Adherent (0.02 m render and water-based paint)	SW (89.64)	0.04	80	CHB (0.22, plus stabilised masonry mortar)	0.36	0.35
W2			EPS (15)	0.0396			0.36	0.35
W3			ICB (110)	0.04			0.36	0.35
W4			PUR (35)	0.023	60		0.30	0.33
W5			XPS (30)	0.036	80		0.33	0.35
W6		ICS2 - Adherent to the wall structure (adhesive, gypsum plasterboards and water-based paint)	SW	0.04			0.35	0.35
W7			EPS	0.0396			0.35	0.35
W8			ICB	0.04			0.35	0.35
W9			PUR	0.023	60		0.29	0.33
W10			XPS	0.036	80		0.33	0.35
W11	ECS4 - Fastened to a supporting structure - VRF (0.02 m render in the outer surface of the CHB, and WPC structure and boards creating a ventilated cavity)	ICS1	SW	0.04			0.37	0.39
W12			EPS	0.0396			0.36	0.39
W13			ICB	0.04			0.37	0.39
W14			PUR	0.023	60		0.30	0.37
W15			XPS	0.036	80		0.34	0.39
W16		ICS2	SW	0.04			0.36	0.39
W17			EPS	0.0396			0.35	0.39
W18			ICB	0.04			0.36	0.39
W19			PUR	0.023	60		0.29	0.37
W20			XPS	0.036	80		0.33	0.39
W21	ECS5 - GFRC precast panels with 12 cm EPS boards as void formers (can also be considered an element of the wall structure)	ICS1	-			CHB (0.15, plus stabilised masonry mortar)	0.26	0.37
W22		ICS2					0.26	0.37

Table 7.IV.2 - Single-leaf walls - No insulation

External wall	External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]	Thickness (m)
			Material	λ [W/(m.ºC)]	Thickness (mm)			
W23	ECS1 - Adherent (0.02 m render and water-based paint)	ICS1	-			LCB (0.38, plus stabilised masonry mortar)	0.38	0.42
W24		ICS2					0.38	0.42
W25	ECS2 - One-coat mortar	ICS1					0.38	0.42
W26		ICS2					0.37	0.42

Table 7.IV.3 - Single-leaf walls - Internal insulation

External wall	External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]	Thickness (m)
			Material	λ [W/(m.ºC)]	Thickness (mm)			
W27	ECS1	ICS3 - Adherent to the insulation material [adhesive, (insulation), gypsum plasterboards and water-based paint]	SW	0.04	80	CHB (0.22, plus stabilised masonry mortar)	0.36	0.34
W28			EPS	0.0396			0.35	0.34
W29			ICB	0.04			0.36	0.34
W30			PUR	0.023	60		0.29	0.32
W31			XPS	0.036	80		0.33	0.34
W32	ECS2		SW	0.04			0.35	0.34
W33			EPS	0.0396			0.35	0.34
W34			ICB	0.04			0.35	0.34
W35			PUR	0.023	60		0.29	0.32
W36			XPS	0.036	80		0.33	0.34

Table 7.IV.4 - Cavity walls - Thermal insulation completely filling the cavity

External wall	External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m².ºC)]	Thickness (m)
			Material [Density (kg/m³)]	λ [W/(m.ºC)]	Thickness (mm)			
W37	ECS1	ICS1	LECA (297)	0.1	80	CHB (cavity wall - 0.15+0.11, plus stabilised masonry mortar and internal 0.02 m render)	0.54	0.38
W38		ICS2					0.52	0.38
W39	ECS2	ICS1					0.53	0.38
W40		ICS2					0.51	0.38

Table 7.IV.5 - Cavity walls - Thermal insulation partially filling the cavity

External wall	External cladding	Internal coating	Insulation			Elements of the wall structure [Thickness (m)]	Heat transfer coefficient (U-value) [W/(m^2.ºC)]	Thickness (m)
			Material	λ [W/(m.ºC)]	Thickness (mm)			
W41	ECS1	ICS1	SW	0.04	60	CHB (cavity wall - 0.15+0.11, plus stabilised masonry mortar and internal 0.02 m render)	0.37	0.38
W42			EPS	0.0396			0.36	0.38
W43			ICB	0.04			0.37	0.38
W44			PUR	0.023			0.26	0.38
W45			XPS	0.035			0.34	0.38
W46		ICS2	SW	0.04			0.36	0.38
W47			EPS	0.0396			0.36	0.38
W48			ICB	0.04			0.36	0.38
W49			PUR	0.023			0.26	0.38
W50			XPS	0.03			0.33	0.38
W51	ECS2	ICS1	SW	0.04			0.36	0.38
W52			EPS	0.0396			0.36	0.38
W53			ICB	0.04			0.36	0.38
W54			PUR	0.023			0.26	0.38
W55			XPS	0.035			0.34	0.38
W56		ICS2	SW	0.04			0.36	0.38
W57			EPS	0.0396			0.35	0.38
W58			ICB	0.04			0.36	0.38
W59			PUR	0.023			0.26	0.38
W60			XPS	0.035			0.33	0.38

Table 7.IV.6 - Maintenance, repair and replacement operations of the external cladding and internal coatings

Cladding or coating solution	Maintenance, repair and replacement operations
ECS1 - Adherent (0.02 m render and water-based paint)	Total cleaning and repainting every 5 years and repair of 35% of the area at 25 years
ECS2 - One-coat mortar	
ECS3 - Adherent [0.02 m render, adhesive, (insulation), glass fiber mesh, 0.01 m render and water-based paint] within an ETICS	
ECS4 - Fastened to a supporting structure - VRF (0.02 m render in the outer surface of the CHB, and WPC structure and boards creating a ventilated cavity)	Total cleaning of WPC boards every 5 years, and their replacement every 15 years
ECS5 - GFRC precast panels with 12 cm EPS boards as void formers	Total cleaning every 5 years
ICS1 - Adherent (0.02 m render and water-based paint)	Total cleaning and repainting every 5 years; repair of 5% of the area each 10 years
ICS2 - Adherent to the wall structure (adhesive, gypsum plasterboards and water-based paint)	
ICS3 - Adherent to the insulation material [adhesive, (insulation), gypsum plasterboards and water-based paint]	

Notes to Appendix 7.IV:

- External cladding systems (ECS) - ETICS (External Thermal Insulation Composite System), GFRC (Glass Fibre Reinforced Concrete), VRF (Ventilated Rainscreen Façades) and WPC (Wood-plastic composite);
- Internal cladding systems (ICS);
- Insulation materials - EPS (Expanded Polystyrene), ICB (Insulation Cork Board), LECA (Light Expanded Clay Aggregate), PUR (Polyurethane), SW (Stone wool) and XPS (Extruded Polystyrene);
- Elements of the wall structure - CHB (Hollow fired-clay bricks, horizontally perforated) and LCB (Lightweight - with LECA - concrete blocks, vertically perforated).

