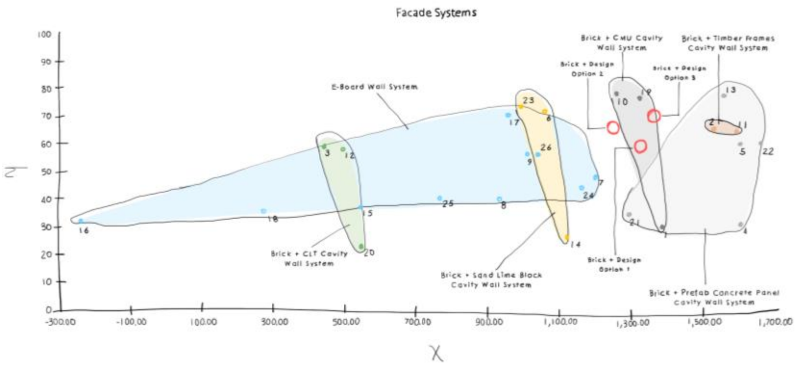
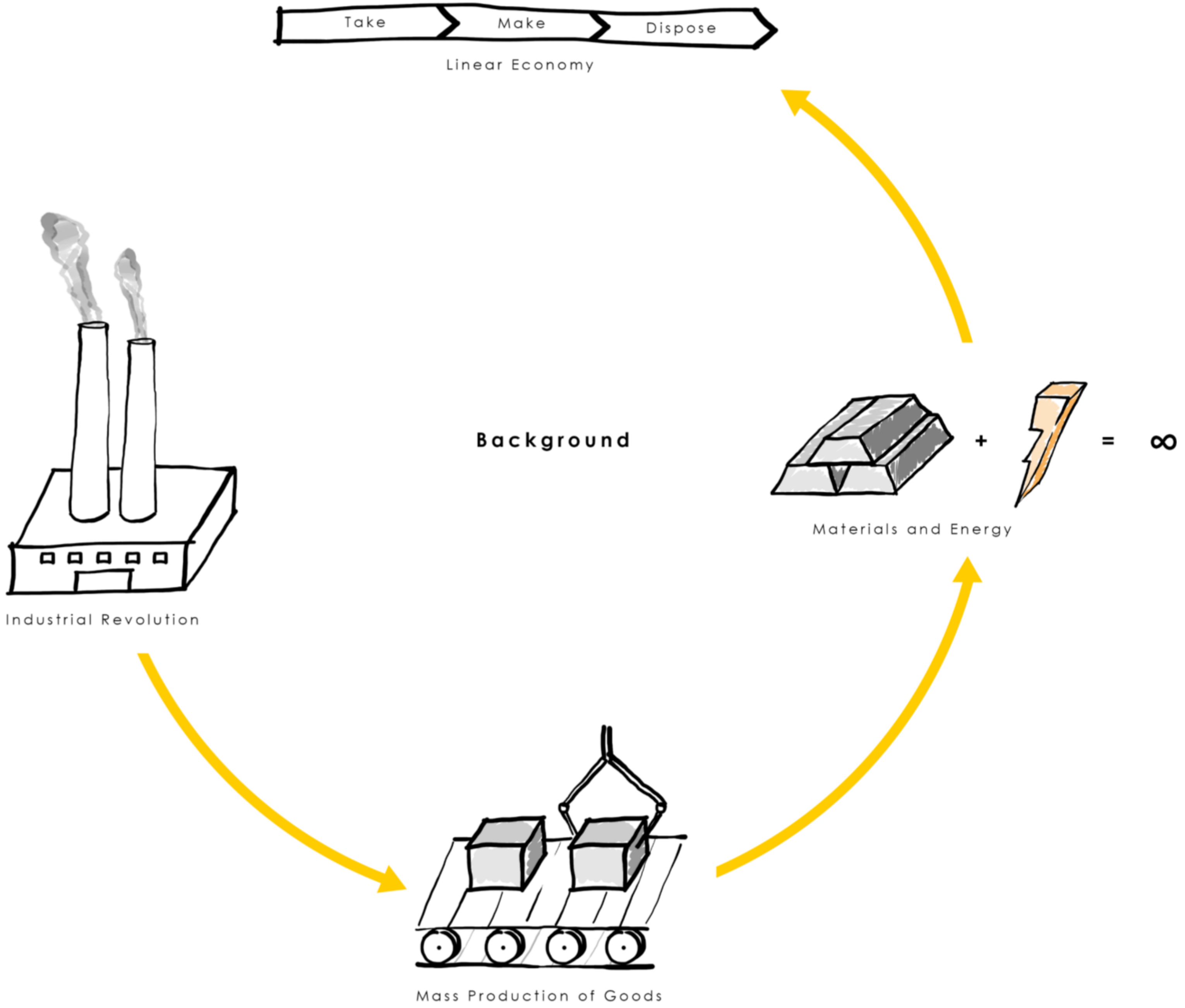
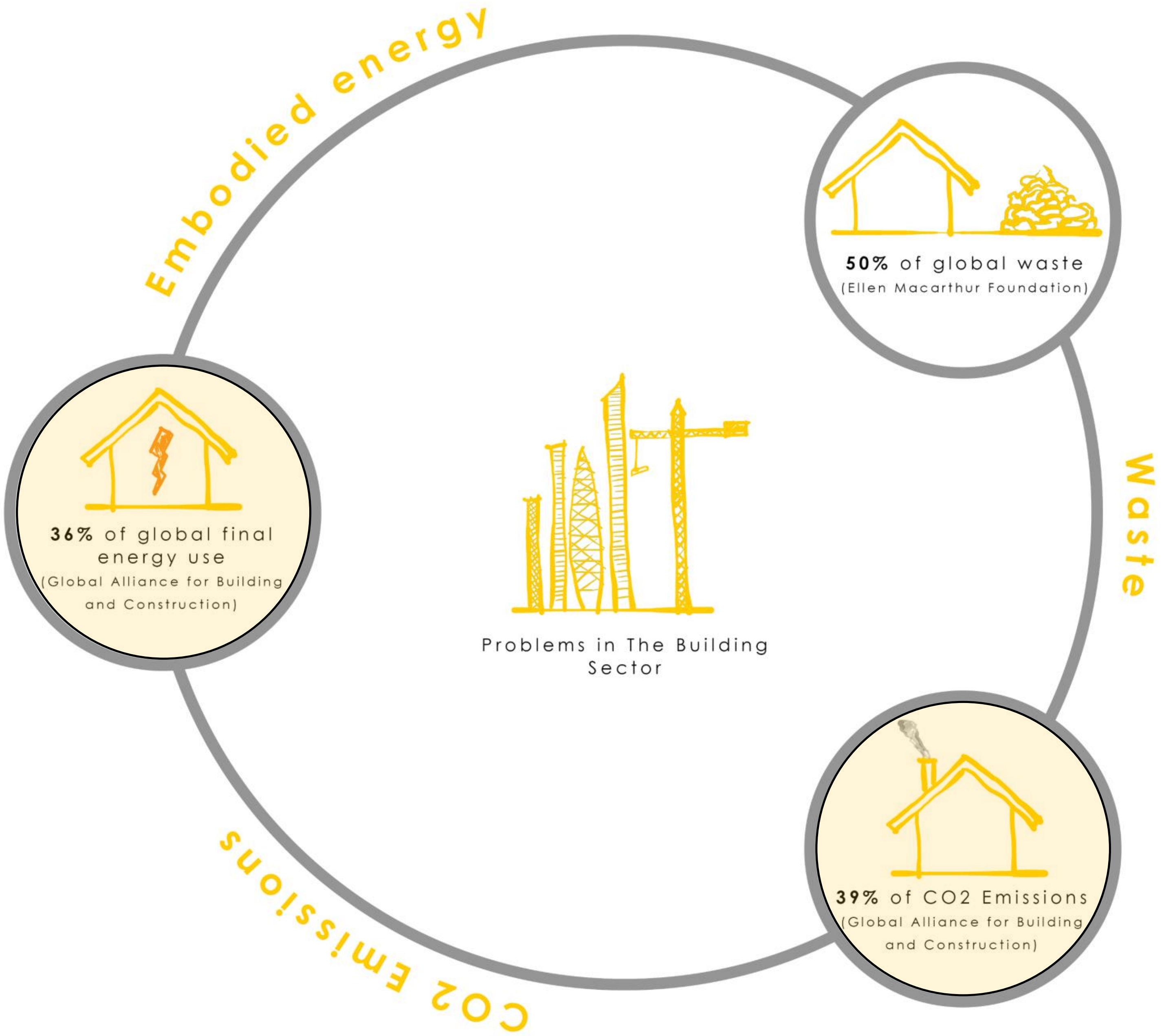


Redesign of a Facade System Based on an Environmental Impact Assessment Framework

Giancarlo Manzanares (4916352)
Arie Bergsma (First Mentor)
Fred Veer (Second Mentor)
Clara Garcia Sanchez (Delegate Board of Examiners)

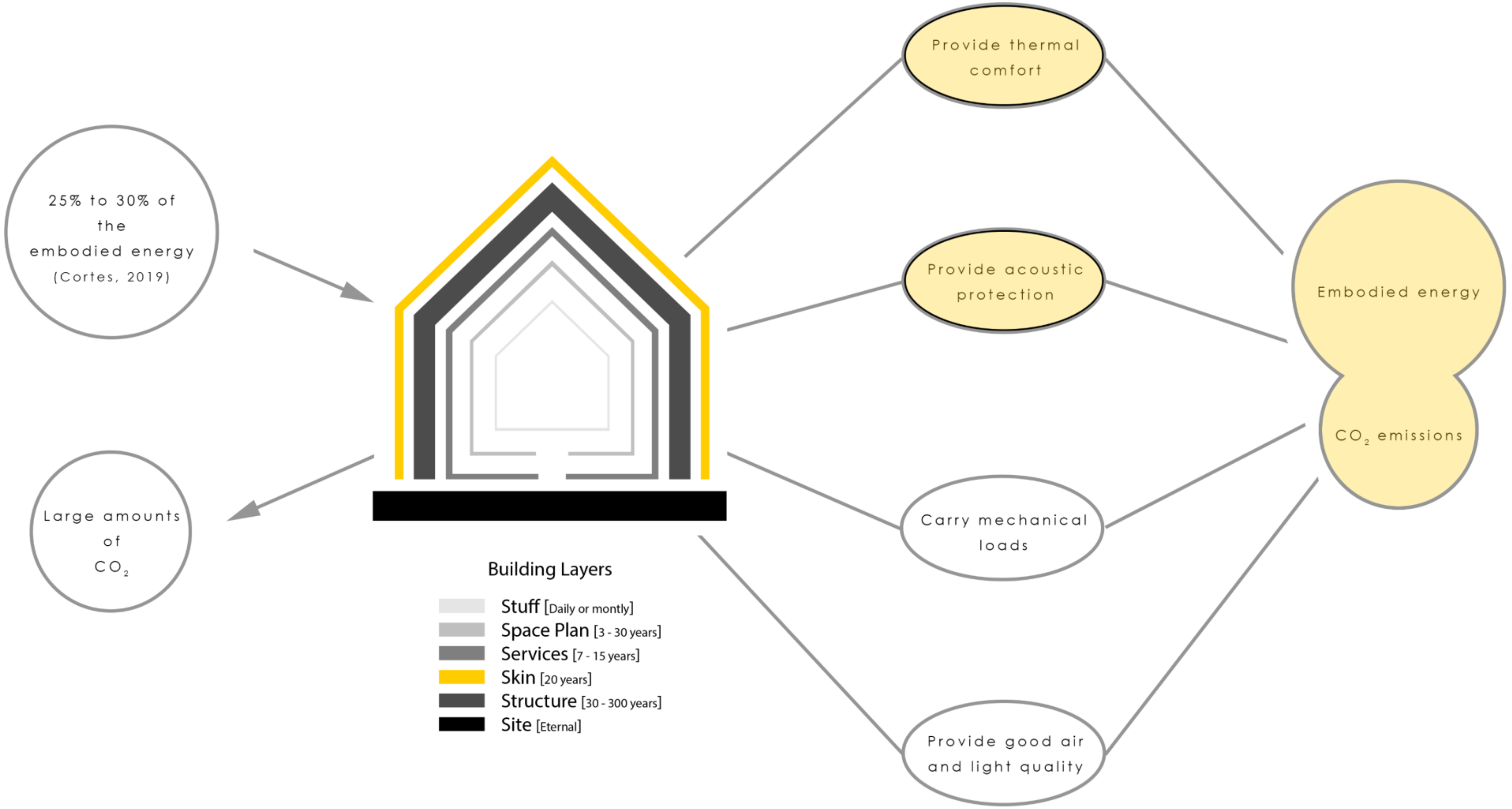
Background


Take
Make
Dispose
Linear Economy
Industrial Revolution
Mass Production of Goods
Materials and Energy
+
=
∞



Embodied energy
Waste
CO2 Emissions
50% of global waste
(Ellen Macarthur Foundation)
36% of global final energy use
(Global Alliance for Building and Construction)
Problems in The Building Sector
39% of CO2 Emissions
(Global Alliance for Building and Construction)

Focus at Façade Level



Main Objective

The development of a framework that can evaluate facade systems regarding their environmental impact, acoustic and thermal performance, and used as an optimization tool for designing an environmentally friendly facade.

Sub-Objectives

S-O1) Identify which facade system predominates in the Netherlands Today.

S-O2) Analyze the identified facade systems in terms of acoustic and thermal performance, and environmental impact.

S-O3) Provide the evaluation criteria to rate and select potential facade systems to be improved in terms of environmental impact.

S-O4) Define the design requirements to decrease the environmental impact of a facade.

Main Research Question

How can a facade system be design or optimized in the most environmentally friendly way without reducing the acoustic and thermal performance?

S-Q1) How can environmental impact, acoustic and thermal performance be related?

S-Q2) How can a facade system be addressed in terms of environmental impact and performance?

S.Q3) How can a framework be provided to identify the opportunities to design or optimize a facade system in order to reduce the environmental impact.

Methodology

Literature Research and Review

- Environmental Impact Assessment Methods
- Façade systems in the Netherlands Today
- Building and Product Examples

Evaluation Framework Development

- Façade System Assessment Strategy
- Thermal Performance vs Environmental Impact
- Acoustic Performance vs Environmental Impact
- Identifying the Most Critical Façade System

Design Option Proposals

- Design Optimization Strategy
- Material Optimization to reduce the environmental impact without decreasing the thermal or acoustic insulation.
- Shape Optimization to reduce the environmental impact without decreasing the thermal or acoustic insulation.
- Comparison Among the Design Options

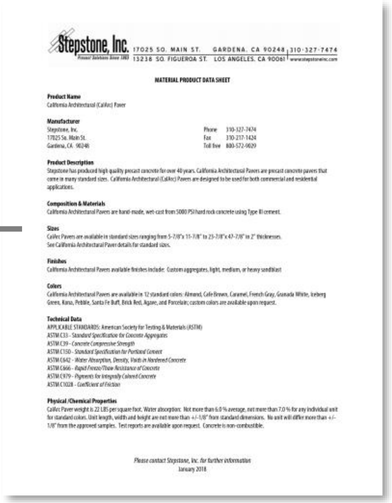
Conclusion and Further Research

- Conclusion
- Further Research

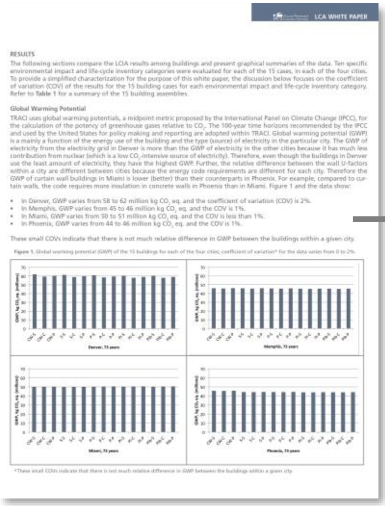
Environmental Impact Assessment Methods

Product Data Sheet (PDS)

Self-reported information about a product, provided by the manufacturer.


Stepstone, Inc.

MATERIAL PRODUCT DATA SHEET

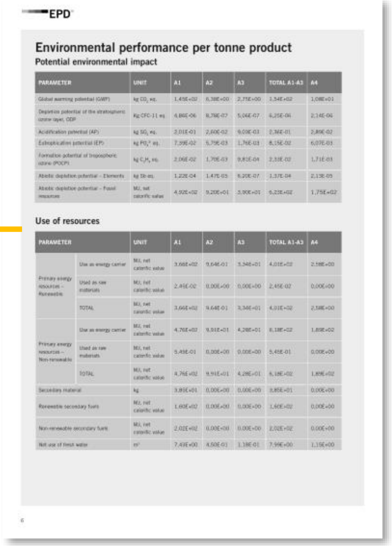

LCA WHITE PAPER

RESULTS

Global Warming Potential

Life - Cycle Assessment (LCA)

Most extensive form of environmental assessment, but expensive and hard to interpret by a designer.


EPD

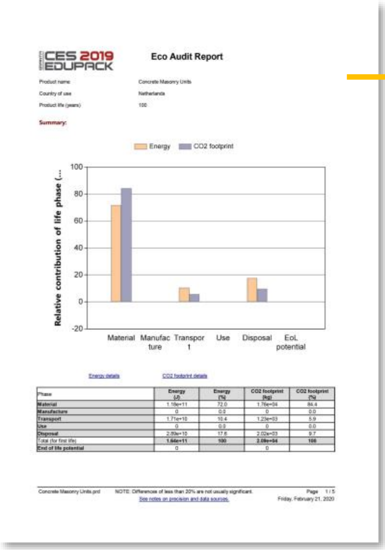
Environmental performance per tonne product

Potential environmental impact

Use of resources

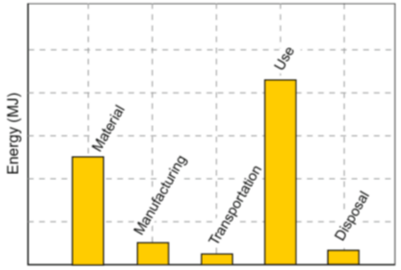
Environemntal Product Declaration (EPD)

- Shorter version of an LCA
- Contains numerical data on the environmental impact of products:
  - Embodied energy
  - Carbon footprint
  - Fresh water cons.
  - Ozone Layer dep.
  - Others



Eco - Audit (Tool)

- Adopts simple metrics of environmental stress: **Embodied energy** and **CO_2 emissions**.
- Distinguish the phase of life of most concern.