Appendix 7.V

Silvestre, J. D.; Silva, A. & de Brito, J. (2012). Uncertainty modelling of service life and environmental performance to reduce risk in buildings design decisions. *Journal of Civil Engineering and Management, accepted for publication, December*

Uncertainty modelling of service life and environmental performance to reduce risk in buildings design decisions

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Abstract:

Life-cycle assessment (LCA) is increasingly used to quantify the environmental impacts of construction materials. However, the relationship between the durability and LCA of these complex products with long life-cycles must be analysed in detail, namely using stochastic data from service life prediction (SLP) studies. However, SLP uncertainty is not yet considered in LCA, thus resulting in insufficiently sound decisions at the design stage.

This paper presents the modelling of the uncertainty of SLP using advanced statistical methods and its application in the estimation of SL and corresponding number of replacements of claddings (renderings and stone claddings). These results are used in an interdisciplinary study of SLP and LCA to apply in the stochastic comparison of the LCA of claddings. This methodology aids in the choice of the option with better environmental performance right at the design stage, via the comparison of their standard, deterministic and stochastic LCA results.

Keywords: building design, claddings, decision-making, life cycle assessment, service life prediction

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1. Introduction

Concern with the economic and environmental sustainability of the construction sector has been growing over the past 20 years, since it is responsible for using a significant part of the material, energy and electricity resources of Europe (Balaras et al. 2005). The construction industry consumes a large quantity of environmental resources and is also one of the largest polluters (Shen et al. 2005). Pearce (2003) says that the concept of sustainable development is leading to a fundamental re-evaluation of the contribution the construction industry makes to the quality of life. Life-cycle assessment (LCA) considers the environmental impact over the lifetime of a product by identifying and quantifying the environmental emissions and consumption of energy and materials. Building materials and assemblies are complex products with long life-cycles, and defining a functional unit and the boundary of the assessment for an LCA study is both complex and constraining. This is even more important when the relationship between the durability and LCA of building materials and components is analysed because service life prediction (SLP) is central to achieving a sustainable built environment (Abbott et al. 2007). However, SPL is not yet included in LCA studies and a deterministic analysis of the life cycle of building components is normally performed.

ISO 15686-6 (ISO 2004) and FprEN 15804:2011 (CEN 2011) already establish the interface between LCA and service life planning and describe how to consider the service life of construction materials and buildings in LCA studies. They particularly stress that the use phase should be included and that LCA results will be significantly dependent on scenarios and assumptions about the duration and the processes involved in the use phase (CEN 2011). Realistic scenarios require the incorporation of information obtained from the SLP studies. The reference service life of a product can be based on empirical, probabilistic, statistical, deemed to satisfy or research (scientific) data and must always take into account the intended use (description of use) (CEN 2011).

There is already a common understanding that LCA results are uncertain and that several factors contribute to this uncertainty (e.g. parameters of the LCA model or uncertainty in model structure). Despite that, most LCA results present deterministic figures even though this is not the best option when the final aim is to use LCA as a decision-support tool. Providing the results together with uncertainty information permits the assessment of their stability and can sometimes lead to changes in the ranking order of the different solutions being evaluated. Therefore, uncertainty information is of paramount importance to making decisions based on the result of a study, and it has an increasing practical relevance. Uncertainty is always important for decision-makers, regardless of their attitude towards risk, and also to showing the quality of data and to motivating the search for data with better quality (Ciroth 2004).

There is uncertainty inherent to each SLP method that results from its characteristics of reliability, degree of precision and confidence. The corresponding LCA results are affected by this uncertainty. However, the uncertainty of neither the SLP methods nor the corresponding LCA results has yet been studied in detail with appropriate statistical tools. Therefore, the aim of this paper is to present an interdisciplinary study of the interrelation between SLP and LCA via modelling the uncertainty of SLP methods and applying it in the stochastic comparison of the LCA of building assemblies. In particular, these uncertainty models are applied to the LCA of cladding solutions for external walls.

The results presented in this paper are of paramount importance for designers who need to choose from alternative claddings for external walls of buildings using environmental criteria, especially early in the design stage, where there is an opportunity to decrease the environmental impacts of the project via the selection of adequate materials (Shen et al. 2007). The method proposed in this paper would make SLP more accurate by incorporating advanced statistical methods that aid the choice of the solution with the best environmental performance, particularly by calculating the stochastic LCA for each solution.

2. Degradation of external cladding

External claddings play a fundamental role in building performance. They increase the structure’s durability, protect it from environmental agents and are very important in terms of aesthetics. Besides quality/cost criteria, the selection of the cladding must take into account the conditions it will be subjected to throughout its service life (Ho et al. 2004).

In theory claddings are very durable elements. This is demonstrated by many buildings a hundred years old and more that retain all their original cladding elements and still have a satisfactory performance (Ashworth 1996). But it is very often found that these elements have a much shorter service life than the building itself and periodic maintenance of cladding is required over the building’s life-cycle; it sometimes even has to be refurbished or replaced.

Cladding degradation has economic and environmental implications for the built environment, so tools are needed to evaluate the performance of claddings throughout their life cycle. These tools must allow rational and technically informed planning of the maintenance and repair actions through analysis of their environmental impacts, thus avoiding unfounded premature repairs or replacements and allowing for an extension of the corresponding service life (Norvaišiene et al. 2004).

2.1. Quantification of the global degradation of external claddings

Estimates of the life expectancy of building components result in different outputs depending on what is required of them. In theory, many of the components of buildings are capable of lasting a very long time, as is proved in very old buildings where an original component continues to perform well. However, in practice, the life expectancy of building components is frequently much shorter, for a variety of reasons. The obsolescence that eventually afflicts both design and technology is perhaps the main reason why generally sound components are removed and replaced. Otherwise, components decay, are damaged or misused (Ashworth 1996).

In this study the degradation of external claddings is studied based only on visual inspection. Data on degradation in real in-service conditions is therefore acquired. This method is an alternative to the lab tests that some authors believe represent a simplification of reality and whose results do not have a clear correspondence with the complexity of the phenomena associated with natural degradation under real in-use conditions (Kus et al. 2004, Daniotti and Paolini 2005), even if these conditions are known, the mechanisms of deterioration are understood and the causes of deterioration are identified (Norvaišiene et al. 2004).

Overall degradation of the claddings analysed was quantified using the method put forward by Gaspar and de Brito (2008) and Gaspar (2009). These authors proposed a numerical “severity of degradation” index which is obtained as the ratio between the extent of the façades degradation, weighted as a function of the degradation level and the severity of the anomalies, and a reference area, equivalent to the maximum theoretical extent of the degradation for the façade under analysis, as in expression (1).

$$S_w = \frac{\Sigma\left(A_n \times k_n \times k_{a,n}\right)}{A \times k} \qquad (1)$$

Where: S_w - Normalised severity of degradation of the façade, in percentage; A_n - area of cladding affected by an anomaly, in m^2; k_n - anomaly’s “n” multiplying factor, as a function of its condition (between 0 and 4); $k_{a,n}$ - weighting coefficient corresponding to the relative importance of each anomaly ($k_{a,n} \in R^+$) (if no instructions are provided , one should assume $k_{a,n} = 1$); k - weighting factor equal to the highest degradation level in the façade; A - total area of the cladding, in m^2.

Therefore this indicator takes into account both the degraded area of the cladding, affected by the different types of anomaly, and the severity level of the anomalies, also designated “condition”. The anomalies are classified in terms of condition through a weighting factor (k_n) using a discrete scale of values from the most favourable condition (level 0 - absence of visible degradation) to the most unfavourable (level 4 - extensive degradation or loss of function).

2.2. Service life prediction (SLP) of external claddings

ISO 15686-1 (ISO 2000) defines the reference service life as the period of time that a building or its parts are expected to last with standard in-use conditions. Predicting the service life of buildings or building elements can be complex and time-consuming. To date, SLP methods have not been developed into an exact science because of the many conditioning factors that make a thorough SLP an interdisciplinary activity.

Many studies have examined service life prediction. Hovde (2004) says that it can be a complex and lengthy process with many associated variables. According to some authors (Daniotti 2003, Moser 2004, Lacasse and Sjöström 2004), the main methods used to estimate service life may be classed as deterministic, probabilistic and engineering (a symbiosis of the previous two).

Deterministic methods are based on an analysis of the factors and degradation mechanisms that affect the elements studied, and quantifying them in terms of degradation. The great impetus for these methods came from Japan, through the “Japanese principal guide for service life planning of buildings” (AIJ, 1993) that proposed the factor method for the first time. More than a method, it is a general framework for service life estimation. Its flexibility and relative ease of application led to the factor method developing into one of the main tools offered, and it became the basis of the international standard for durability, partially published, the ISO 15686: 2000 (ISO 2000).

Probabilistic methods came along based on the general concept that no two buildings degrade in exactly the same way during their life cycle since degradation depends on a series of random factors. Therefore, these methods look at degradation as a stochastic process that evolves probabilistically over time, where only the initial parameters are known (Moser 1999). These models are generally highly complex since they endeavour to handle different statistics and include the uncertainty resulting from the time periods considered (Kliukas and Kudzys 2004).

Rudbeck (1999) proposes to improve existing methods with the use of statistical tools. Moser (2004) looks at the work of various authors in this area and concludes that more studies are needed to identify the parameters that influence the service life of construction elements and that it is necessary to create viable mathematical formulae to enable these methods to be applied.

2.2.1. SLP - Determinist approach

Various studies and standards in the area of service life prediction have mentioned the intention of estimating a reference service life for buildings and their components. The first standard to dwell on the durability and service life prediction issues was the Japanese guide developed in 1989 by the Architectural Institute of Japan and later translated into English (AIJ 1993). This was pioneering at world level and represented the genesis of the factor methods, where the estimated service life of an element is obtained as the product of a reference service life by a series of factors modified as a function of the specific conditions of the element under analysis. According to this document the end of the service life is determined on the basis of the physical deterioration and the functional obsolescence of the element. The guide prescribes that external claddings should have a service life of at least 10 years.

In 1992 the British Standards Institute published standard 7543 for durability "British guide to durability of building elements, products and components" (BS 7543:1992) that lists various methods to estimate the service life of construction products, from past experience to accelerated degradation tests (Gaspar 2009). BS 7543 proposes defining the service life of buildings as a function of the type of use envisaged, and therefore five categories are proposed: temporary buildings, with a service life of less than 10 years; short-lived buildings, such as storehouses, with a service life of at least 10 years; average buildings, such as industrial buildings, with a service life of at least 30 years; current buildings, such as new housing, hospitals and schools, with a service life of at least 60 years; long-lived buildings, such as public buildings, with a service life of at least 120 years. The standard also prescribes that façade claddings must guarantee a service life similar to that of the building, with proper periodic maintenance.

Inspired by the Japanese guide the International Organization for Standardization (ISO), based on a recommendation of RILEM (International Union of Testing and Research Laboratories for Materials and Structures) suggests a standard for service life prediction (Frohnsdorff et al. 1999). This standard, called ISO/DIS 15686 "Building Service Life Planning" presently consists of 11 parts that define the general principles, framework and procedures of the method of service life prediction proposed. Furthermore, it defines the functional performance criteria that must be respected at the design stage and throughout the service life of constructions, and this will ultimately contribute to defining the end of the service life of the elements analysed (Hed 1999). ISO 15686 suggests that façade claddings must have a service life of 25 years in current buildings whose service life is 60 years.

Standards relating to service life prediction have been published in countries that include: New Zealand (New Zealand Building Code, 1992), which establishes a service life of 50 years for buildings and allows their components to have different service lives, depending on easy access, repair and anomaly detection; Australia (Guideline on durability in buildings, 2003); the United States, through the Partnership for Advancing Technology in Housing (PATH) that has funded a series of publications relating to the service life of buildings, and the American Society for Testing and Materials (ASTM); and Canada (Standard S478: Guideline on durability in buildings) (Koymans and Abbott, 2006).

Besides standards the Institute of Technology of Israel has produced several studies on the degradation of façades and the determination of their service life (Shohet and Paciuk 2004, Shohet et al. 1999). They propose a classification of façade degradation through the average of the physical and the visual degradation. Physical degradation includes all aspects related to the degradation mechanisms façades are subjected to while visual degradation takes into account the area of the façade affected by the various anomalies. This analysis is performed using visual inspections. Once the façade's degradation is quantified, the authors propose that degradation patterns are defined that permit the evaluation of loss of performance over time. The end of the service life is reached when, for a given sample, the average degradation curve reaches a minimum admissible level of performance. Shohet and Paciuk (2004) define two minimum performance levels: one for situations when claddings must have a high performance level; the other for a lower performance level, when the building owners want to minimise maintenance actions on the claddings.

Table 1 shows the reference service life proposed by various authors and standards for two types of external claddings under analysis.

All of these studies look at the service life of façade claddings as a deterministic value. This approach has been the target of much criticism because of service life being seen as an absolute value, with no data on the degradation process or on the transition from one degradation state to the next one (Mc Duling et al. 2008), therefore it fails to incorporate all the variability associated with degradation processes (Hovde 2000).

2.2.2. SLP - Stochastic approach

The studies developed by the Institute of Technology of Israel (Shohet and Paciuk 2004, Shohet et al. 1999) led to the development of empirical methods implemented to evaluate the durability (or loss of performance) of a building or its components in real in-service conditions at different stages of the service life, through extensive field work (Gaspar and de Brito 2011). These methods make it possible to represent graphically the degradation patterns of various types of claddings and statistically analyse the performance of the claddings throughout their life cycle, with the aim of estimating their service life as a function of the level of demand.

For this, various cases are analysed in real in-service conditions and different degradation states. Using the model developed by Gaspar and de Brito (Gaspar and de Brito 2008, Gaspar 2009) it is possible to define the global degradation of the façade claddings. Each case corresponds to a coordinate (x, y) where *x* represents the age of the cladding (age here is the time since the last corrective, at the time of the inspection) and *y* represents the degradation observed. Once all the coordinates are determined they are represented graphically, leading to a cloud of points that depicts the case studies of the field study. Using a simple regression analysis it is then possible to obtain the function that best fits the cloud of points. This method is usually called the graphic method.

Gaspar (2009) used this method to evaluate the service life and durability of current renderings, based on a study of 100 coatings in the Lisbon region. For a maximum level of degradation of 20% the author obtained a reference service life of 15 years. By analysing the estimated service life of each case of the sample the author determined an average value of 17.5 years, with a standard deviation of 5.35 years and a confidence interval of ±1.05 years.