Façade Systems in the Netherlands Today

Panel Systems
- Brick + Prefab Concrete Cavity Wall
- Brick + CLT Cavity Wall

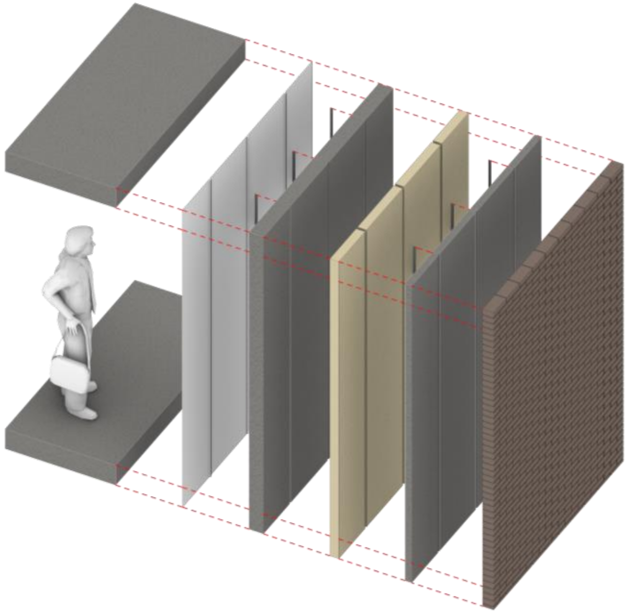
Frame Systems
- Brick + Timber Frames Cavity Wall

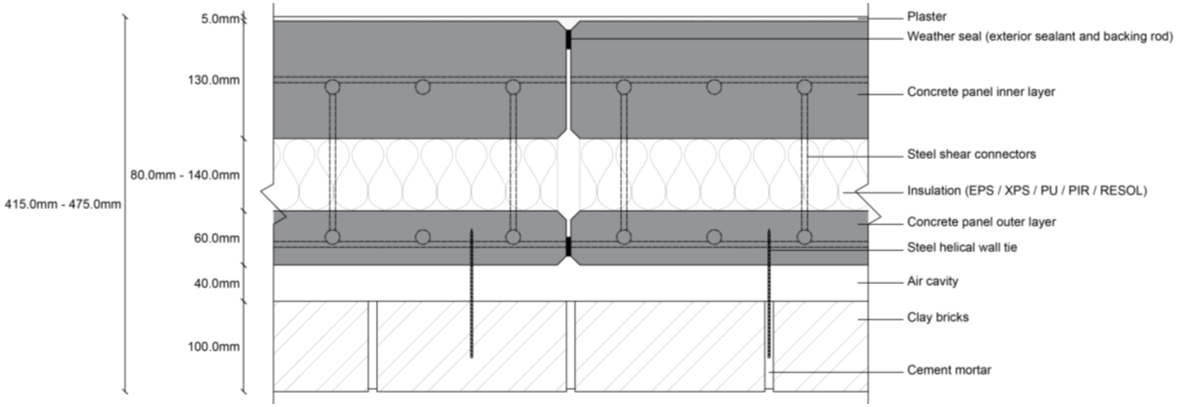
Masonry Systems
- Brick + Sand Lime Block Cavity Wall
- Brick + CMU Cavity Wall

Board Systems
- E-board + Prefab Concrete Wall
- E-board + CLT Wall
- E-board + Sand Lime Block Wall
- E-board + CMU Wall
- E-board + Timber Frames Wall