Based on the same method Silva et al. (Silva et al. 2011a) analysed 140 stone claddings (directly adhered to the substrate) and found that the reference service life of this type of cladding is 68 years. By performing the same analysis of the estimated service life of each case study the authors found an average value of 66 years, with a standard deviation of 8.54 years and a confidence interval of ±1.40 years.

Another statistical method that can be used to predict the service life of façade claddings is multiple linear regression analysis. This is an extension of simple linear regression analysis in that it is based on the same hypotheses. However, multiple regression involves more than one independent variable (Satapathy et al. 2009). Wooldridge (2009) notes that since multiple regression allows the addition of more factors that contribute to explaining the dependent variable it is expected that more efficient models are obtained.

A study by Silva et al. (2012b) applies multiple linear regression analysis to the prediction of the service life of current renderings. The authors conclude that age, exposure to humidity, the type of render and the level of protection of the façades are conditioning variables that explain a façade's degradation. The authors thus propose a mathematical function that is used to estimate the service life of this type of cladding based on these four variables, which leads to an average estimated service life of 15 years, with a standard deviation of 2.90 years and a confidence interval of ±0.57 years.

In a similar study Silva et al. (2012a) used the same statistical tool to evaluate the service life of stone cladding. In this case they found that the conditioning variables to explain the degradation of façades are age, distance from the sea, the type of finishing, and the area of the stone plates. Based on the mathematical expression that relates the degradation of the façades with these variables the authors found an average estimated service life of 77 years, with a standard deviation of 11.21 years and a confidence interval of ±1.86 years.

Artificial neural networks are another statistical method employed in service life prediction. This statistical tool is usually an emulation of the human biological system. The networks "learn" from a series of patterns that are provided in relation to a given problem and based on data acquired are capable of predicting the behaviour of new patterns. Silva et al. (2012b) applied this tool to the prediction of the service life of current renderings. Taking as independent variables those that were considered in the multiple linear regression analysis (age, exposure to humidity, the type of render and the level of protection of the façades) the authors determined a mathematical function produced by the neural networks that permitted the evaluation of the degradation of rendered façades. For a maximum admissible level of degradation of 20% the average estimated service life found was 17.5 years, with a standard deviation of 2.74 years and a confidence interval of ±0.90 years.

In a similar study on stone claddings Silva et al. (2011b) evaluated their service life using the same artificial neural networks. Once again they considered the same relevant variables as those in the multiple linear regression analysis (age, distance from the sea, the type of finishing and the area of the stone plates). Based on the mathematical function obtained through the neural networks, the authors found an average estimated service life of 80 years, with a standard deviation of 9.34 years and a confidence interval of ±3.10 years.

Table 2 shows a summary of the service lives estimated by the various statistical methods.

The life cycle of a building or its components is the period of time from when it is put into service until it reaches the end of its service life. In most codes it is considered that a current building reaches the end of its service life at 50 years. Over that period the claddings whose service life is shorter than that of the building, such as current renderings, go through various life cycles. It is assumed that each life cycle is independent of the next one, thus considering degradation as stochastic process; this means that the fact that during the first life cycle the rendering reached the end of its service life at 25 years does not mean that the new, replacement, rendering, even though subjected to the same exposure conditions, will reach the end of its service life after the same period of time.

To proceed to the life cycle assessment (LCA) of the claddings studied in order to evaluate the corresponding environmental impact, the estimated number of replacements over 50 years must be established. To take uncertainty into account when determining the number of replacements needed in 50 years it is assumed that the service life estimated by each method for each life cycle until replacement follows a Normal distribution. This assumption is quite often fundamental in the process of statistical inference. One of the rules used to ascertain whether a variable follows a Normal distribution is the central limit theorem, which states that the distribution of an average will tend to be Normal as the sample size increases (Barnes 1994). The central limit theorem states that the sampling distribution tends to be Normal in big samples - regardless of the shape of the data actually collected (and the sampling distribution will tend to be Normal regardless of the population distribution in samples of 30 or more), which means that the sample studied is normally distributed (Field 2008, Motulsky 1999).

The linear combination theorem shows that the sum of or difference between two or more random independent variables with Normal distribution is also a Normal random variable, thus allowing the average and standard deviation of the sample distributions to be summed. If each life cycle period until replacement follows a Normal distribution and since they are independent, the linear combination theorem is used to show that the set of the various life cycles up to 50 years also follows a Normal distribution.

In this case the sample used to predict the service life of current renderings using the graphic method and multiple linear regression analysis is composed of 100 case studies, a significantly bigger sample than needed by definition to state that the variable has a Normal distribution. For stone claddings the sample consists of 140 case studies. Based on the central limit theorem and on the size of the samples it can be considered that the service life values (SLVs) estimated by these methods follow a Normal distribution (as $n >> 30$ then one can say that $SLV \sim N(\mu, \sigma)$).

For the artificial neural networks the overall sample is split into two main subsamples: the learning sample, used to learn from a set of patterns fed into the network; and the test sample, which is used to check whether the prediction model defined through the learning sample can safely be generalised. In this study the test sample for estimating the service life of stone claddings consists of only 35 case studies, and 36 case studies for current renderings. In this case it seems less reasonable to assume that the sample size is sufficient to justify adopting the hypothesis that the service life estimated by the neural networks follows a Normal distribution. Therefore, to test whether that is true, two statistical tests were performed: the Kolmogorov-Smirnov (K-S) test (Chakravarti et al.) and the Shapiro-Wilk test (Shapiro and Wilk 1965). The K-S test was performed with the Lilliefors correction (Lilliefors 1967). Two hypotheses are tested: the null hypothesis (H_0) that indicates the sample analysed follows a Normal distribution, and the alternative hypothesis (H_1) that indicates that the sample does not follow a Normal distribution. Using dedicated software the p-value associated with each of the normality tests was obtained. If the p-value of the tests is higher than the significance level defined than the null hypothesis is accepted, and it can be stated that the sample does follow a Normal distribution. For current renderings the K-S test with the Lilliefors correction yields a p-value of 0.145 and the Shapiro-Wilk test a p-value of 0.408. Conversely, for stone claddings the K-S test with the Lilliefors correction yields a p-value of 0.20 and the Shapiro-Wilk test a p-value of 0.462. This indicates that for a 5% significance level the estimated service life of both claddings follows a Normal distribution (Table 3).

The number of replacements is evaluated based on the ratio between the reference service life of the building (50 years) and the estimated service life of each of the claddings analysed, and this ratio is determined through the various methods used to predict the service life and for each case study. Based on the central limit theorem and on the size of the samples used to predict the service life of external claddings by the graphic method and multiple linear regression analysis (100 case studies of current renderings and 140 case studies of stone claddings), it can be considered that the number of replacements follows a Normal distribution. For neural networks it seems less reasonable to assume that the sample is large enough to justify adopting the hypothesis that the number of replacements follows a Normal distribution and the Kolmogorov-Smirnov (K-S) and the Shapiro-Wilk test were performed to ensure that. For current renderings the K-S test with the Lilliefors correction yields a p-value of 0.199 and the Shapiro-Wilk test a p-value of 0.109. Conversely, for stone claddings e K-S test with the Lilliefors correction yields a p-value of 0.177 and the Shapiro-Wilk test a p-value of 0.069. This indicates that for a 5% significance level the estimated service life of both cladding types follows a Normal distribution (Table 4).

There is an uncertainty associated with the determination of the service life using the statistical methods presented in Table 2. For that reason the estimated service life is presented as an average value, associated with a standard deviation and a 95% confidence interval. Consequently this uncertainty will always be present when determining the number of cladding replacements in the period under analysis. Table 5 thus includes a reference value for the average number of replacements (deterministic) as well as a stochastic value that takes uncertainty into account.

3. Environmental performance of external claddings

The envelope of the building is a key element because it strongly influences its comfort, safety and aesthetics. Because it is in close contact with the environment it is constantly affected by the weather and atmospheric pollution, which can speed up the degradation rate, with likely serious implications for safety and user comfort. One of its elements, the external cladding, directly influences the thermal and environmental performance of the building envelope because of its share in the envelope's initial embodied energy and life cycle cost. External cladding is the first and outermost layer that separates the inner space from environmental agents and is therefore particularly prone to failures and defects, with direct consequences for the quality of urban space, user comfort, and repair and maintenance costs. For all these reasons and also because of the relatively long service life of buildings, both the LCA and the SLP of this building assembly are of the utmost importance (Silvestre et al. 2011a, b, Silvestre and Lasvaux 2012). This section of the paper explains the application of the LCA method to each cladding solution through an internationally standardised procedure (ISO 2006c, d), using both the corresponding deterministic and stochastic service life.

3.1. LCA study - Scope and functional unit

The LCA method considers the environmental impacts during the life cycle of a product by identifying and quantifying the environmental emissions and consumption of energy and materials (Ortiz et al. 2009). LCA implementation is divided into four phases according to ISO standards (ISO 2006c, d): goal and scope definition, inventory analysis, impact assessment and interpretation. The first phase describes the product to be assessed, the scope of the associated system and the functional unit.

The construction of buildings differs from other industrial processes by yielding a product that: incorporates a high quantity of products and processes; has a long life-cycle; contains components that have different service lives; has a dynamic that differentiates it from other standard industrial products, in particular during the execution, use and end-of-life phases (Blok et al. 2007, Chevalier and LeTeno 1996, Kibert 2002). The definition of a functional unit (that is a service and not only a product) and the boundary of the assessment in LCA studies is therefore even more important, in order to lessen the sensitivity and errors of the results (Erlandsson and Borg 2003, Ozik 2006). Previous LCA studies of construction materials and buildings (Silvestre et al. 2011a, b, Silvestre and Lasvaux 2012) confirmed the relevance of the definition of a functional unit and of the boundary in this type of study.

The characteristics of each external wall cladding compared in this study are summarised in Table 6. The functional unit of the study is a square meter of cladding applied on the external surface of the external wall of a building. This table also includes the Ecoinvent system processes used to model each of these cladding solutions in the LCA calculations.

3.2. Boundaries of the LCA study

The LCA calculations took into account the different stages of the life cycle for each external wall cladding solution. The operations considered in the LCA calculations that occur in each life cycle stage for each external wall cladding are summarised in Table 7.

The construction process (A4-transport to the building site and A5-installation into the building) and use stages (information modules related to the operation of the building) (B6-operational energy use and B7-operational water use) were not included in the LCA calculations because they were considered to be the same for both solutions under analysis. The maintenance actions (B2) were not included in the LCA calculations either, because it was considered that the corresponding environmental impacts are the same for both solutions under analysis (and are also negligible - e.g. cleaning with water, compared with replacement) and a similar approach was used for the B1, B3, B5, C1 and C2 stages.

The LCA from the production of each construction material ("cradle to gate" approach - stages A1-A3 in Table 7) was calculated using appropriate software (SimaPro) and available "Life cycle Inventory" (LCI) databases, in particular the "Ecoinvent database system processes" mentioned in Table 6, taking into account the European reference case and previous research works (Silvestre et al. 2011a, b, Silvestre and Lasvaux 2012). This database was also used to model each cladding replacement (stage B4) during the service life of the building (50 years). But each rendering and stone cladding replacement generates demolition waste. Therefore, the environmental impacts of the "End-of-life stage" (C) and the "Benefits and loads beyond the system boundary" (stage D) were considered only for the demolition waste from the replacement operations. It was assumed for comparison purposes that in the 50th year the state of conservation of the claddings would be the same as when they were applied and the LCA of the demolition of the claddings in that year was therefore not considered (the service life of the building assumed in the design phase is 50 years but it was considered that the building does not actually reach the end of its service life in that year). This is the only approach that allows a balanced comparison of the solutions and the consideration of partial rates of replacement. In fact, using the reference number of replacements presented in Table 5 - e.g. 3.53, the parcel of 0.53 replacements is considered to mean that 53% of total sample of claddings will reach the end of their service life before or at 50 years and have to be totally replaced in order to restore the initial state of repair.

For the "End-of-life stage" (C) it was considered that the cement mortar and any paint are mixed after demolition and therefore have to be considered as undifferentiated CDW (waste code 17 09 04 - mixed construction and demolition waste (EC 2000)) and sent to landfill. The mixture of stone plates and mortars (waste code 17 01 07 - mixtures of concrete, bricks, tiles and ceramics (EC 2000)) yielded by demolishing stone cladding can be sent for "rock crushing" (with an output of 80%) to reduce the use of natural aggregates, thus generate "Benefits and loads beyond the system boundary" (stage D), which highlights that the end-of-life phase can make a positive contribution to the environmental performance of construction materials (Silvestre et al. 2011b).

The reference study period was set at 50 years because this is the service life considered for a building at the design stage.

3.3. LCA results using standard SLP

LCA is a procedure that aims at studying the environmental aspects and potential impacts of a product, starting with the raw materials' extraction and going on to product manufacturing, until the use and final disposal stages. In the inventory phase, all the relevant inputs and outputs of the system are identified and quantified, which requires data collection and calculation procedures. These inputs and outputs are "use of resources" (raw materials and energy) and "emissions to air, water and soil". In the impact assessment stage the results of the inventory analysis are assigned to environmental impact categories in order to provide an environmental performance of the product through an internationally standardised procedure (ISO 2006c, d).

The environmental performance of the external wall solutions was compared following the LCA method (based on ISO 14040:2006 and ISO 14044:2006 international standards (ISO 2006c, d)). This procedure allows LCA results from different studies to be compared and used to make meaningful choices (Ekvall 2005, Krigsvoll et al. 2007). This assessment also followed most of the principles already included in the draft standards FprEN 15643-2:2010: "Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance" and prEN 15978:2010: "Sustainability of construction works - Assessment of environmental performance of buildings - Calculation methods", such as:

- The assessment of the environmental performance shall apply the LCA approach in accordance with the guidelines and requirements of ISO 14040:2006 (ISO 2006d);
- The results of the assessments shall be organised into three main groups: impacts specific to building fabric and site (results from the product stage and from the construction process stage); impacts and aspects specific to building in operation (maintenance, repair, replacement, water and energy use and all activities with an environmental impact), and results from the end-of-life stage of the building;
- The impacts and aspects related to benefits and loads beyond the building life cycle, e.g. those that result from further reuse, recycling potential and energy recovery and other recovery operations, may be included as supplementary information. They are essential to promoting and allowing a cradle-to-cradle (C2) approach in the life-cycle of the buildings and their assemblies;
- The default value for the reference study period shall be the required service life of the building and the estimated service life of the assemblies shall take into account rules and guidance contained in the ISO standards 15686-1,-2,-7 and -8 (ISO 2006a, 2000, 2001, 2006b).