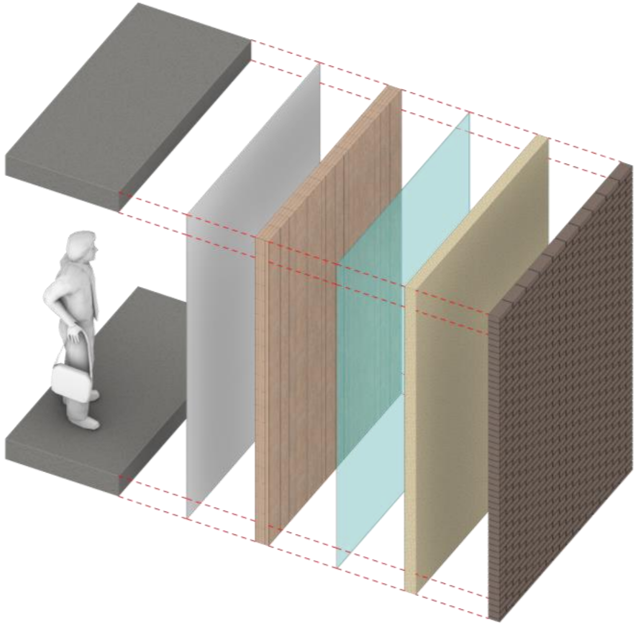
Panel Systems

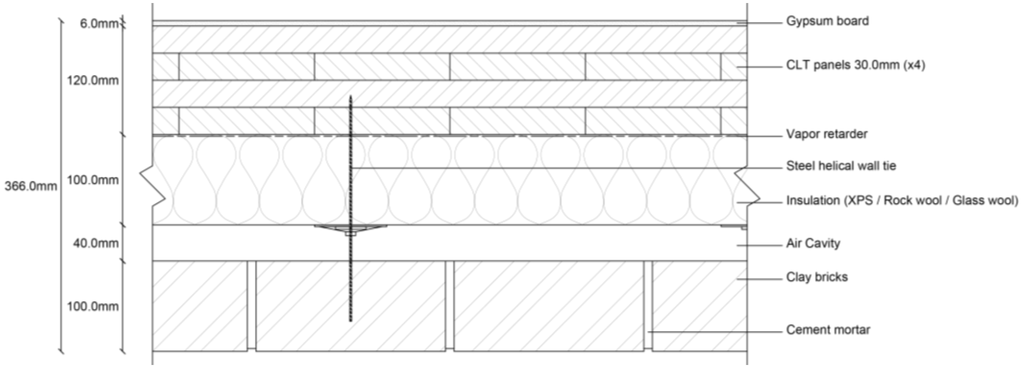
Brick + Prefab Concrete Cavity Wall





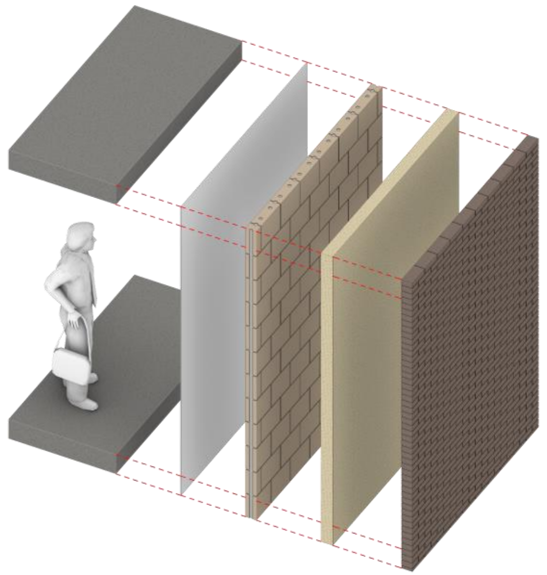
Brick + CLT Cavity Wall

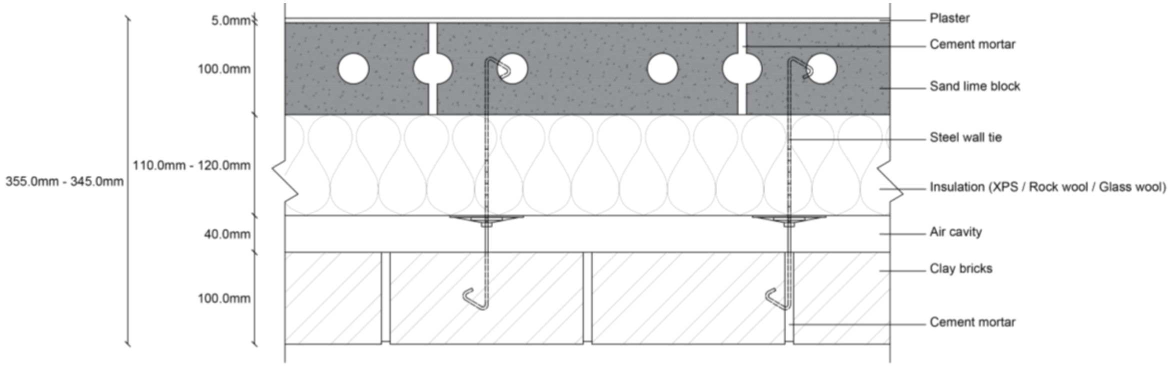




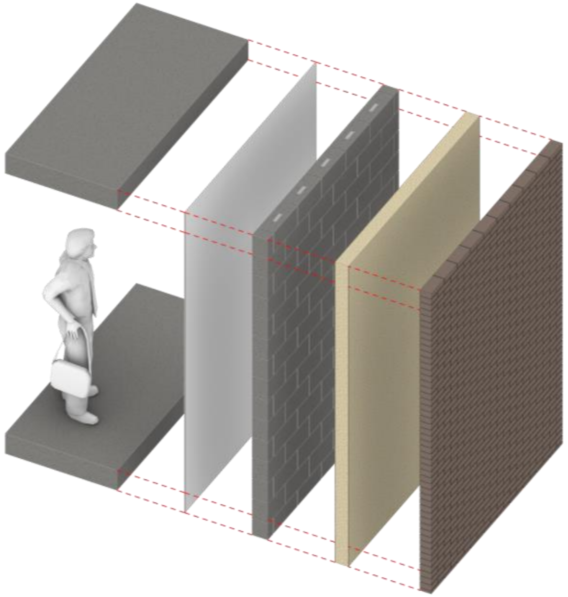
Masonry Systems

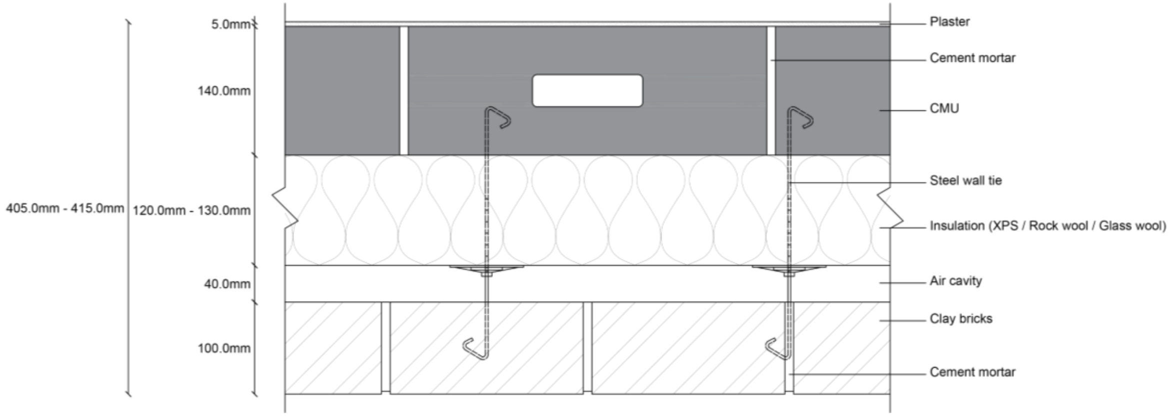
Brick + Sand Lime Block Cavity Wall





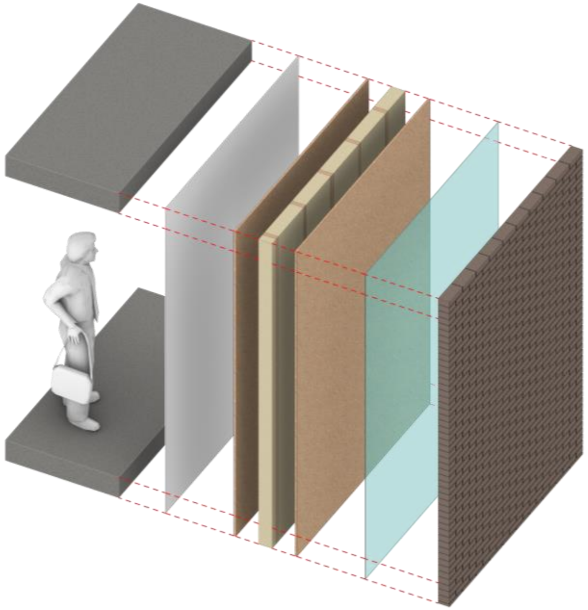
Brick + CMU Cavity Wall

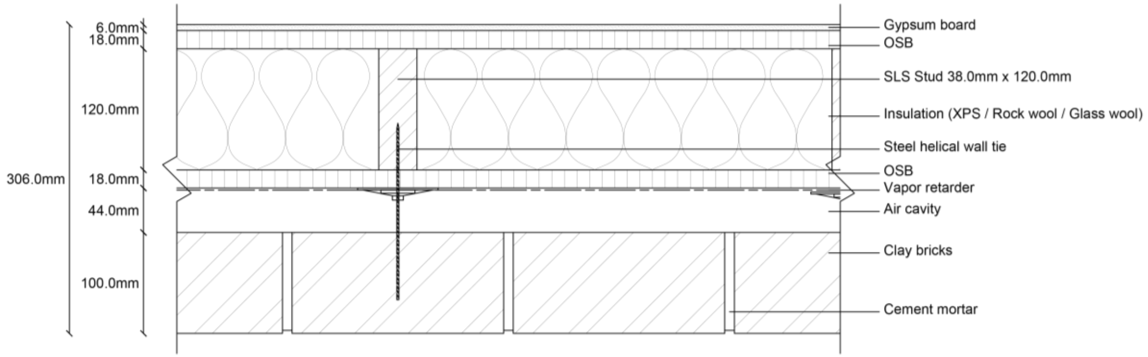




Frame Systems

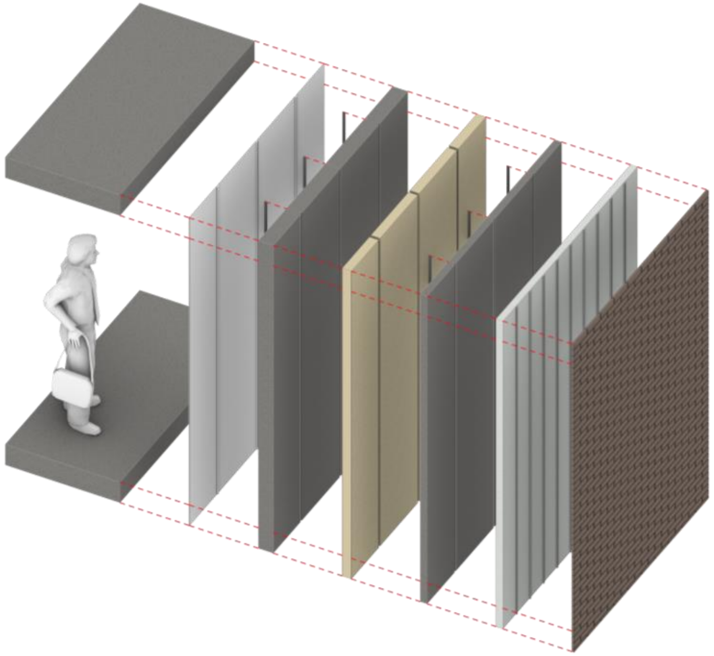
Brick + Timber Frames
Cavity Wall

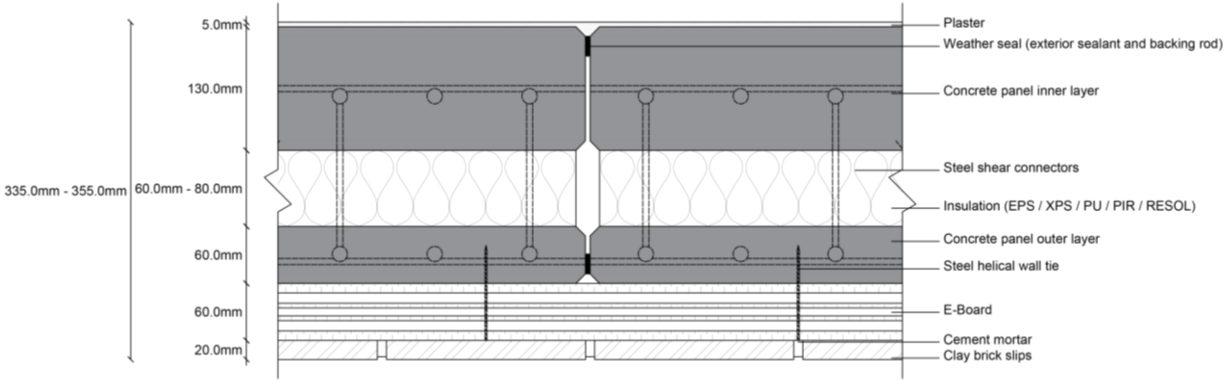




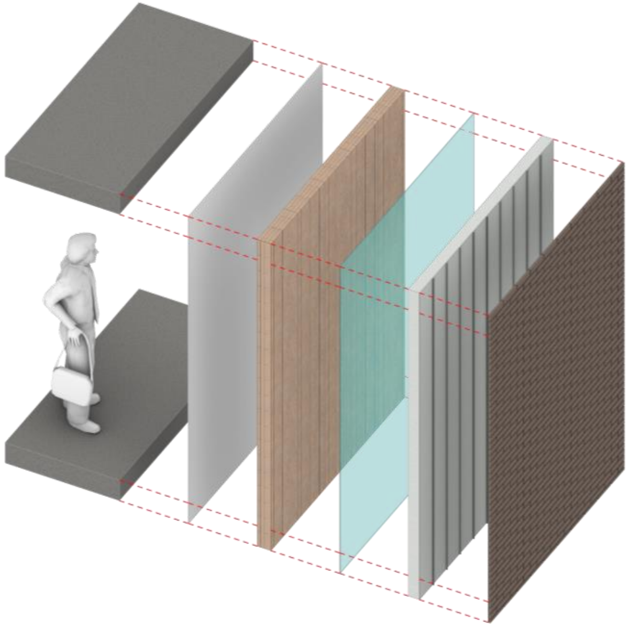
Board Systems

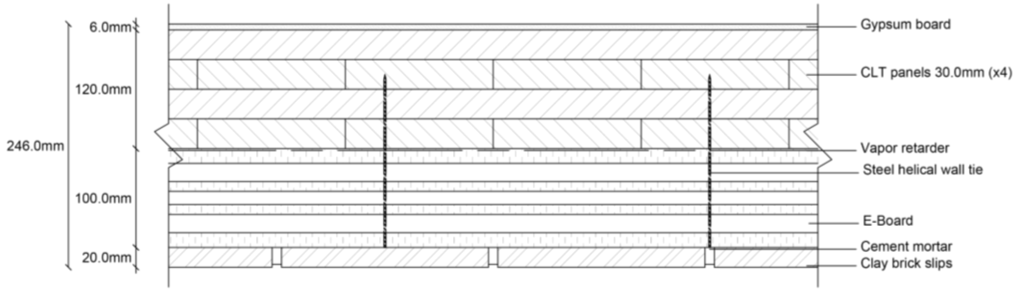
E-Board + Prefab Concrete Wall





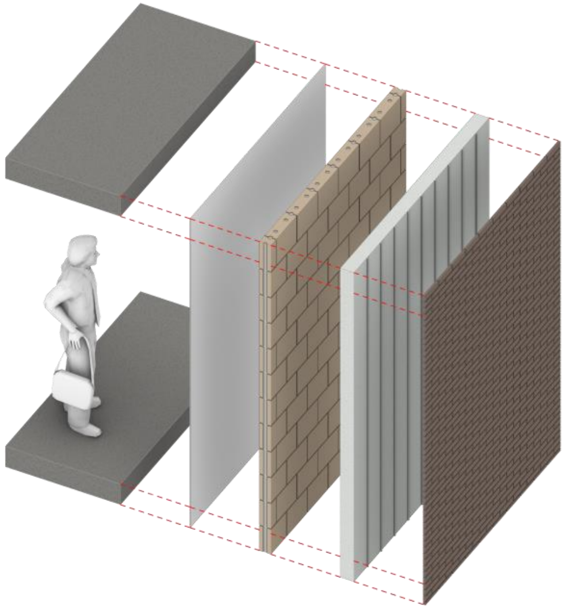
E-Board + CLT Wall

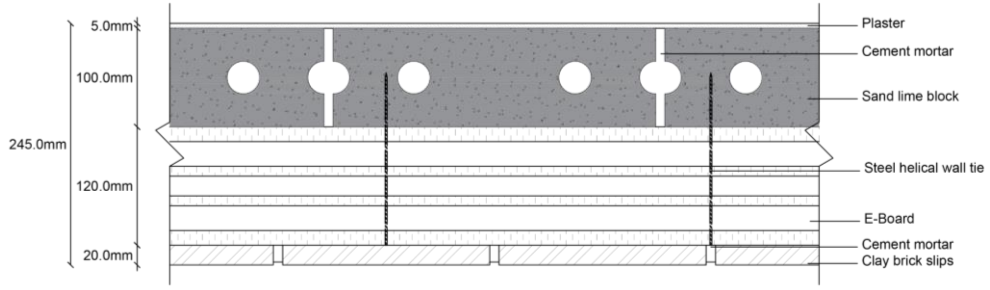




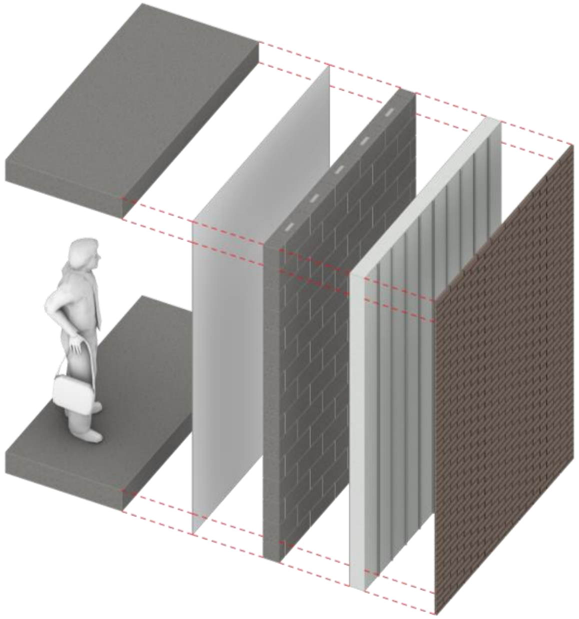
Board Systems

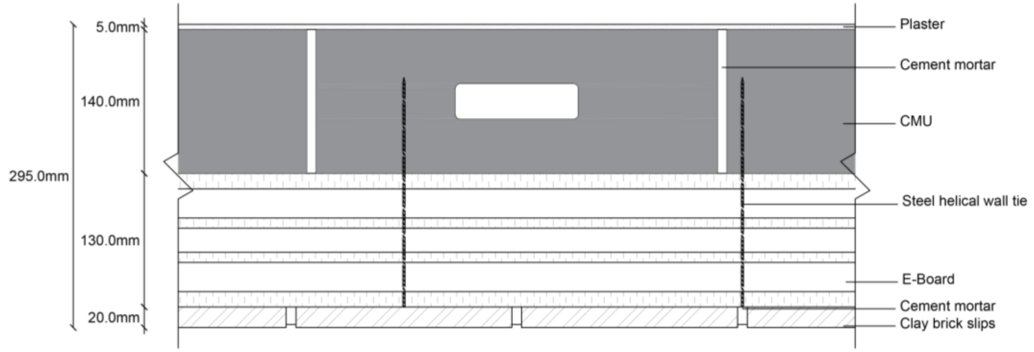
E-Board + Sand Lime Block Wall





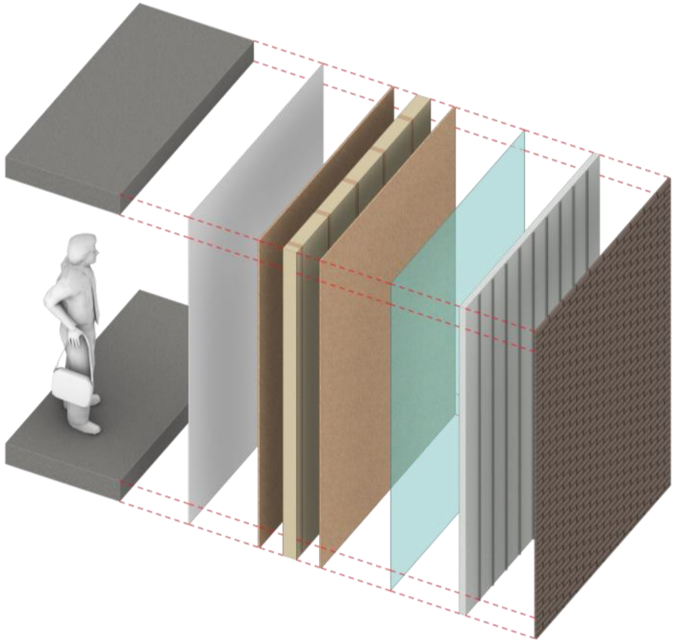
E-Board + CMU Wall

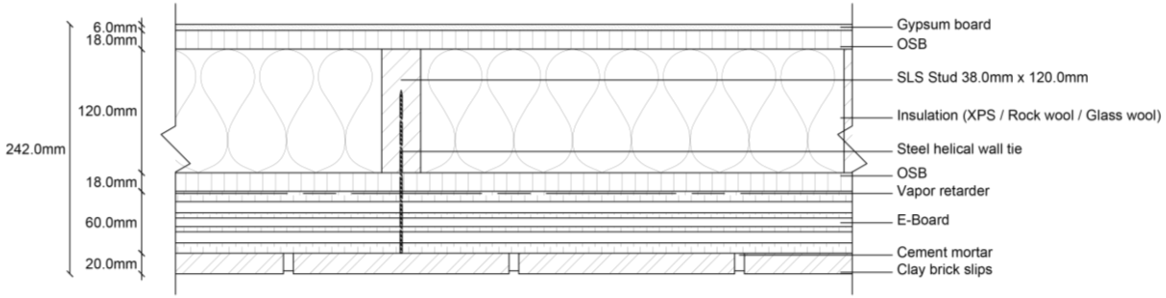




Board Systems

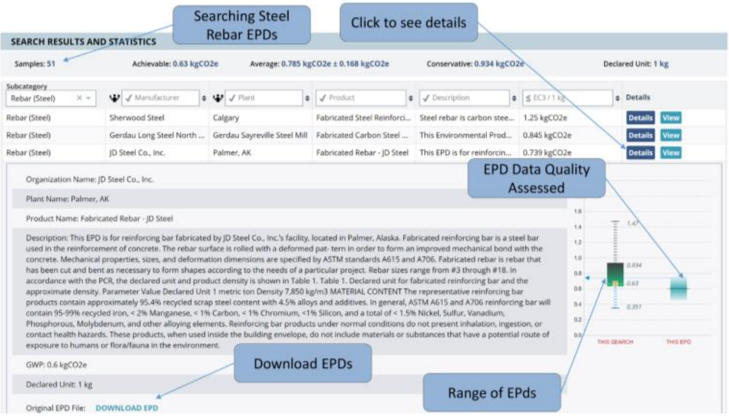
E-Board + Timber Frames Wall





Building and Product Examples

1) EC3



- Free digital calculator
- Embodied carbon in a construction
- Gathers data from EPD´s

2) Canada's Earth Tower

- Facades and columns made of timber
- Reduced green house effects
- Lightweight materials (less environmental impact)

3) The K-briq

- 90% waste materials
- Reduced manufacturing energy and CO_2 emissions
- Improved thermal insulation

Façade Systems Assessment Strategy

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Clay Brick	85	100	1.05E-03	2,000	2.10	178.50	3.66	0.29	7,320.00	574	653.31	51.23	CES (Eco-Audit)
Clay Brick (Slip)	85	20	2.10E-04	2,000	0.42	35.70	3.66	0.29	7,320.00	574	130.66	10.25	CES (Eco-Audit)
CMU	12	140	1.08E-02	2,500	*21.00	252.00	1.48	0.17	3,700.00	422.5	478.74	54.67	CES (Eco-Audit)
Prefab Concrete Panels	1	100	1.00E-01	2,500	250.00	250.00	1.48	0.17	3,700.00	422.5	370.00	42.25	CES (Eco-Audit)
Sand Lime Block	12	100	7.85E-03	1,900	* 13.00	156.00	** 1.17	** 0.14	2,226.80	258.4	209.71	24.34	
E-Board (EPS)	1	100	1.00E-01	25	2.50	2.50	-25.52	1.88	-** 637.99	** 46.95	-63.80	4.70	
XPS	1	100	1.00E-01	34	3.37	3.37	61.12	4.72	2,059.81	158.92	**205.98	** 15.89	EXIBA, 2014
Rock Mineral Wool	1	100	1.00E-01	55	5.50	5.50	** 16.32	** 1.31	897.60	72.05	89.76	7.21	
Glass Mineral Wool	1	100	1.00E-01	56	5.60	5.60	26.47	1.28	** 1,482.20	** 71.70	148.22	7.17	Bre Global, 2015
EPS	1	100	1.00E-01	20	2.00	2.00	-31.90	2.35	-** 637.99	** 46.95	-63.80	4.70	
PU	1	100	1.00E-01	31	3.10	3.10	** 69.90	** 2.90	2,166.90	89.90	216.69	8.99	PU Europe, 2014
PIR	1	100	1.00E-01	32	3.20	3.20	110.08	5.29	3,522.50	169.38	** 352.25	** 16.94	
RESOL	1	100	1.00E-01	35	3.50	3.50	84.75	2.82	2,966.40	98.60	** 296.64	** 9.86	
Gypsum Plaster	1	5	5.00E-03	827	4.14	4.14	** 2.91	** 0.18	2,405.58	146.88	12.03	0.73	
Gypsum Board	1	6	6.00E-03	1,000	6.00	6.00	7.48	0.31	7,478.40	306.08	** 44.87	** 1.84	USG, 2019
OSB	1	18	1.80E-02	650	11.70	11.70	20.00	0.933	13,000.00	606.45	234.00	10.92	CES (Eco-Audit)
Vapour Retarder	1	2	2.00E-03	1,695	3.39	3.39	74.93	3.50	127,006.35	5,937.59	254.01	11.88	CES (Eco-Audit)
CLT Board	1	30	3.00E-02	471	14.13	14.13	-6.19	-0.63	-** 2,913.37	-** 298.41	-87.40	-8.95	

* The mass of some materials are directly obtained from the producer, therefore small variations are possible. These variations occur because some materials might have some irregularities in their shape and might not be completely solid.

** All these values are obtained from the producer´s Environmental Product Declaration (EPD) since they are products composed of many different materials, which composition is not always clearly specified.

→ Embodied energy and CO_2 emissions of façade system components

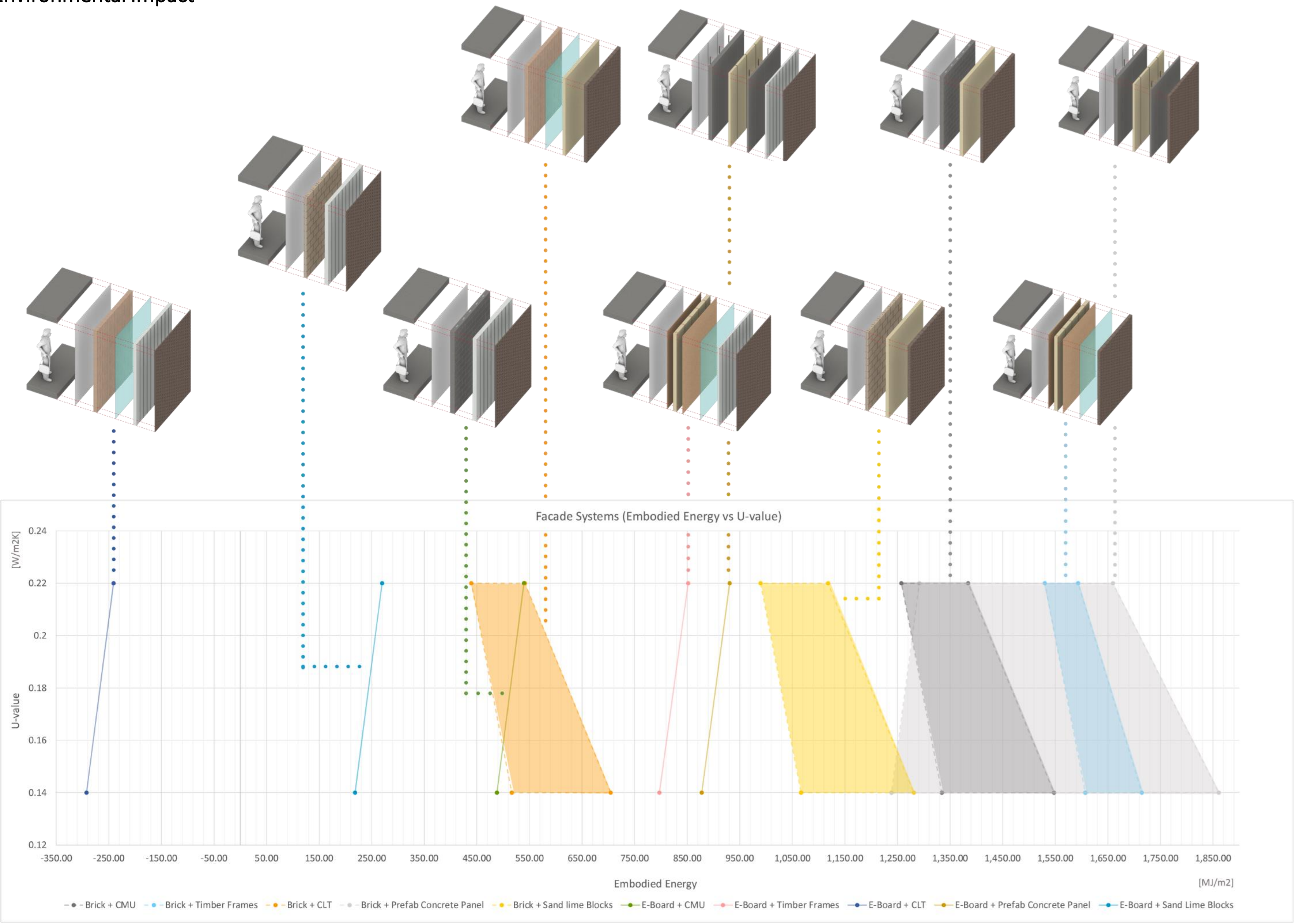
Thermal Insulation (Brick + Timber Frames)							
		d [mm]	Themal Conductivity [W/mK]	Rc [m2K/W]	U-value [W/m2K]	Energy [MJ/m2]	CO2 [kg/m2]
1	Re	-	-	0.04		-	-
2	Clay Bricks	100	0.55	0.18		653.31	51.23
3	Air Cavity	40	-	0.17		-	-
4	OSB	18	0.13	0.14		230.40	10.75
5	Rock Mineral Wool	120	0.033	3.64		107.71	8.65
6	Vapor Barrier	2	0.26	0.01		190.46	7.23
7	OSB	18	0.13	0.14		230.40	10.75
8	Gypsum Board	6	0.19	0.03		44.87	1.84
9	Ri	-	-	0.13		-	-
	Total	-	-	4.47	0.22	1,457.15	90.44

→ Embodied energy and CO_2 emissions of façade system and their components based on required U-value

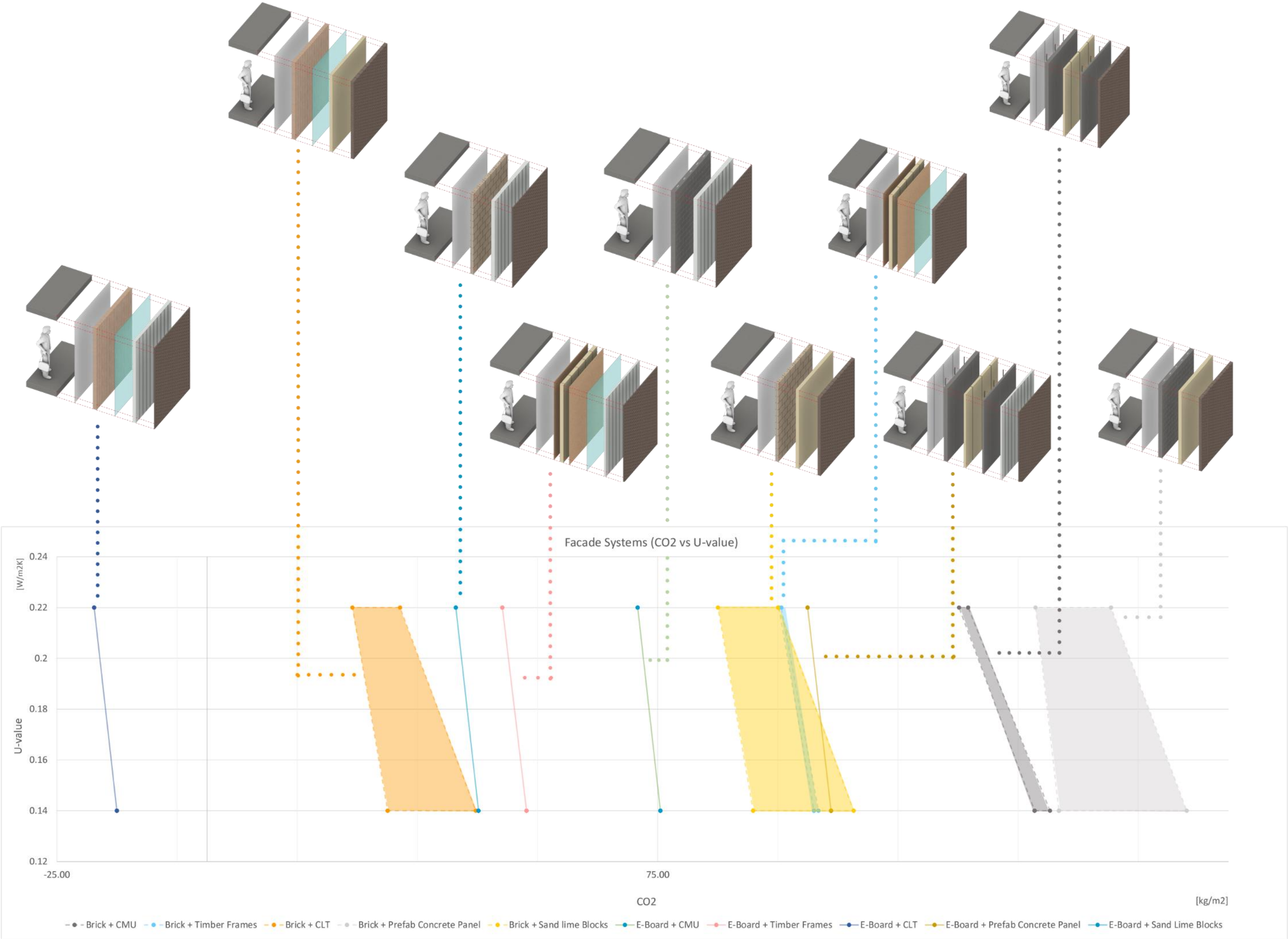
Thermal Insulation (Brick + Timber Frames)													
		d [mm]	Density [kg/m3]	m_1 [kg/m2]	m_2 [kg/m2]	m_3 [kg/m2]	m_4 [kg/m2]	m_5 [kg/m2]	m_6 [kg/m2]	f_{ms} [Hz]	R_θ [dB]	Energy [MJ/m2]	CO2 [kg/m2]
1	Clay Bricks	100	2000	200.00								653.31	51.23
2	Air Cavity	40	-	-	-	-	-	-	-			-	-
4	OSB	18	640		11.52							230.40	10.75
5	XPS	100	33.7			3.37						205.98	15.89
	Vapor Retarder	2	1070.00				2.14					190.46	7.23
6	OSB	18	640					11.52				230.40	10.75
7	Gypsum Board	6	1000						6.00			44.87	1.84
	Total	-	-							109.67	109.60	1,555.42	97.69

→ Embodied energy and CO_2 emissions of façade system and their components based on required airborne sound insulation

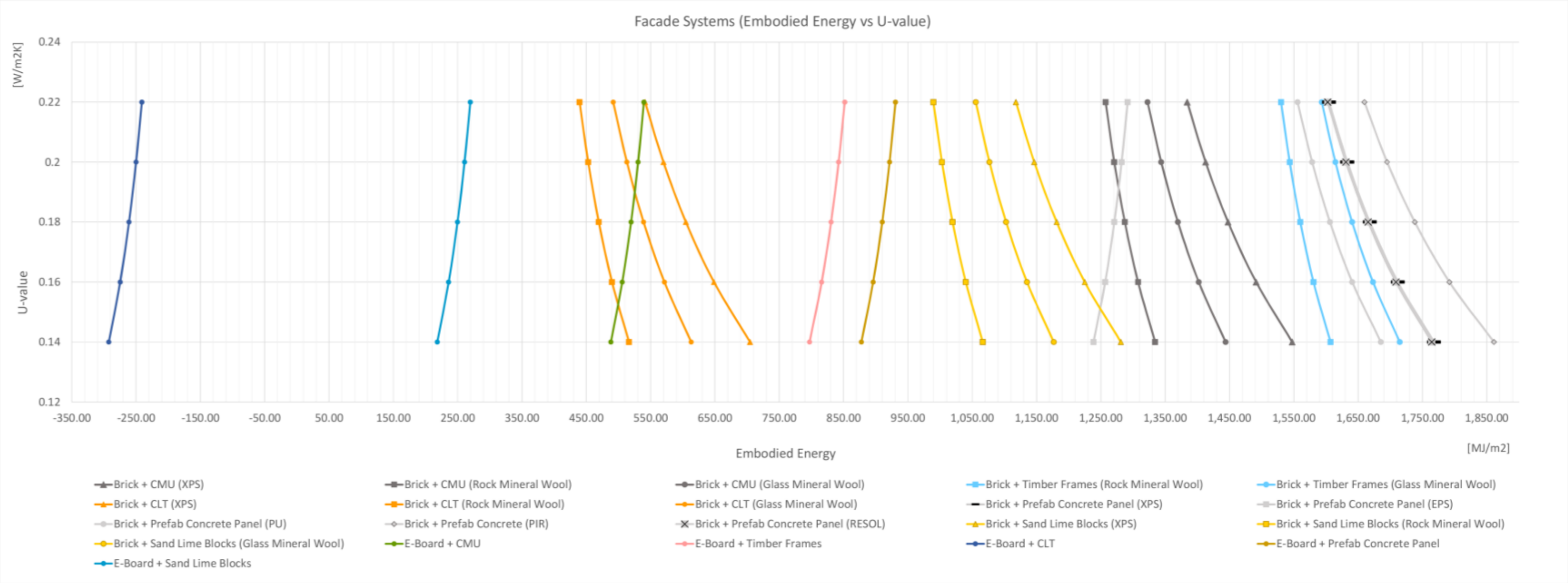
Thermal Performance vs Environmental impact