The LCA results in six of the environmental categories defined in the European Standards specified (using an EIAM with a mid-point approach - CML 2001 version 2.05) for the cladding solutions being evaluated, and using a standard SLP, these are presented in Table 8 for cumulative stages "A1-A3 and B4" and "A1-A3, B4, C3-C4, and D". The reference value used for the service life of the two solutions was 25 years because it is the period suggested for building components in the International Standard (see Table 1), which is a reference that can be, and often is, used by building designers in this area of knowledge if they want to take into account in a very simplified way the durability for both solutions (despite this not being a realistic assumption).

The results presented in Table 8 show that the consideration of standard SLP (two replacements of each solution within 50 years) leads to the choice of the rendering solution. In fact, the higher environmental impacts of the application (stages A1-A3 plus the same number of replacements - B4 stage - for both solutions) of the stone cladding (between 4.3 and 8.4 times higher than the rendering) prevent it from being an alternative, even taking the replacement operations and end-of-life of demolition waste into account (stages A1-A3, B4, C3-C4, and D). In fact, only in one environmental category (Eutrophication) does the rendering perform slightly worse, due to the impact of landfilling the demolition waste.

The LCA results presented in this section comply with the common approach used in building design. Therefore, it is important to analyse its consequences on the decision process and to find which other decisions and questions arise from the use of stochastic SLP instead of this approach. The next section of this paper aims to shed some light on this issue.

3.4. LCA results using stochastic SLP

The technical service life (hypothetically correct use/maintenance/replacement conditions) is normative in most LCA studies of buildings (Lassandro et al. 2007) and its use has a positive effect on the outcome of the LCA, because components in the calculation are in general supposed to have a longer service life than the real situation (Hendriks et al. 2004). Nevertheless, a more realistic forecast of the maintenance and its effect on the global and local environmental impacts of a building must also be made.

The LCA results in six environmental categories (Table 8) for the cladding solutions being evaluated and using the stochastic SLP reference value (Table 5) are presented in Figures 1 and 2 for cumulative stages “A1-A3 and B4” and “A1-A3, B4, C3-C4, and D”. Each service life prediction method is identified by an acronym (GM for graphic method, MLR for multiple linear regression and ANN for artificial neural networks).

Figure 1 presents results that are similar to the ones in Table 8 for cumulative stages “A1-A3 and B4”, even though the difference between the environmental performance of the rendering and stone cladding solutions decreases because a higher reference value of stochastic service life was assumed for the last solution.

The LCA results presented in Figure 2 considered not only the replacement operations (B4 stage) but also the corresponding end-of-life of demolition waste (stages C3-C4, and D). Therefore, this approach led to an inversion in the preferred solution in three out of six environmental categories: EP, GWP and POCP. This is caused by the impact of landfilling the demolition waste from a greater number of rendering replacements and also by the benefits of reusing stone demolition waste as aggregate.

Figure 2 raises some questions. Maintenance operations (B4 and the corresponding end-of-life of demolition waste - C3-C4, and D) during service life are often very uncertain. But their frequency depends directly on the service life of the cladding solutions. Since this paper has already characterised the uncertainty inherent to each of the three SLP methods (and probed the possibility of using Normal distribution to model the number of replacements of each solution over a 50-year life cycle - see section 2.2.2), these data can be used to evaluate the uncertainty of LCA calculations. In fact, it is possible to apply Monte Carlo analysis in SimaPro software (and only using “system processes” from Ecoinvent to avoid including uncertainty in parameters other than SLP), which is a statistical approach that incorporates parameter uncertainty to compare solutions that are not correlated (Jolliet et al. 2010). This approach can be completed in five steps (Heijungs et al. 2008):

1. Define the number of replacements as a stochastic variable with a specified probability distribution - Normal - and corresponding parameters (average values and standard deviations presented in Table 5 for each SLP method and cladding solution);
2. Build the LCA-model with one specific realisation of every stochastic parameter;
3. Determine the LCA-results with this particular realisation;
4. Repeat this for a large number of realisations - e.g. N (number of runs) = 1000;
5. Investigate statistical properties of the sample of LCA-results - e.g. the mean, the standard deviation, the confidence interval, or the distribution.

In each iteration of the Monte Carlo analysis, the number of replacements of each cladding solution is randomly selected according to the corresponding distribution. Then the LCA is recalculated for each cladding solution and the difference between one result and the other is stored. After 1000 runs the distribution of results is plotted. Conclusions can be drawn from this plot but if there are more than 10% of contradictory runs the results are considered too uncertain to draw conclusions.

It is important to highlight that, in each iteration, the solutions are held to be mutually independent because they are considered to be exposed to the same average conditions (which is reflected in the expected service life and standard deviation). However, the causes related to the application or quality of materials can lead to a longer or shorter service life of each solution in each iteration, but those are inherent to each solution and therefore not intercorrelated.

A Monte-Carlo analysis was used to evaluate the uncertainty of the LCA results presented in Figure 2 and the results are in Table 9. In at least one environmental category (GWP, which is one of the most-often used internationally) this approach can provide an improved understanding of the differences between alternatives. It can also test their similarity because the analysis of the results achieved using the reference value of stochastic SLP is not sufficiently clear, because it does not consider the uncertainty of this parameter.

The results presented in Table 9 provide a better understanding of the relative environmental performance in every category of the solutions under analysis. In fact, the difference between the environmental impacts of stone claddings and renderings is negative in more than 90% of the runs for EP and POCP (using any SLP method) and is always positive for ADP, AP and ODP. Therefore, it can be concluded that stone claddings have a worst environmental performance than renderings in these three last categories but have a better one in EP and POCP. But a Monte-Carlo analysis does not definitively identify the solution that performs better environmentally in the GWP category. The answer obtained by the Normal distribution defined according to the GM method is similar to the one given by the other two SLP methods, but it yields more than 10% of contradictory runs (20%). Therefore, the results for GWP using the GM method are considered too uncertain to enable conclusions to be drawn, while the results achieved using the ANN or MLR methods indicate a better environmental performance of stone claddings in this category but with a number of contradictory runs near 10%. From these results it can be taken that stone claddings also perform better in the GWP environmental category (the only result below 90% was achieved using the GM method, for which the number of replacements is maximum for stone claddings and the standard deviation is maximum for renderings, within the different SLP methods - see Table 5), and therefore each cladding solution is preferred in three out of six environmental categories. This conclusion can only lead to a final decision by the designer if weighting factors are associated with each environmental category, especially under a national regulation or a voluntary building environmental assessment system (BEAS).