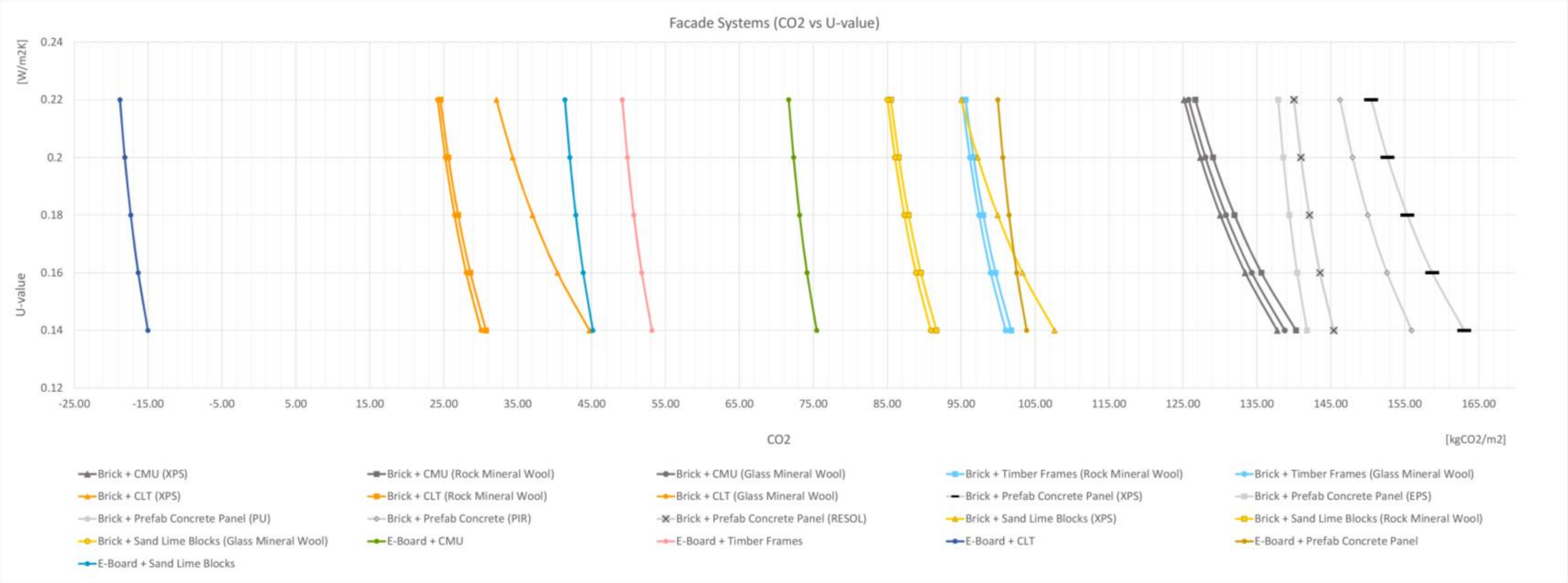


Thermal Performance vs Environmental impact



Thermal Performance vs Environmental impact

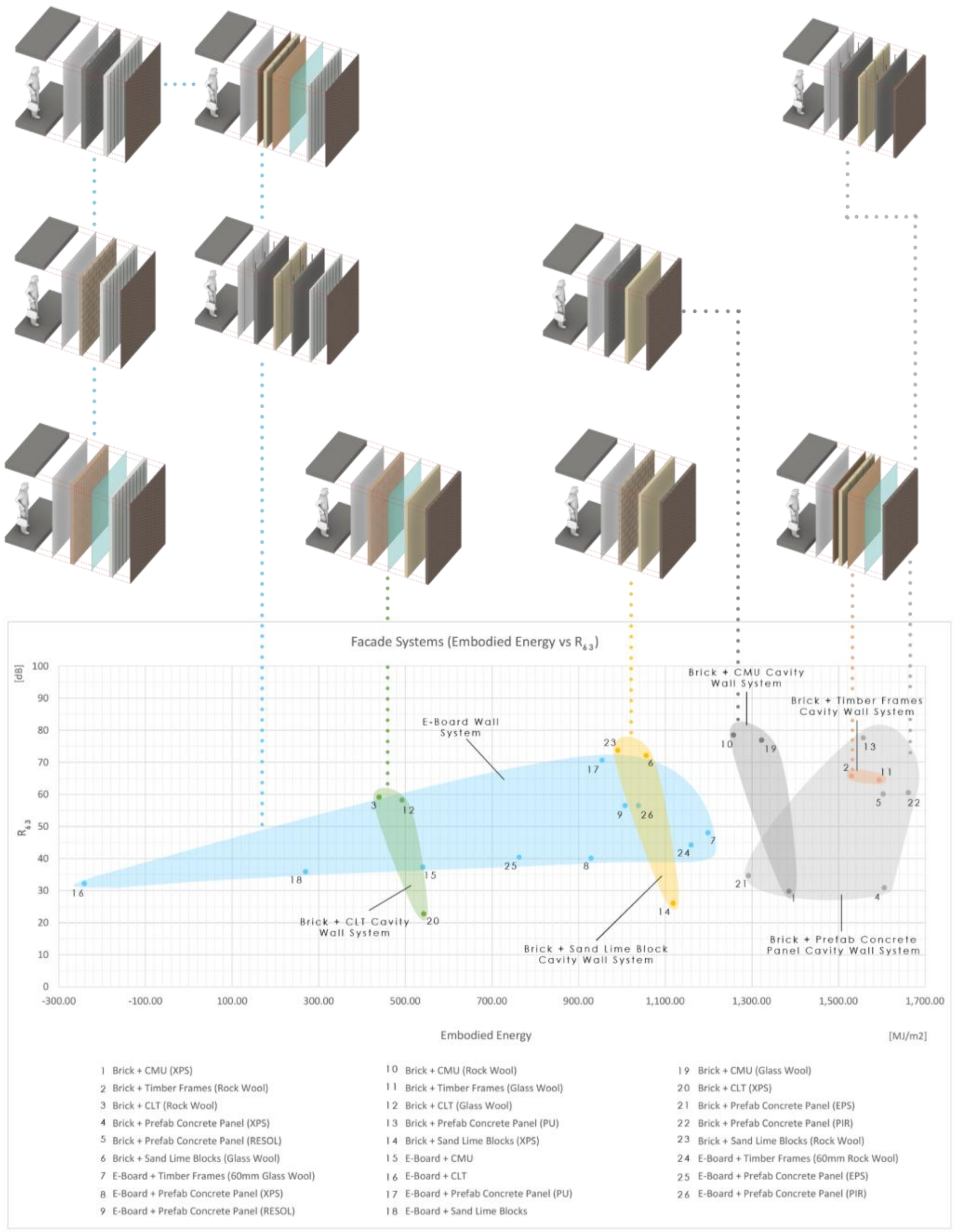


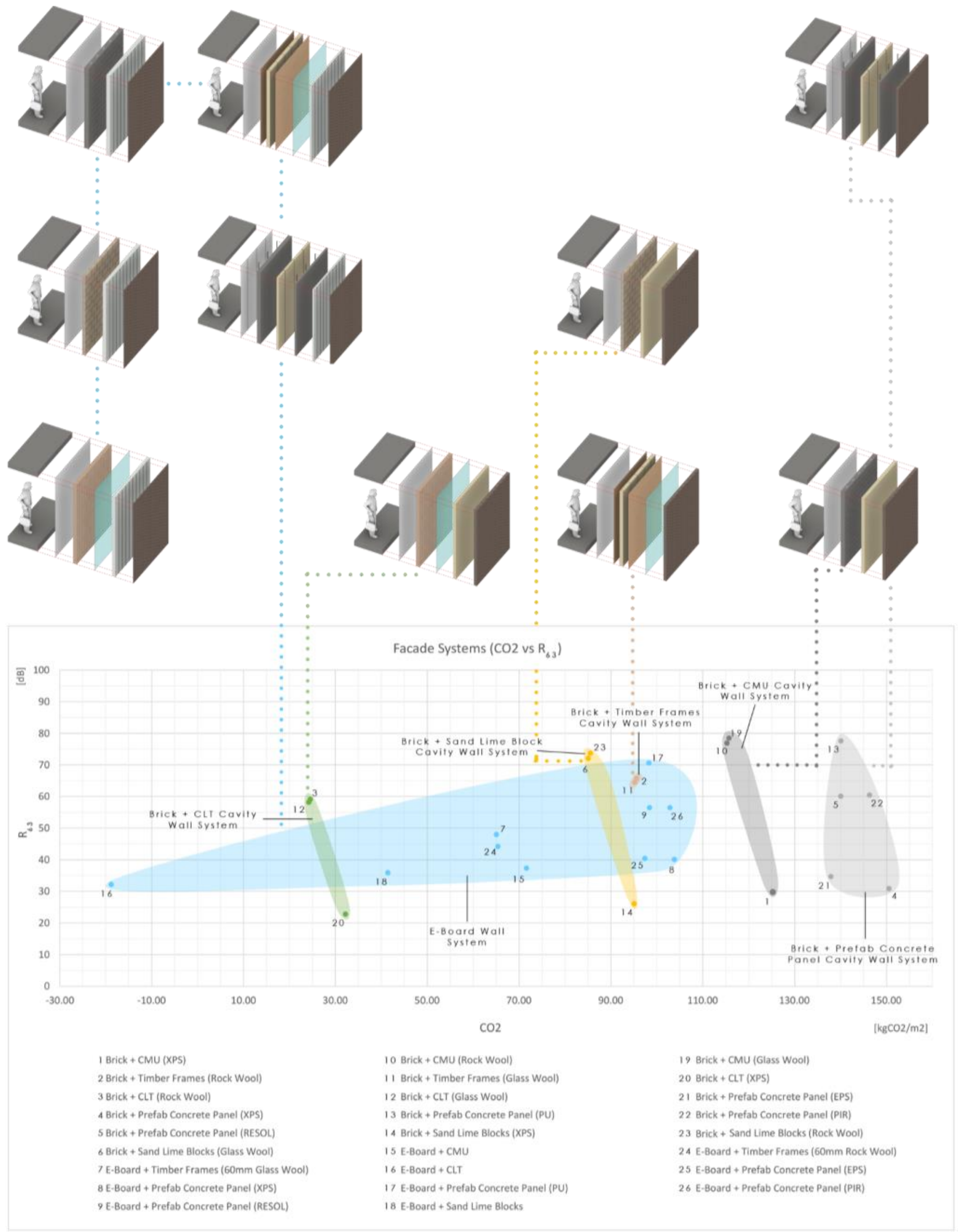


Airborne Sound Insulation of Façade Systems for U-value = 0.22 W/m2K

Facade Systems [dB]		Frequency [Hz]						
		63	125	250	500	1k	2k	4k
Panel Systems	Brick + Prefab Concrete Panel Cavity Wall (EPS)	34.7	41.2	54.5	81.1	132.0	164.5	111.6
	Brick + Prefab Concrete Panel Cavity Wall (XPS)	30.9	38.8	50.8	74.5	127.8	164.4	101.8
	Brick + Prefab Concrete Panel Cavity Wall (PU)	77.6	106.0	130.0	188.7	197.0	197.0	197.0
	Brick + Prefab Concrete Panel Cavity Wall (PIR)	60.5	80.9	97.6	144.5	196.8	197.0	197.0
	Brick + Prefab Concrete Panel Cavity Wall (RESOL)	60.1	80.5	97.2	143.9	196.7	197.0	197.0
	Brick + CLT Cavity Wall (XPS)	22.8	36.6	45.5	59.9	95.5	83.4	105.0
	Brick + CLT Cavity Wall (Rock Wool)	59.1	84.6	123.6	167.0	196.9	197.0	197.0
	Brick + CLT Cavity Wall (Glass Wool)	58.2	83.2	121.7	164.3	196.9	197.0	197.0
Masonry Systems	Brick + Sand Lime Block Cavity Wall (XPS)	26.1	35.4	44.8	57.3	94.9	84.1	103.0
	Brick + Sand Lime Block Cavity Wall (Rock Wool)	73.7	107.4	136.4	187.7	197.0	197.0	197.0
	Brick + Sand Lime Block Cavity Wall (Glass Wool)	72.1	105.2	133.3	183.8	197.0	197.0	197.0
	Brick + CMU (XPS)	29.8	38.4	49.3	66.5	103.0	89.0	106.8
	Brick + CMU (Rock Wool)	78.5	110.7	141.1	193.2	197.0	197.0	197.0
	Brick + CMU (Glass Wool)	76.9	108.5	138.1	190.1	197.0	197.0	197.0
Frame Systems	Brick + Timber Frames Cavity Wall (Rock Wool)	65.7	89.6	122.2	149.8	196.3	197.0	197.0
	Brick + Timber Frames Cavity Wall (Glass Wool)	64.5	87.9	119.8	150.2	195.3	197.0	197.0
Board Systems	E-Board + Prefab Concrete Panel Wall (EPS)	40.4	42.1	44.9	58.6	88.5	116.8	135.7
	E-Board + Prefab Concrete Panel Wall (XPS)	40.1	42.0	41.8	51.9	80.4	114.0	130.0
	E-Board + Prefab Concrete Panel Wall (PU)	70.6	94.6	113.4	150.2	183.9	197.0	197.0
	E-Board + Prefab Concrete Panel Wall (PIR)	56.5	75.8	90.2	119	143.6	188.5	197.0
	E-Board + Prefab Concrete Panel Wall (RESOL)	56.5	76.4	91.2	120.9	144.3	189.4	197.0
	E-Board + CLT Wall	32.2	32.9	36.3	45.3	64.7	79.1	72.2
	E-Board + Sand Lime Block Wall	35.9	35.7	39.2	52.7	71.8	87.1	99.4
	E-Board + CMU Wall	37.3	37.0	42.8	57.0	76.0	91.5	102.9
	E-Board + Timber Frames Wall (Rock Wool)	44.2	54.2	75.6	103.7	127.3	167.0	197.0
	E-Board + Timber Frames Wall (Glass Wool)	48.0	62	84.4	104.9	139.7	179.4	197.0

Acoustic Performance vs Environmental impact





Durability Assessment

Durability of Facade Components (By Mass)

Function	Material	Expected Technical Lifetime [Years]	Density [kg/m3]	Embodied Energy per Technical Lifetime [MJ/kg]	Carbon Footprint per Technical Lifetime [kgCO2/kg]	Embodied Energy per year [MJ/kg]	Carbon Footprint per year [kgCO2/kg]
Facade Inner Leaf	Concrete	100	2,500	1.48	0.169	0.015	0.0017
	Clay Brick	100	2,000	3.66	0.287	0.037	0.0029
	Sand-Lime Block	100	1,900	1.17	0.136	0.01	0.0014
	CLT (Timber)	75	471	-6.19	-0.634	-0.08	-0.0084
	OSB (Timber)	75	650	20.00	0.933	0.27	0.012
Facade Vapour Retarder	Polyamide 66 (Nylon)	75	1,695	74.93	3.503	1.00	0.047
Facade Insulation	Rock Mineral Wool	75	55	16.32	1.31	0.22	0.017
	Glass Mineral Wool	75	56	26.47	1.28	0.35	0.017
	EPS	75	20	-31.90	2.35	-0.43	0.031
	XPS	75	34	61.12	4.72	0.81	0.063
	PU	75	31	69.90	2.90	0.93	0.039
	PIR	75	32	110.08	5.29	1.47	0.071
	Resol	75	35	84.75	2.82	1.13	0.038
Facade Outer Leaf	Clay Brick	100	2,000	3.66	0.287	0.037	0.0029

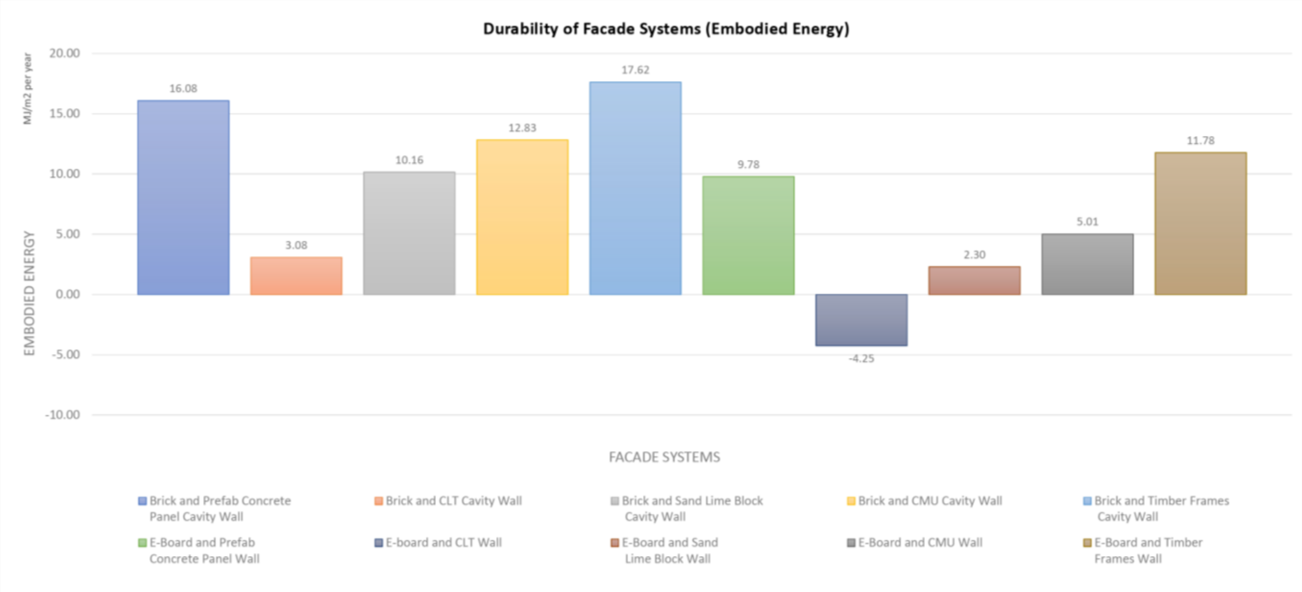
Durability of Facade Components (By Volume)

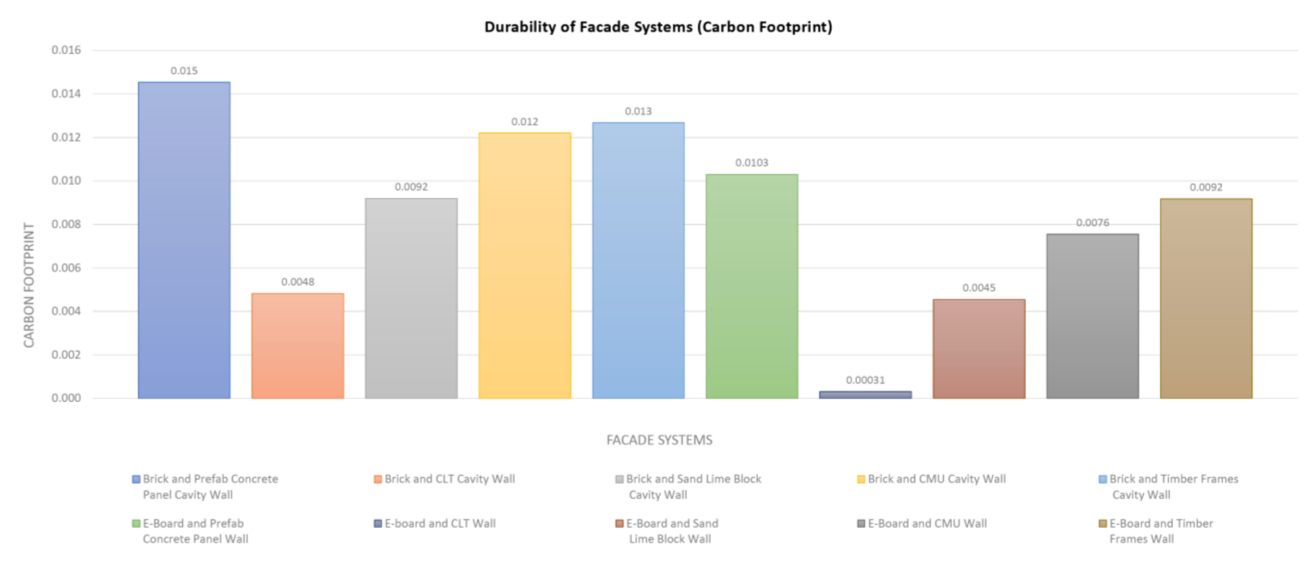
Function	Material	Expected Technical Lifetime [Years]	Density [kg/m3]	Embodied Energy per Technical Lifetime [MJ/m3]	Carbon Footprint per Technical Lifetime [kgCO2/m3]	Embodied Energy per year [MJ/m3]	Carbon Footprint per year [kgCO2/m3]
Facade Inner Leaf	Concrete	100	2,500	3,700.00	4.225	37	0.042
	Clay Brick	100	2,000	7,320.00	5.740	73.2	0.057
	Sand-Lime Block	100	1,900	2,226.80	2.584	22.27	0.026
	CLT (Timber)	75	471	-2,913.37	-3.979	-38.84	-0.053
	OSB (Timber)	75	650	13,000.00	8.086	173.33	0.108
Facade Vapour Retarder	Polyamide 66 (Nylon)	75	1,695	127,006.35	79.168	1,693.42	1.056
Facade Insulation	Rock Mineral Wool	75	55	897.60	0.96	11.97	0.013
	Glass Mineral Wool	75	56	1,482.20	0.96	19.76	0.013
	EPS	75	20	-637.99	0.63	-8.51	0.0083
	XPS	75	34	2,059.81	2.12	27.46	0.028
	PU	75	31	2,166.90	1.20	28.89	0.016
	PIR	75	32	3,522.50	2.26	46.97	0.030
	Resol	75	35	2,966.40	1.31	39.55	0.018
Facade Outer Leaf	Clay Brick	100	2,000	7,320.00	5.740	73.2	0.057

Durability of Facade Systems

Group	Facade System	Material	Embodied Energy per year [MJ/m3]	Carbon Footprint per year [kgCO2/m3]	Volume [m3/m2]	Embodied Energy per year [MJ/m2]	Carbon Footprint per year [kgCO2/m2]
Panel Systems	Brick and Prefab Concrete Panel Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.016	8.70E-02	2.51	0.0014
						16.08	**0.015**
	Brick and CLT Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.013	1.01E-01	1.21	0.0013
		CLT Board (x4)	-155.38	-0.053	3.00E-02	-4.66	-0.0016
						3.08	**0.0048**
Masonry Systems	Brick and Sand Lime Block Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.01	1.28E-01	1.53	0.0016
		Sand lime blocks	22.27	0.03	9.42E-02	2.10	0.0024
						10.16	**0.0092**
	Brick and CMU Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.01	1.26E-01	1.51	0.0016
		CMU	37	0.042	1.29E-01	4.79	0.0055
						12.83	**0.012**
Timber Frames System	Brick and Timber Frames Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Rock Mineral Wool	11.97	0.01	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						17.62	**0.013**
Board Systems	E-Board and Prefab Concrete Panel Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	3.40E-02	-0.29	0.00028
		Concrete Panel Layers	37	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.02	6.00E-02	1.73	0.0010
						9.78	**0.0103**
	E-board and CLT Wall	Clay Bricks (Slips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.01	1.05E-01	-0.89	0.00088
		CLT Board (x4)	-155.38	-0.05	3.00E-02	-4.66	-0.0016
						-4.25	**0.00031**
	E-Board and Sand Lime Block Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.01	1.30E-01	-1.11	0.0011
		Sand lime blocks	22.27	0.03	9.42E-02	2.10	0.0024
						2.30	**0.0045**
	E-Board and CMU Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	1.27E-01	-1.08	0.0011
		CMU	37	0.042	1.29E-01	4.79	0.0055
						5.01	**0.0076**
	E-Board and Timber Frames Wall	Clay Bricks (Slips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	7.20E-02	-0.61	0.0006
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Glass Mineral Wool	11.97	0.013	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						11.78	**0.0092**

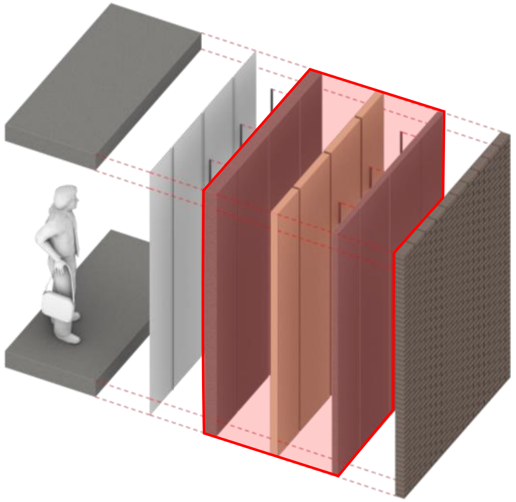
Durability Assessment



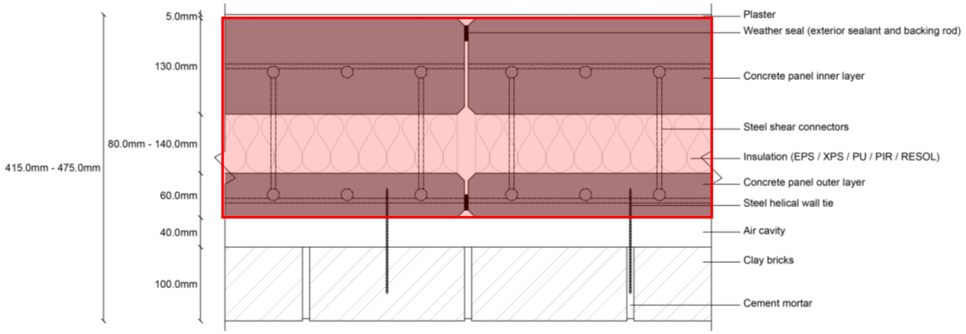


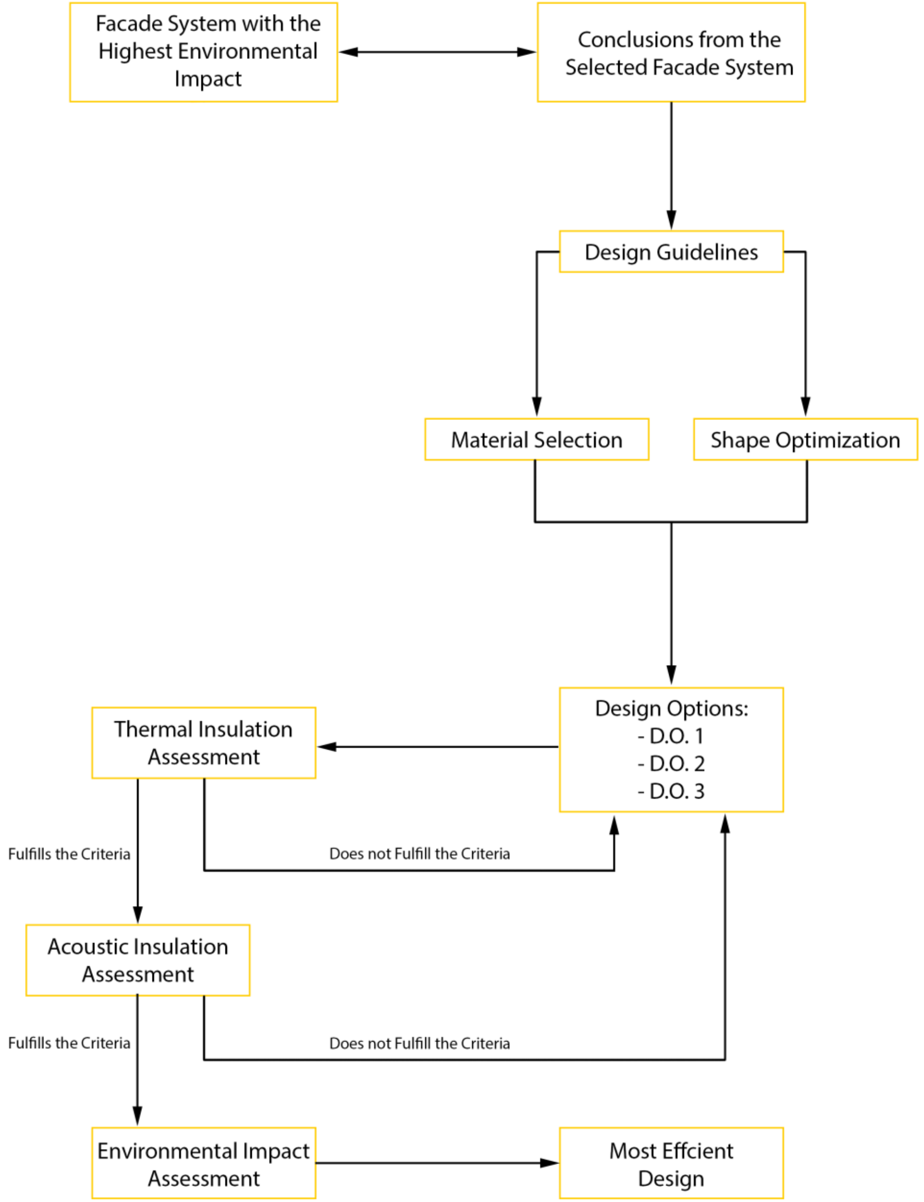
Durability of Facade Systems							
Group	Facade System	Material	Embodied Energy per year [MJ/m3]	Carbon Footprint per year [kgCO2/m3]	Volume [m3/m2]	Embodied Energy per year [MJ/m2]	Carbon Footprint per year [kgCO2/m2]
Panel Systems	Brick and Prefab Concrete Panel Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.016	8.70E-02	2.51	0.0014
						16.08	**0.015**
	Brick and CLT Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.013	1.01E-01	1.21	0.0013
		CLT Board (x4)	-155.38	-0.053	3.00E-02	-4.66	-0.0016
						3.08	**0.0048**
Masonry Systems	Brick and Sand Lime Block Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.01	1.28E-01	1.53	0.0016
		Sand lime blocks	22.27	0.03	9.42E-02	2.10	0.0024
						10.16	**0.0092**
	Brick and CMU Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.01	1.26E-01	1.51	0.0016
		CMU	37	0.042	1.29E-01	4.79	0.0055
						12.83	**0.012**
Timber Frames System	Brick and Timber Frames Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Rock Mineral Wool	11.97	0.01	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						17.62	**0.013**
Board Systems	E-Board and Prefab Concrete Panel Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	3.40E-02	-0.29	0.00028
		Concrete Panel Layers	37	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.02	6.00E-02	1.73	0.0010
						9.78	**0.0103**
	E-board and CLT Wall	Clay Bricks (Slips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.01	1.05E-01	-0.89	0.00088
		CLT Board (x4)	-155.38	-0.05	3.00E-02	-4.66	-0.0016
						-4.25	**0.00031**
	E-Board and Sand Lime Block Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.01	1.30E-01	-1.11	0.0011
		Sand lime blocks	22.27	0.03	9.42E-02	2.10	0.0024
						2.30	**0.0045**
	E-Board and CMU Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	1.27E-01	-1.08	0.0011
		CMU	37	0.042	1.29E-01	4.79	0.0055
						5.01	**0.0076**
	E-Board and Timber Frames Wall	Clay Bricks (Slips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	7.20E-02	-0.61	0.0006
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Glass Mineral Wool	11.97	0.013	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						11.78	**0.0092**

Design Optimization Strategy



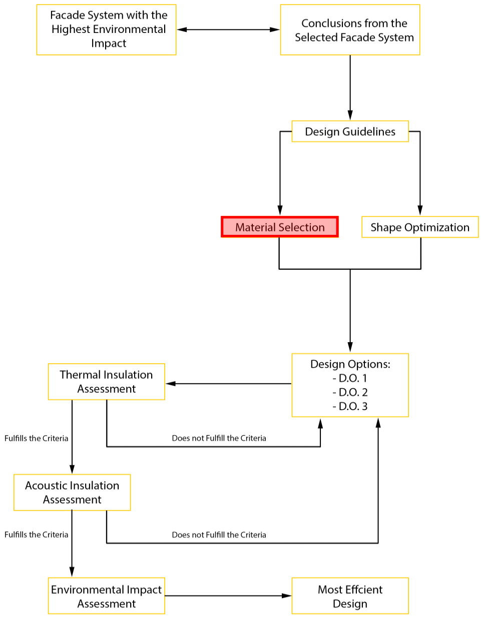
Brick + Prefab Concrete
Cavity Wall

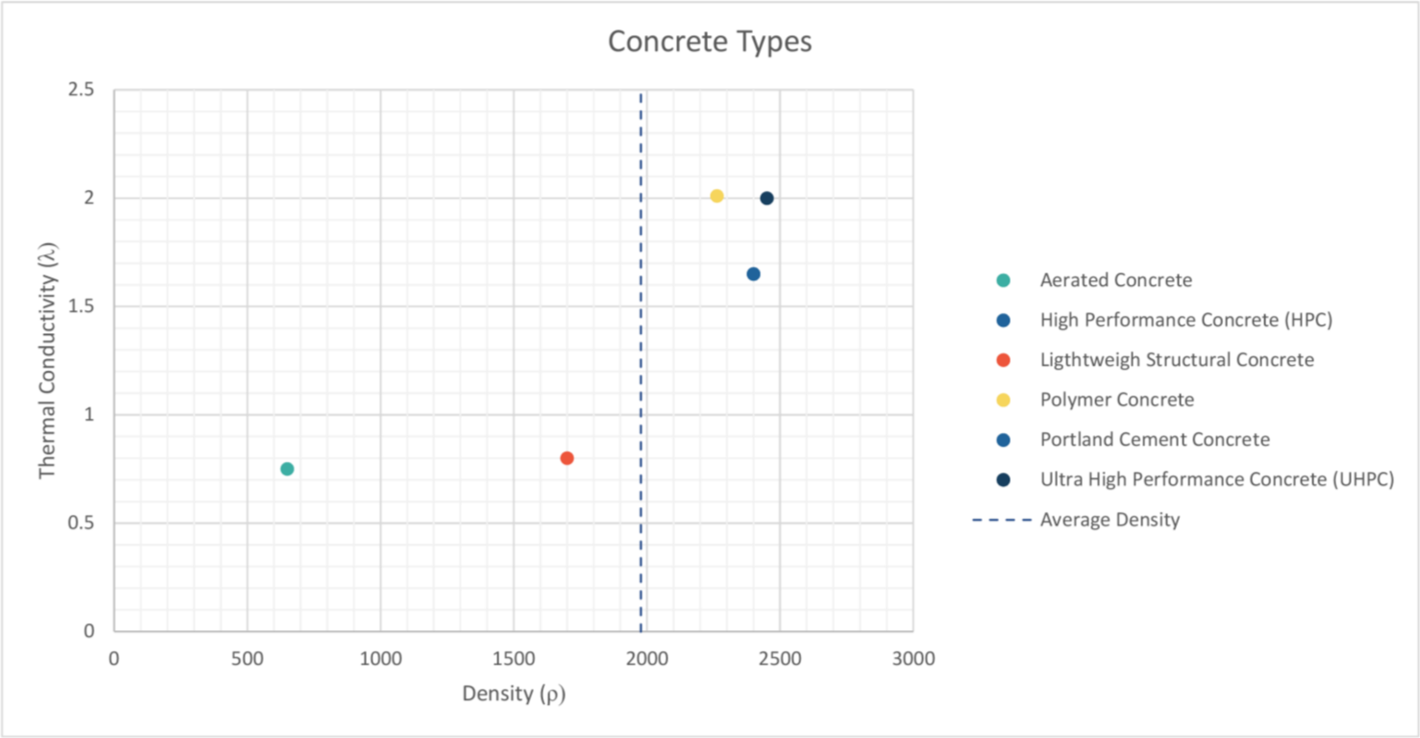




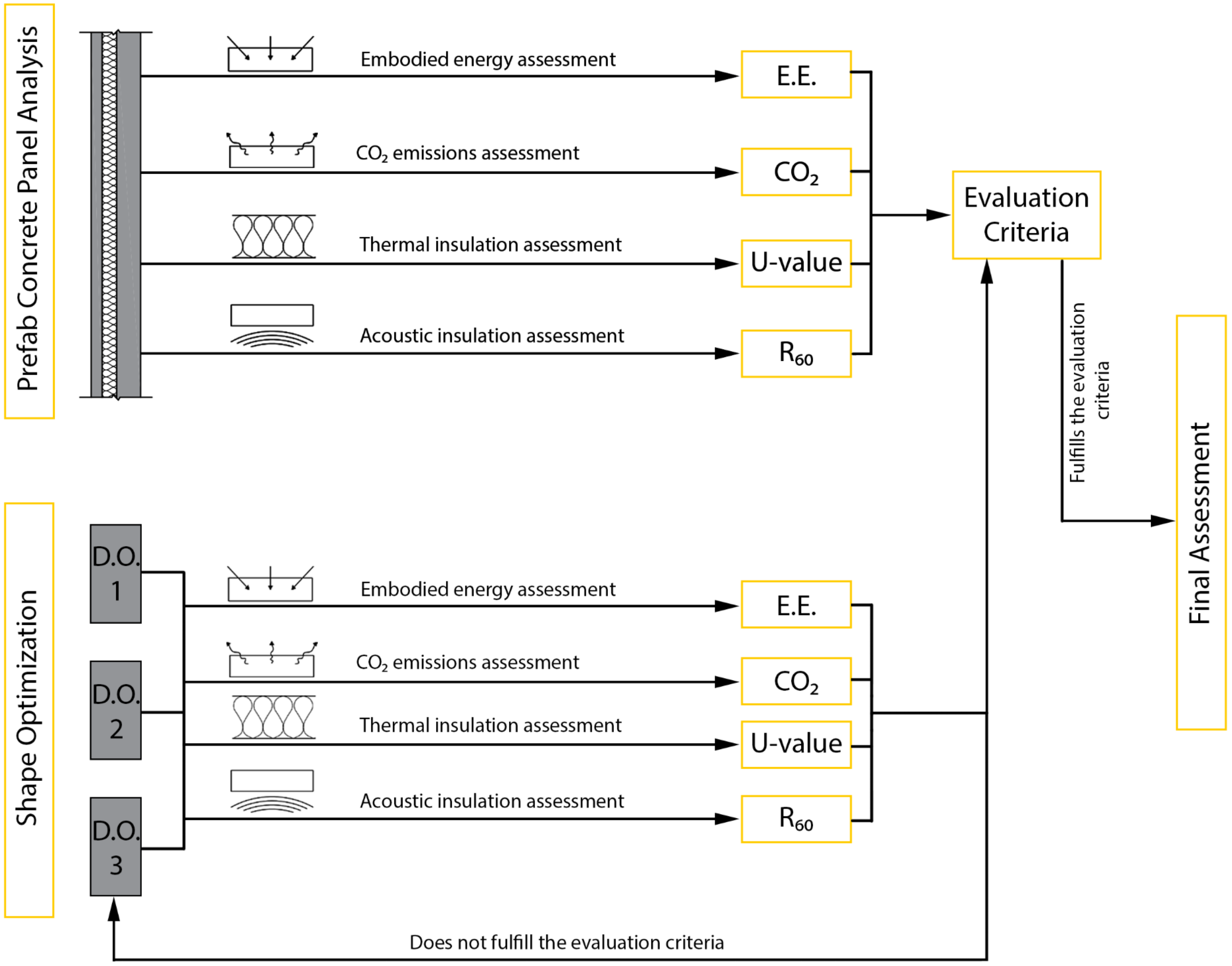
Material Selection

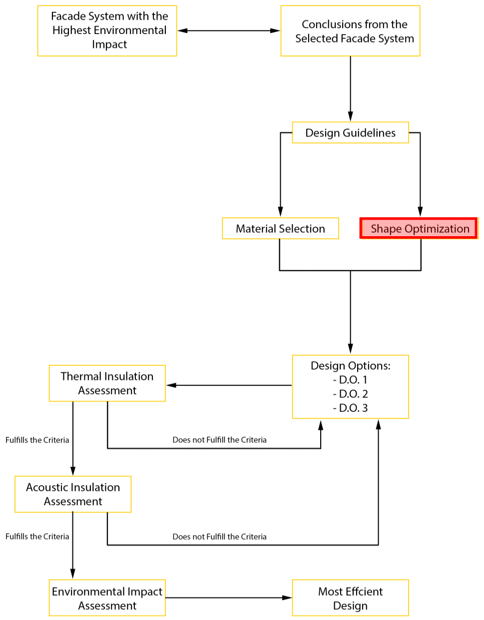
	Concrete Types			
	Type	Density [kg/m3]	Thermal Conductivity [W/mK]	Reference
1	Aerated Concrete	650	0.75	CES (2019)
2	High Performance Concrete (HPC)	2400	1.65	CES (2019)
3	Lightweight Structural Concrete	1,700	0.8	CES (2019)
4	Polymer Concrete	2,263	2.01	Elalaoui et al. (2012)
5	Portland Cement Concrete	2,400	1.65	CES 2019
6	Ultra High Performance Concrete (UHPC)	2,450	2.0	Yang & Park (2019)



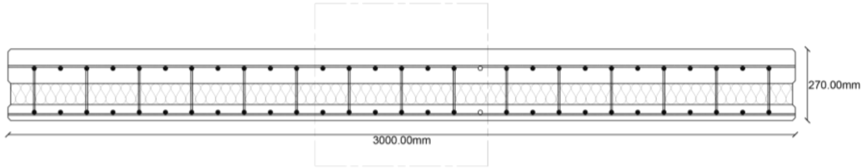


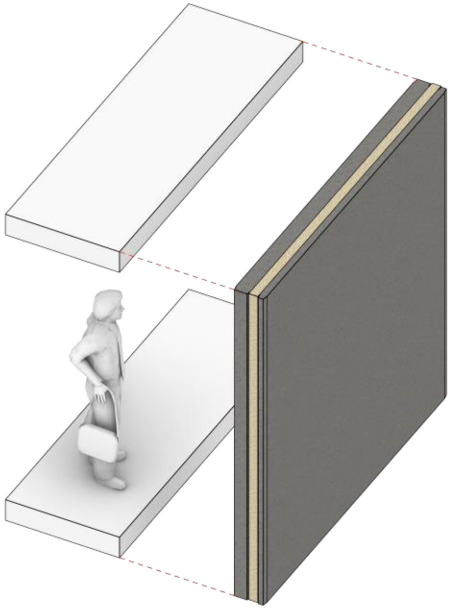
Shape optimization Workflow

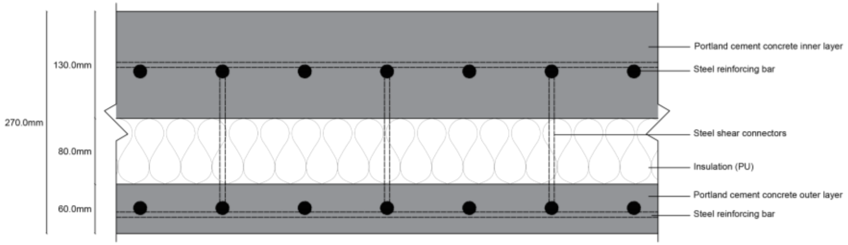




Prefab Concrete Sandwich Panel Assessment



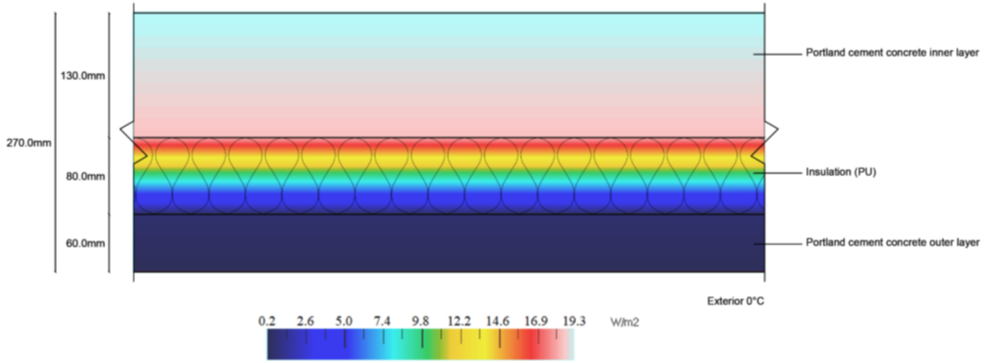




Evaluation Criteria Establishment

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Prefab Concrete Panels (Interior Layer)	1	130	1.30E-01	2,500.00	325.00	325.00	1.48	0.17	3,700.00	422.50	481.00	54.93	CES (Eco-Audit)
PU Insulation	1	87	8.70E-02	31	2.70	2.70	** 69.90	** 2.90	2,166.90	89.90	188.52	7.82	PU Europe, 2014
Prefab Concrete Panels (Exterior Layer)	1	60	6.00E-02	2,500.00	150.00	150.00	1.48	0.17	3,700.00	422.50	222.00	25.35	CES (Eco-Audit)
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**891.52**	**88.10**	