Table 10 provides an overview of the different levels of complexity that characterise the combined use of statistical models in the SLP and LCA of building assemblies and it shows the external cladding solution that offers the better environmental performance according to the results of each approach and the relevant design choice.

According to Table 10, the choice of wall cladding can also depend on the design stage, when the decision process is quite uncertain. At the final design stage, for instance, there is less uncertainty about the type of material to be used (it has indeed already been chosen), the maintenance procedures that will be put into practice during the building's service life and the level of demand of the building owner/users (they are already known and are also interrelated). A higher level of demand, for example, can lead the designer to use a higher reference value for the number of replacements in LCA calculations than the values presented in Table 5.

4. Conclusion

Modelling the uncertainty associated with each of the SLP methods selected allowed the uncertainty associated with the service life of each cladding solution to be estimated. Therefore, an SLP method (with uncertainty modelled) for building assemblies is proposed in this paper.

The service life considered for each element of buildings can have a bigger influence on LCA results than the characteristics of their components. In fact, the question of a building's service lifespan is critical in LCA studies where just a few grams of material may cause an enormous environmental burden (Hendriks et al. 2004). Construction, disposal and deconstruction are processes that can be generally traced and described to calculate environmental impacts, whereas the building's use, maintenance and management are characterised by the utmost variability. These stages involve other variables that are totally unpredictable and hard to define because they depend on decisions about building operation and maintenance scheduling, thus creating limitations to the actual reliability of LCA studies. Therefore, only a thorough interdisciplinary study of the interrelation between the service life prediction (SLP) and LCA of buildings or building elements permits the characterisation of the dependence between their durability and environmental impacts along the entire life cycle. The importance of this interrelation is increasing, largely because of several research studies that compare different options based on their service life or environmental performance (Nunen 2010).

The results of the LCA study presented in this paper related to a standard, a deterministic and a stochastic environmental performance of each cladding solution for external wall. These results are compared, including a thorough analysis of their consequences for the choice made by the designer at an early stage of the building project and a forecast of the changes that can be made to the decision later in design stage. The deterministic and stochastic environmental performances of the wall cladding solutions under analysis were also compared to ascertain the relative advantages and disadvantages of these approaches and the influence of the uncertainty modelling in the environmental ranking of the solutions studied. This ranking provides a basis for decision-making under (modelled) uncertainty while reducing the risk of the decisions made at the design stage.

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Table 1 - Reference service life proposed by different authors and normative documents

Authors	**External cladding solution**	
	Renderings	**Stone claddings**
BSI (1992) Recommended design life (years)	> 60 (most external claddings for buildings with normal life - new housing)	
AIJ (1993) Recommended planned service life (years)	> 10	
Shohet et al. (1999) Standard life expectancy (years)	20	40
ISO 15686 (2000) Suggested service life for components (years)	25 (buildings with a design life of 60 years)	
Shohet and Paciuk (2004) For situations in which components are required to perform at high levels		
Standard life expectancy (years)	15	44
Predicted service life interval (years)	12-19	39-50
Shohet and Paciuk (2004) For situations in which owners want to minimise maintenance costs		
Standard life expectancy (years)	23	64
Predicted service life interval (years)	19-27	59-70

Table 2 - Summary of the service lives estimated by the various statistical methods

Service life prediction methods	**External cladding solution**	
	Renderings	**Stone claddings**
Graphical method		
Reference service life (years)	15	68
Average estimated service life (years)	17.5	66
Standard deviation (years)	5.35	8.54
95% C.I. (years)	±1.05	±1.40
Multiple linear regression		
Average estimated service life (years)	15	77
Standard deviation (years)	2.90	11.21
95% C.I. (years)	±0.57	±1.86
Artificial neural networks		
Average estimated service life (years)	17.5	80
Standard deviation (years)	2.74	9.34
95% C.I. (years)	±0.90	±3.10

Table 3 - Results of the normality tests of the samples used in this study for the artificial neural networks method

Normality tests	**External cladding solution**	
	Renderings	**Stone claddings**
n (sample size)	36	35
K-S	0.145	0.20
Shapiro-Wilk	0.408	0.462

Appendix 7.V - Silvestre, J. D.; Silva, A. & de Brito, J. (2012). Uncertainty modelling of service life and environmental performance to reduce risk in buildings design decisions.

Table 4 - Results of the normality tests of the samples used in this study for the artificial neural networks method

Normality tests	External cladding solution	
	Renderings	**Stone claddings**
n (sample size)	36	35
K-S	0.199	0.177
Shapiro-Wilk	0.109	0.069

Table 5 - Reference and stochastic number of replacements over a 50-year period (considering that the number of replacements follows a Normal distribution)

External cladding solution	Service life prediction methods					
	Graphic method (GM)		**Multiple linear regression (MLR)**		**Artificial neural networks (ANN)**	
	Average reference number of replacements / Standard deviation	**Stochastic number of replacements [μ-σ:μ+σ]**	**Average reference number of replacements / Standard deviation**	**Stochastic number of replacements [μ-σ:μ+σ]**	**Average reference number of replacements / Standard deviation**	**Stochastic number of replacements [μ-σ:μ+σ]**
Renderings	3.10/0.906	[2.20: 4.01]	3.53/0.823	[2.71: 4.35]	2.93/0,476	[2.45: 3.40]
Stone claddings	0.77/0,108	[0.66: 0.88]	0.67/0,111	[0.55: 0.78]	0.64/0,079	[0.56: 0.71]

Table 6 - Characteristics of each external wall cladding and the Ecoinvent system processes used in the LCA calculations

External cladding solution		Ecoinvent database system processes
Rendering and paint	Rendering - 3 cm cement mortar	Cover coat, mineral, at plant/CH
	Paint - two coats of water based paint	Alkyd paint, white, 60% in H_2O, at plant/RER
Stone	3 cm stone plate plus cement mortar and joints material	"Natural stone plate, polished, at regional storage/CH" and "cement mortar, at plant/CH" (mortar and joints material)

Table 7 - Life cycle stages (taken from European standards) considered in LCA calculations for the two external wall claddings (CEN 2011)

Modules	Life-cycle stage name and description		External cladding (EC) solution	
			Rendering and paint	**Stone**
Product stage	**A1**	**Raw material extraction and processing, processing of secondary material input**	X	X
	A2	**Transport to the manufacturer**		
	A3	**manufacturing**		
Use stage - information modules related to the building fabric	**B1**	**Use or application of the installed product**	-	
	B2	**Maintenance**	Total cleaning every 5 years (but not included in LCA calculations)	
	B3	**Repair**	-	
	B4	**Replacement**	Repainting every 10 years and rendering replacement when it reaches the end of its service life	Stone cladding replacement when it reaches the end of its service life
	B5	**Refurbishment**	-	
End-of-life stage	**C1**	**Deconstruction, demolition**		
	C2	**Transport to waste processing**		
	C3	**Waste processing for reuse, recovery and/or recycling**		Stone (from replacement operations) crushing for reuse
	C4	**Disposal**	Cement plaster (from replacement operations and contaminated by paint) to landfill	
Benefits and loads beyond the system boundary	**D**	**Reuse, recovery and/or recycling potential**		Reuse of stone (from replacement operations) crushing avoids the use of natural aggregates