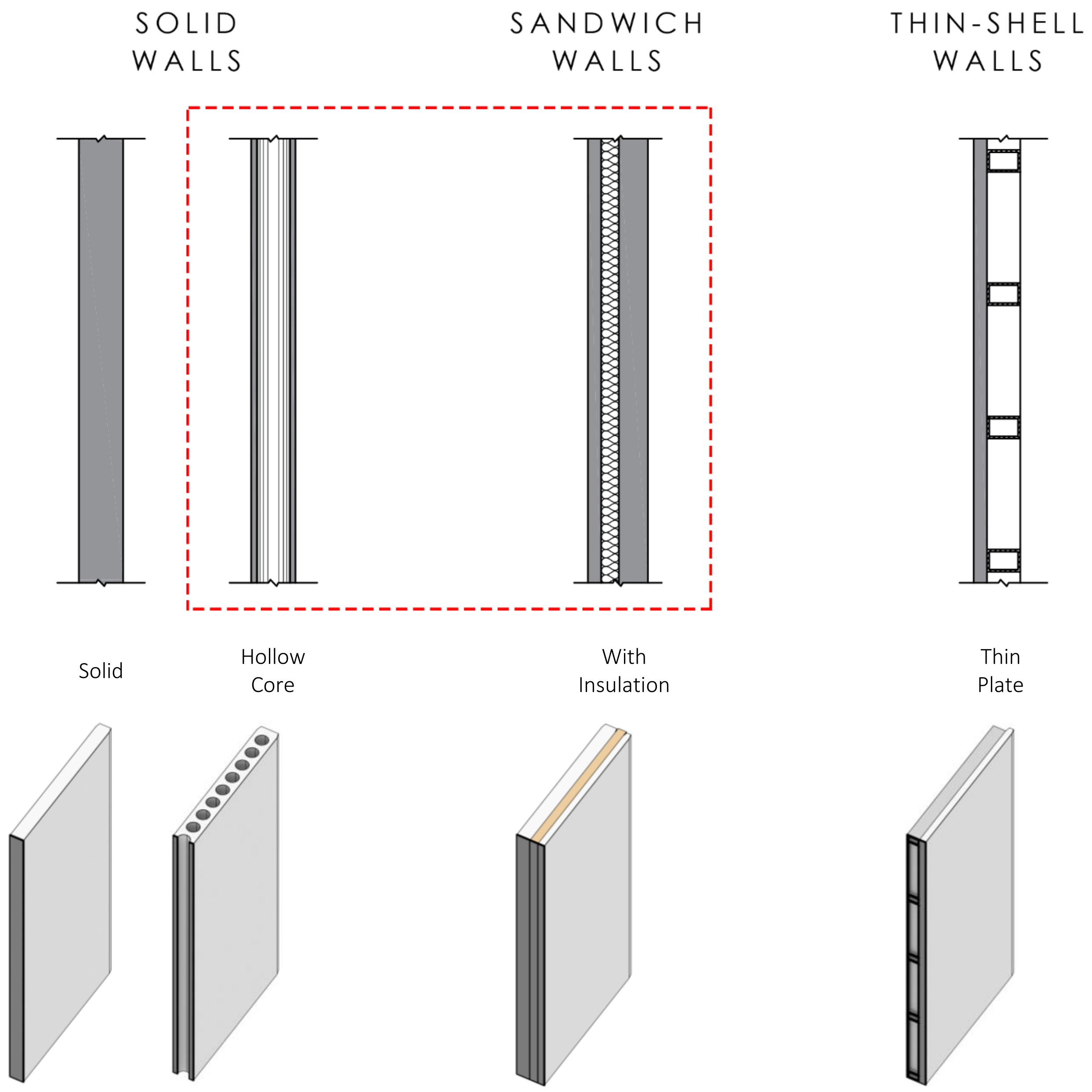
U-value = 0.26 W/m²K



Airborne Sound Insulation of Prefab Concrete Sandwich Panel								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Prefab concrete panel	sol	130.00	2,500.00	2.00E+10	0.00	0.05	0.27
2	PU insulation	liq	87.00	31.00	5.00E+04	0.00	0.00	20,000.00
3	Prefab concrete panel	sol	130.00	2,500.00	2.00E+10	0.00	0.05	0.27
***f* [Hz]**	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**77.3**	107.3	132.1	178.9	197.0	197.0	197.0	197.0

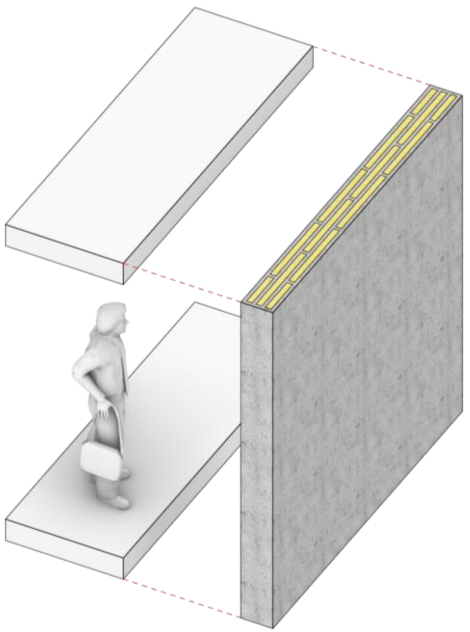
Evaluation Criteria of Prefab Concrete Sandwich Panel	
Embodied Energy [MJ/m2]	**891.52**
CO2 Emissions [kgCO2/m2]	**88.1**
U-value [W/m2K]	**0.26**
R60 [dB]	**77.3**

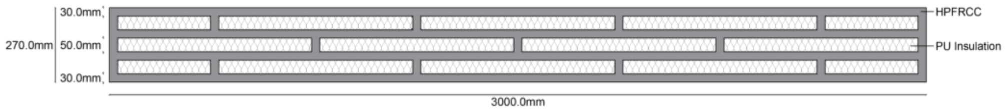
Shape Optimization Concept



Design Option 1

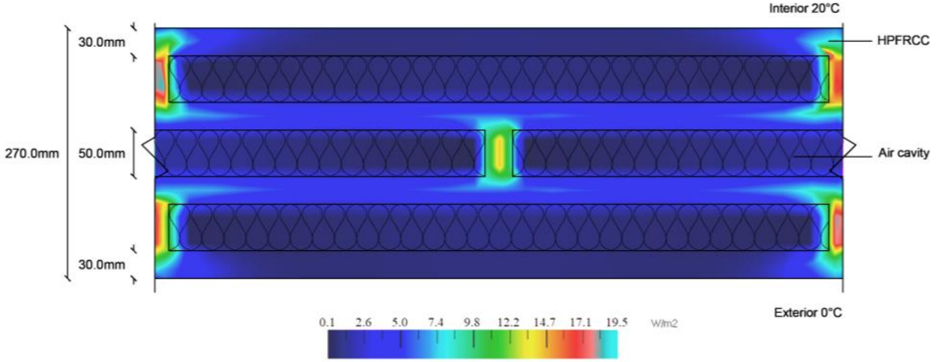
Evaluation Criteria of Prefab Concrete Sandwich Panel	
Embodied Energy [MJ/m2]	**891.52**
CO2 Emissions [kgCO2/m2]	**88.1**
U-value [W/m2K]	**0.26**
R60 [dB]	**77.3**





Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
HPFRCC Layer	-	-	1.29E-01	1,850	237.73	237.73	1.48	0.17	2,738.00	312.65	351.83	40.18	CES (Eco-Audit)
PU Insulation	-	-	1.42E-01	31	4.40	4.40	69.9	2.9	2,166.90	89.9	307.70	12.766	PU Europe, 2014
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**659.53**	**52.94**	

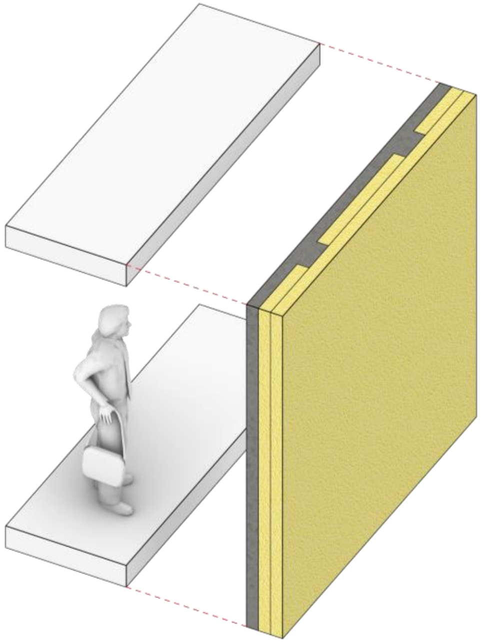
U-value = 0.26 W/m²K

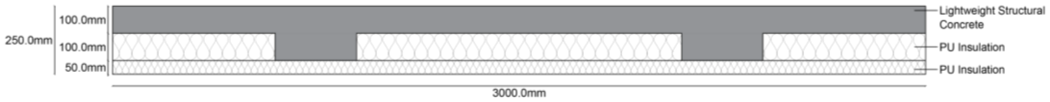


Airborne Sound Insulation of Design Option 1: Variation 2								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
2	PU Insulation	liq	30	31	5.00E+04	0.00	0.00	20000.00
3	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
ƒ [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**61.2**	79	92.5	121.7	146.4	175.5	196.1	197.0

Design Option 2

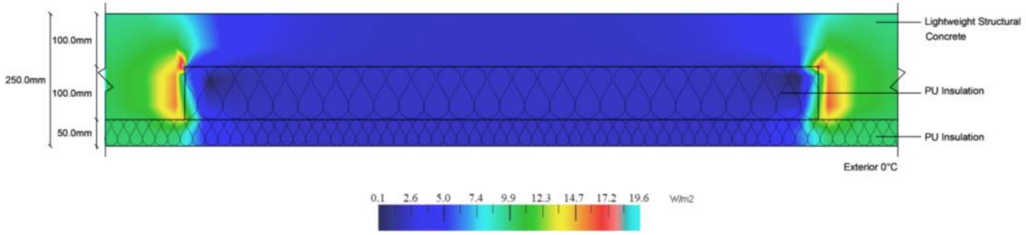
Evaluation Criteria of Prefab Concrete Sandwich Panel	
Embodied Energy [MJ/m2]	**891.52**
CO2 Emissions [kgCO2/m2]	**88.1**
U-value [W/m2K]	**0.26**
R60 [dB]	**77.3**





Environmental Impact of Construction Materials													
Material	**Quantity (per m2) [-]**	**d [mm]**	**Volume [m3/unit]**	**Density [kg/m3]**	**Mass [kg/unit]**	**Mass [kg/m2]**	**Energy [MJ/kg]**	**CO2 [kg/kg]**	**Energy [MJ/m3]**	**CO2 [kg/m3]**	**Energy (Wall) [MJ/m2]**	**CO2 (Wall) [kg/m2]**	**Reference**
Ligthweight Structural Concrete Panel	-	-	1.20E-01	1,700	204.00	204.00	1.48	0.17	2,516.00	287.3	301.92	34.48	CES (Eco-Audit)
PU Insulation	-	-	0.13	31	4.03	4.03	69.9	2.9	2,166.90	89.9	281.697	11.687	PU Europe, 2014
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**583.62**	**46.16**	

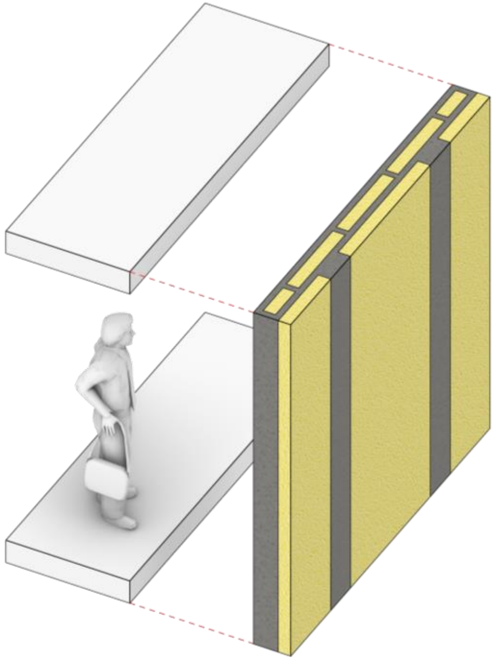
U-value = 0.21 W/m²K

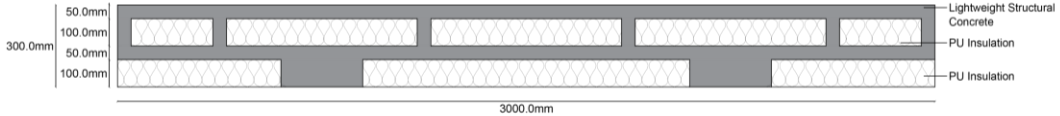


Airborne Sound Insulation of Design Option 2								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Ligthweight Concrete	sol	200	1,700.00	1.60E+10	0.00	0.05	0.27
2	PU Insulation	liq	50	31	5.00E+04	0.00	0.00	20000.00
***f* [Hz]**	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**51.7**	62.0	81.6	105.3	128.0	153.4	187.2	196.9

Design Option 3

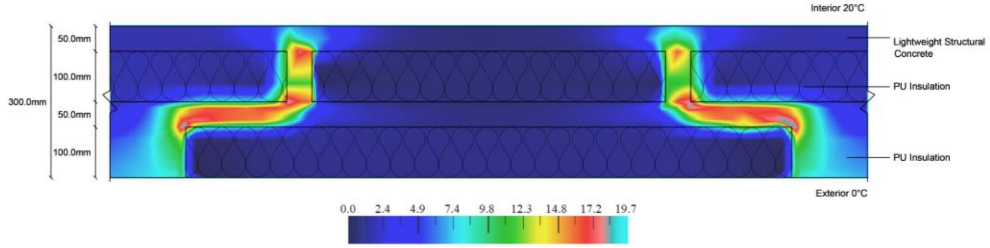
Evaluation Criteria of Prefab Concrete Sandwich Panel	
Embodied Energy [MJ/m2]	**891.52**
CO2 Emissions [kgCO2/m2]	**88.1**
U-value [W/m2K]	**0.26**
R_{60} [dB]	**77.3**





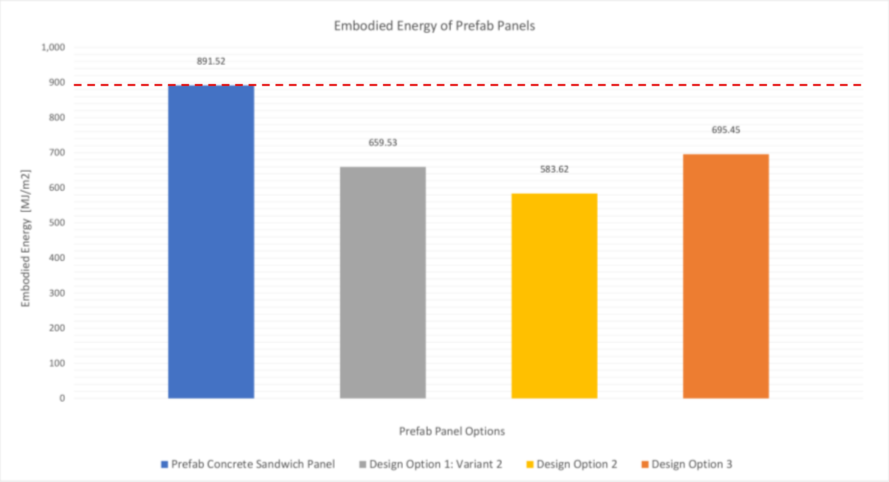
Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Ligthweight Structural Concrete Panel	-	-	1.30E-01	1,700	221.00	221.00	1.48	0.17	2,516.00	287.3	327.08	37.35	CES (Eco-Audit)
PU Insulation	-	-	1.70E-01	31	5.27	5.27	69.9	2.9	2,166.90	89.9	368.373	15.283	PU Europe, 2014
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**695.45**	**52.63**	

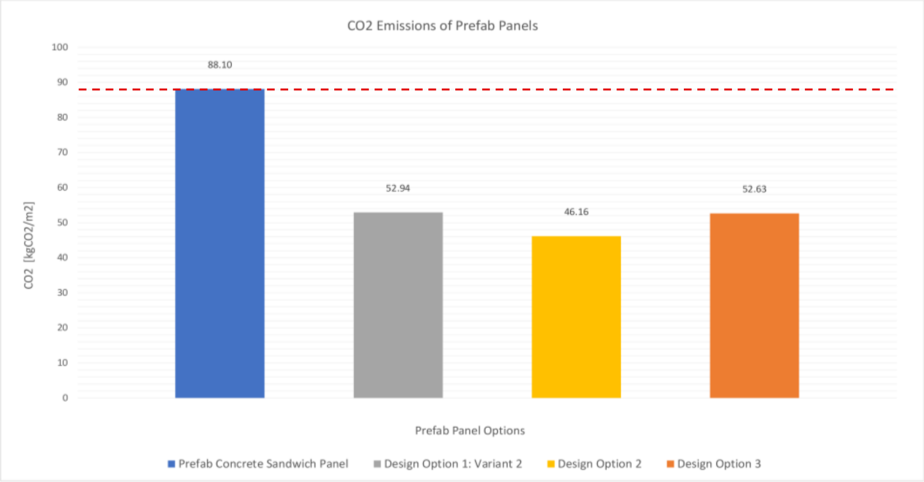
U-value = 0.25 W/m^{2}K

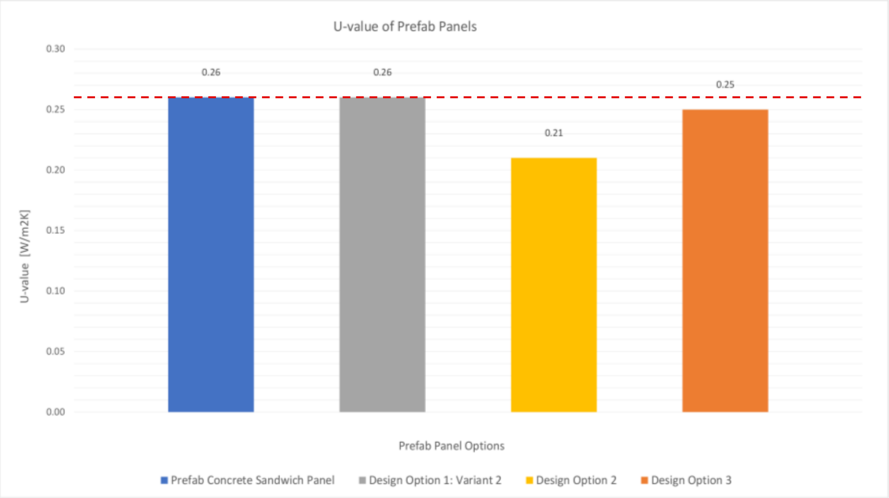


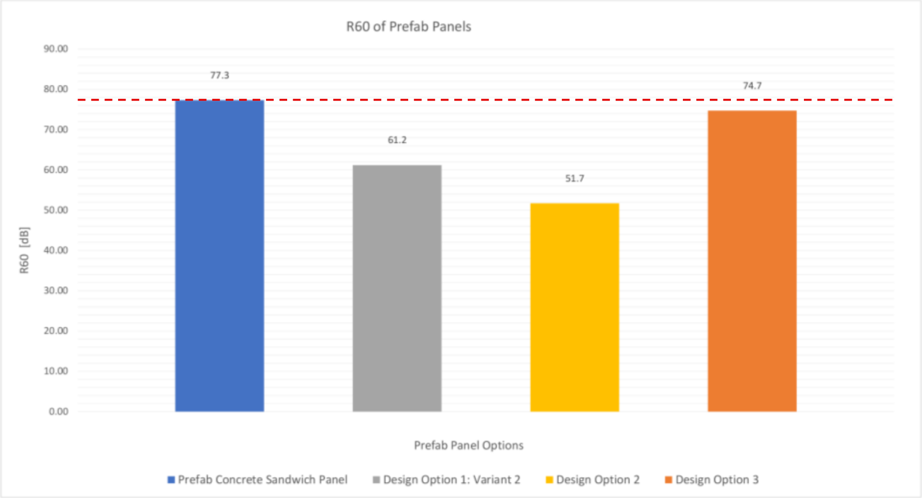
Airborne Sound Insulation of Design Option 3								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Ligthweight Concrete	sol	50	1,700.00	1.60E+10	0.00	0.05	0.27
2	PU Insulation	liq	100	31	5.00E+04	0.00	0.00	20000.00
3	Ligthweight Concrete	sol	150	1,700.00	1.60E+10	0.00	0.05	0.27
***f* [Hz]**	**63**	125	250	500	1,000	2,000	4,000	8,000
R_{60} [dB]	**74.7**	105.7	140.1	189.3	197.0	197.0	197.0	197.0