Table 8 - LCA results of each alternative using standard SLP

Environmental category	Rendering and paint		Stone	
	A1-A3 and B4	**A1-A3, B4, C3-C4, and D**	**A1-A3 and B4/% of difference from rendering and paint**	**A1-A3, B4, C3-C4, and D/% of difference from rendering and paint**
ADP - Abiotic Depletion Potential (kg Sb eq.)	1.27E-01	1.38E-01	6.69E-01/429%	6.63E-01/380%
AP - Acidification Potential (kg SO_2 eq.)	7.02E-02	9.27E-02	5.92E-01/743%	5.80E-01/525%
EP - Eutrophication Potential (kg PO_4^{-3} eq.)	2.20E-02	2.22E-01	2.06E-01/837%	2.06E-01/**-7%**
GWP - Global Warming Potential (kg CO_2 eq.)	1.59E+01	5.16E+01	1.01E+02/531%	9.93E+01/92%
ODP - Ozone layer Depletion Potential (kg CFC-11 eq.)	2.11E-06	2.37E-06	1.25E-05/491%	1.22E-05/413%
POCP - Photochemical oxidation (kg C_2H_4)	3.39E-03	1.39E-02	1.86E-02/449%	1.81E-02/30%

Table 9 - Monte-Carlo analysis of the LCA results (for each environmental category) for cumulative stages “A1-A3, B4, C3-C4, and D” using stochastic SLP

Environmental categories	**ADP**			**AP**			**EP**			**GWP**			**ODP**			**POCP**		
SLP methods	**ANN**	**GM**	**MLR**	**ANN**	**GM**	**MLR**	**ANN**	**GM**	**MLR**	**ANN**	**GM**	**MLR**	**ANN**	**GM**	**MLR**	**ANN**	**GM**	**MLR**
Percentage of the 1000 runs when stone claddings have a better performance	0	0	0	0	0	0	100	98.7	99.7	93.8	*79.9*	92.1	0	0	0	99.9	96	99.5

Table 10 - Overview of the increasing level of complexity in the combined use of statistical models for SLP and LCA of building assemblies, the external cladding solution that offers the better environmental performance and the design choice

Increasing level of complexity	**SLP method**	**Type of SLP method**	**Life cycle stages considered (Table 7)**	**LCA method**	**Best environmental performance**	**Design choice**
1	ISO 15686 (Table 1)	Standard	A1-A3	Deterministic (Table 8)	Render and paint	Render and paint
2			A1-A3, B4			
3			A1-A3, B4, C3-C4, D			
4	Reference value of stochastic SLP (Table 5)	ANN GM MLR	A1-A3	Deterministic (Figures 1 and 2)		
5			A1-A3, B4			
6			A1-A3, B4, C3-C4, D		Depends on the environmental category	Depends on weighting factor or BEAS
7	Stochastic SLP with probabilistic distribution (Table 5)			Stochastic using Monte-Carlo analysis (Table 9)		Depends on weighting factor or BEAS or design stage

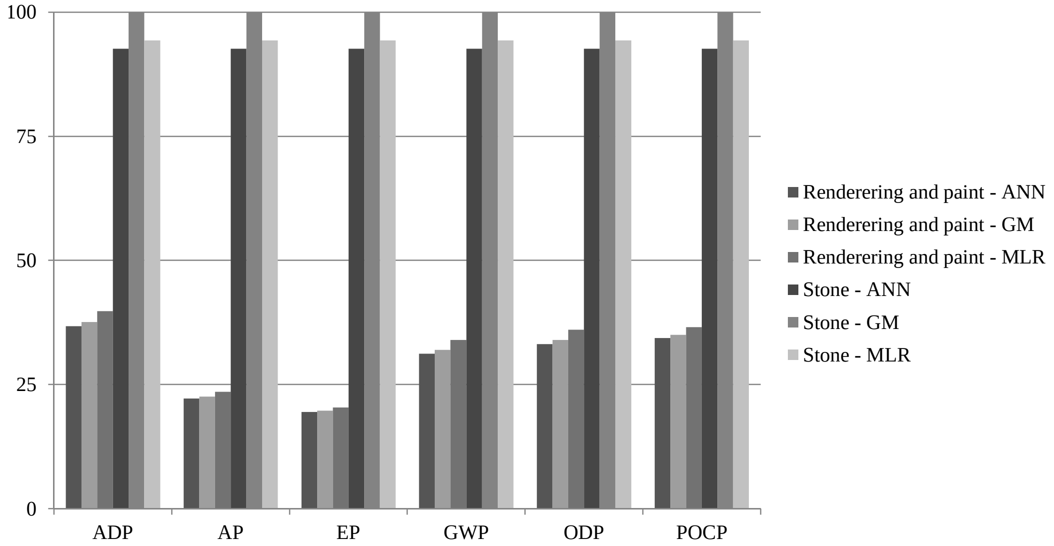

Figure 1 - LCA results (in relative percentage in each environmental category) of each alternative for cumulative stages “A1-A3 and B4” using the reference value of stochastic SLP

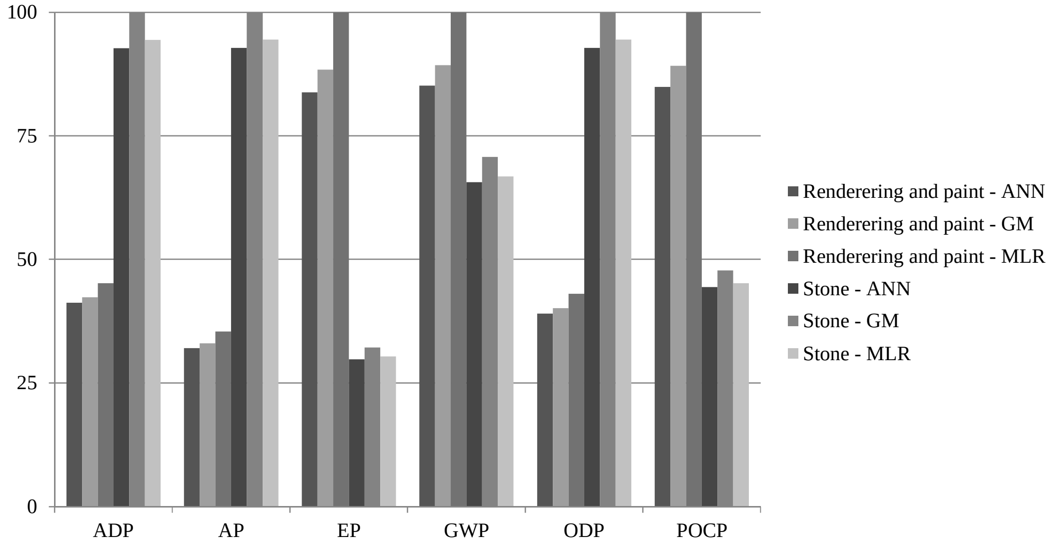

Figure 2 - LCA results (in relative percentage in each environmental category) of each alternative for cumulative stages “A1-A3, B4, C3-C4, and D” using the reference value of stochastic SL