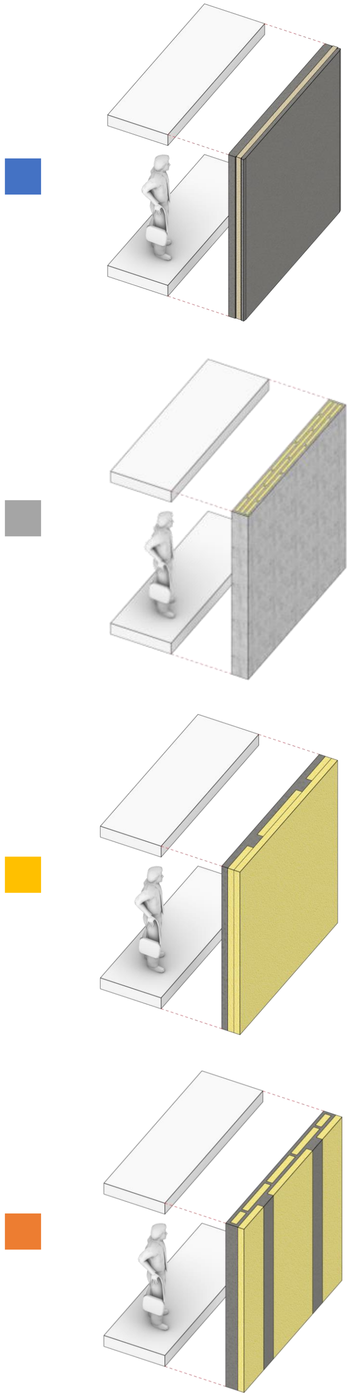
Design Options Overview



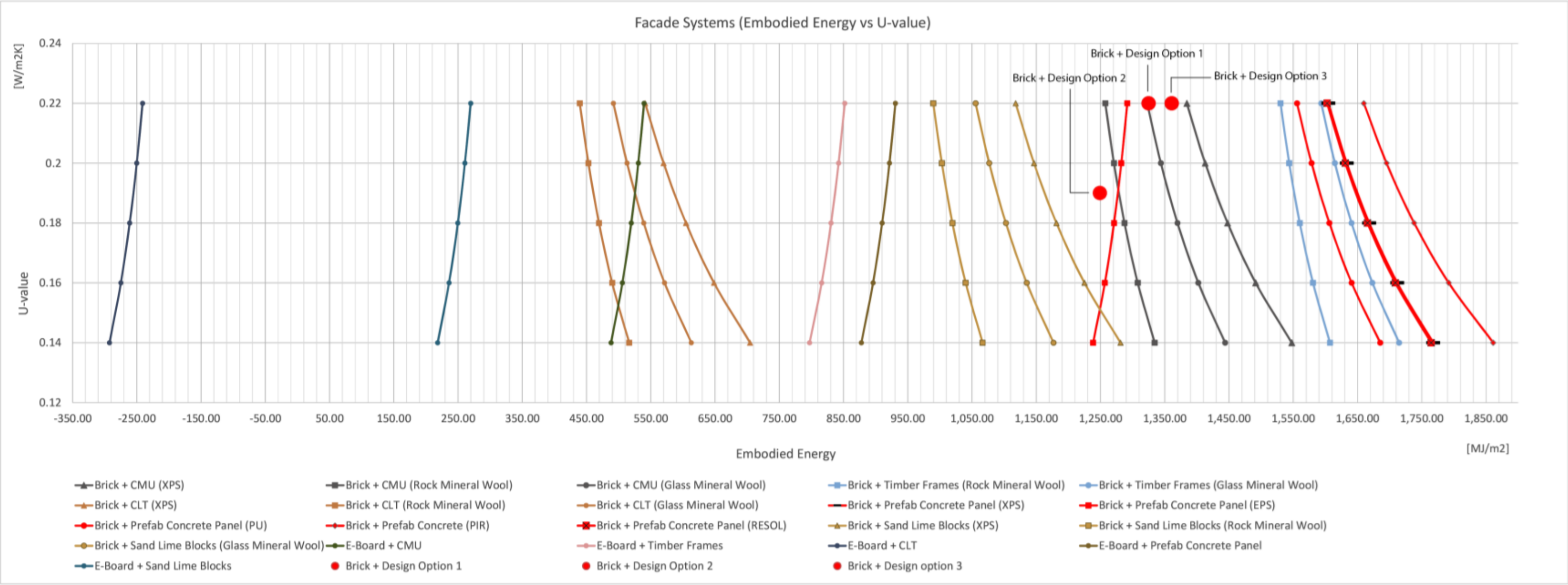


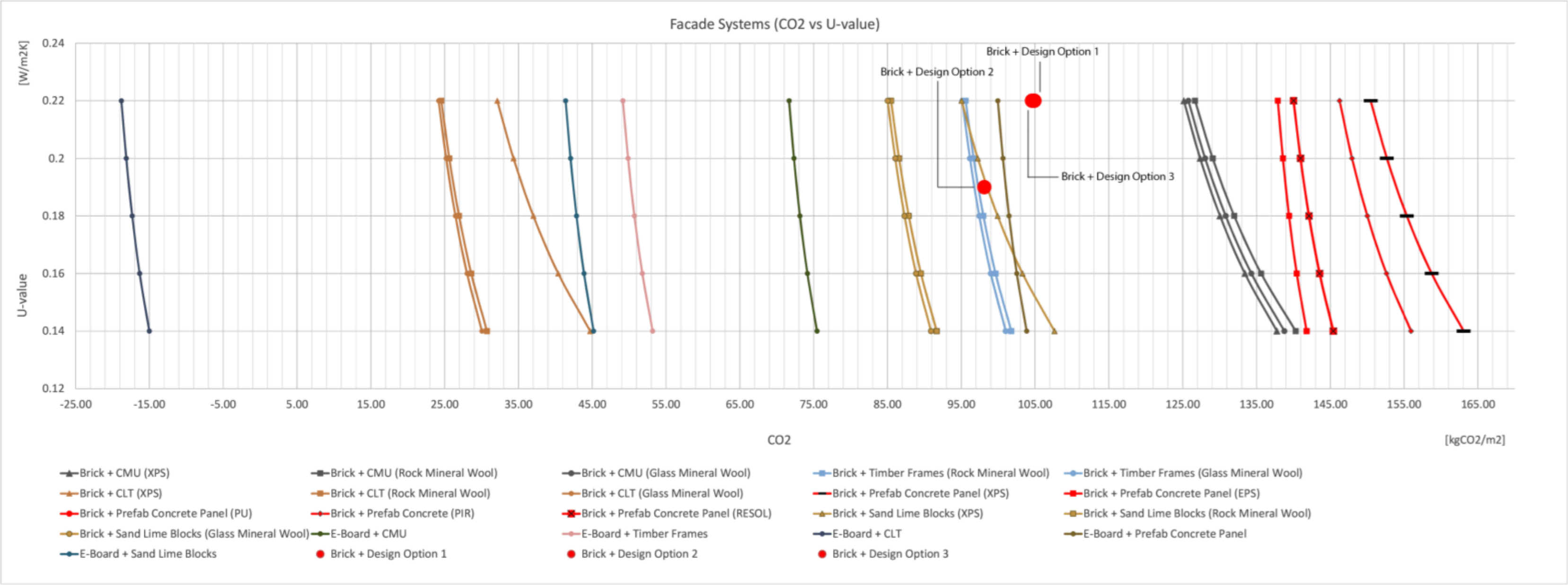




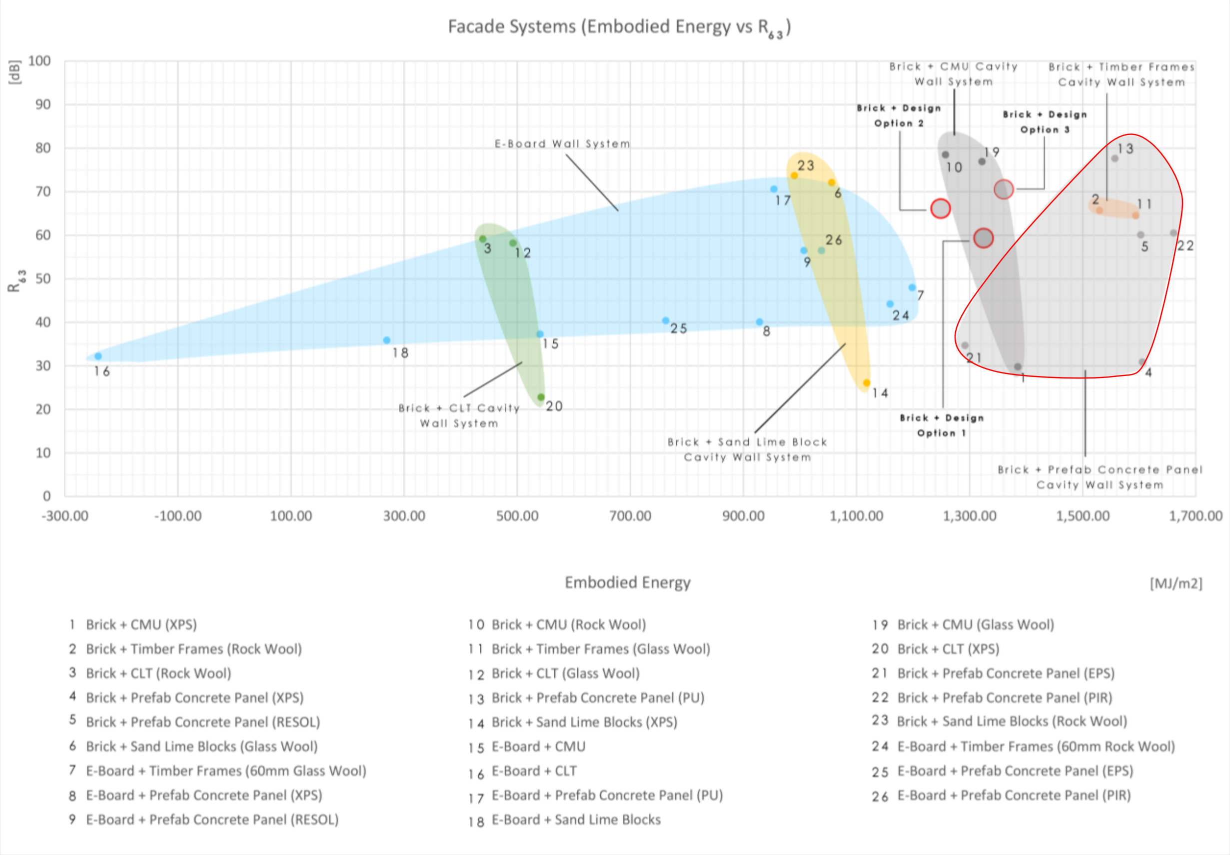


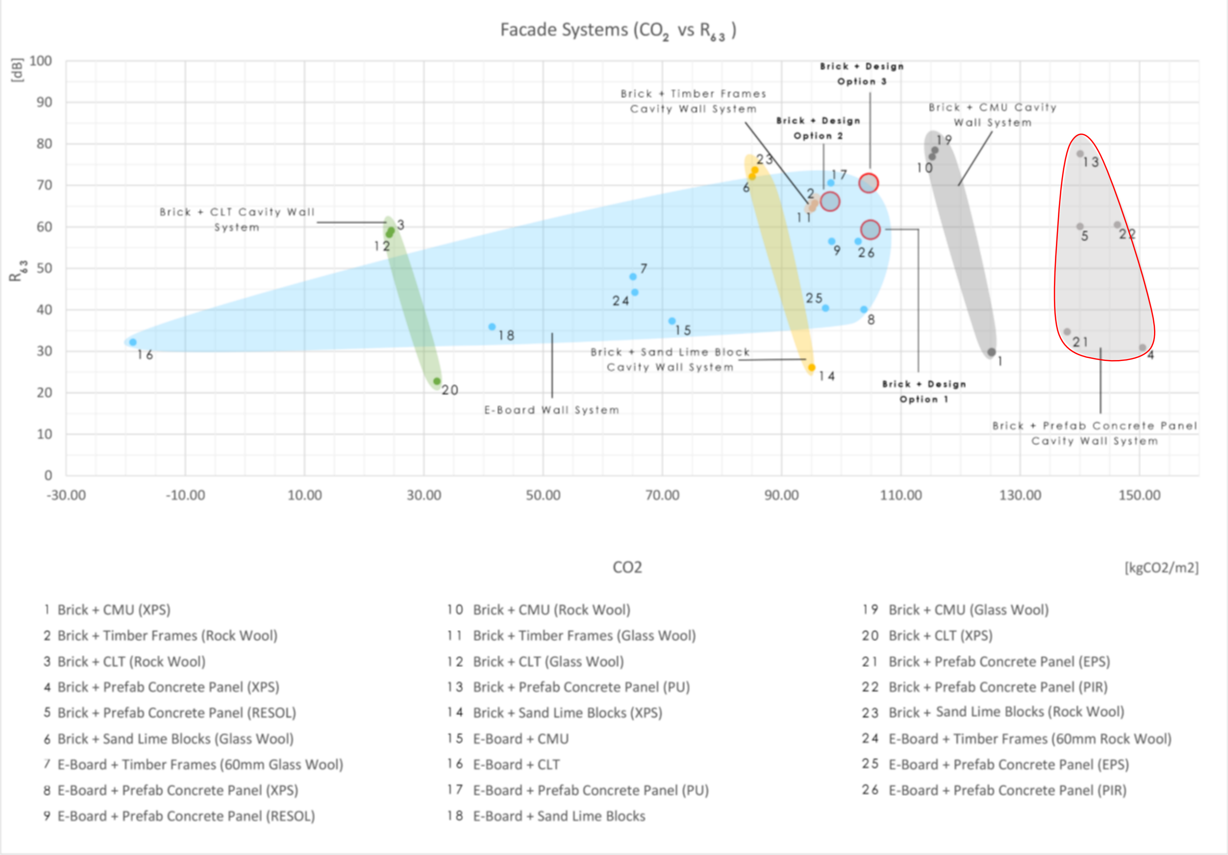
Thermal Insulation vs Environmental Impact: Comparison



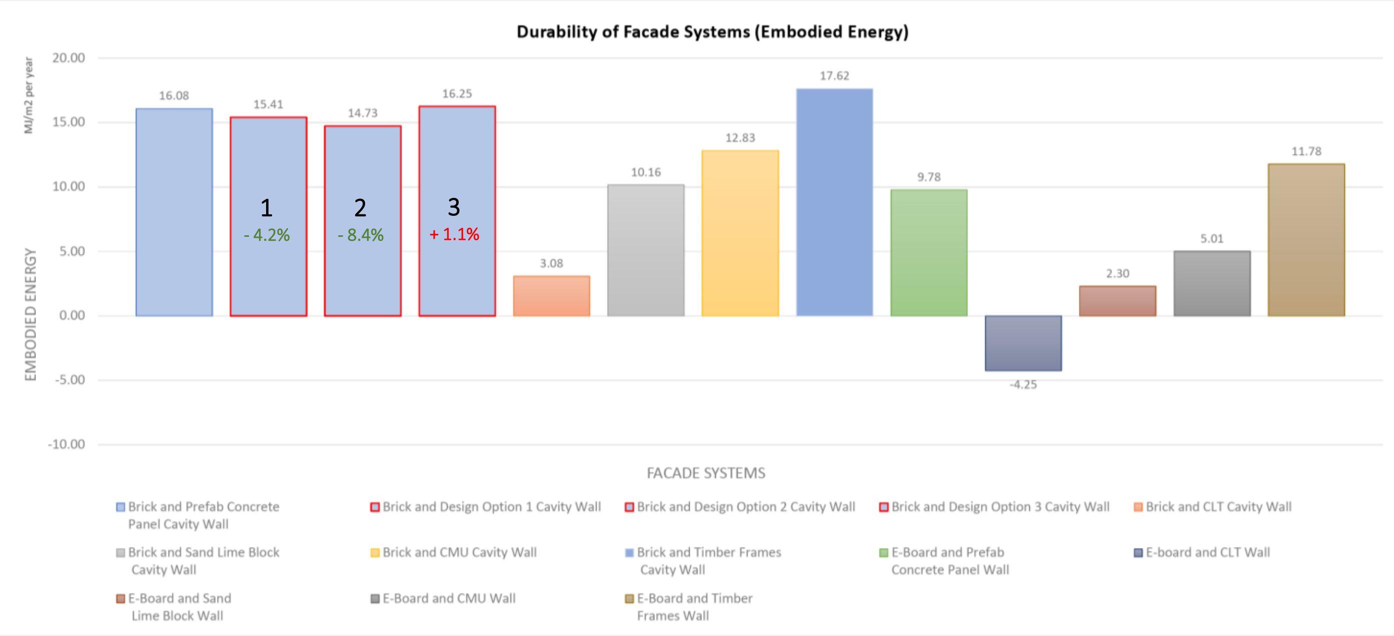


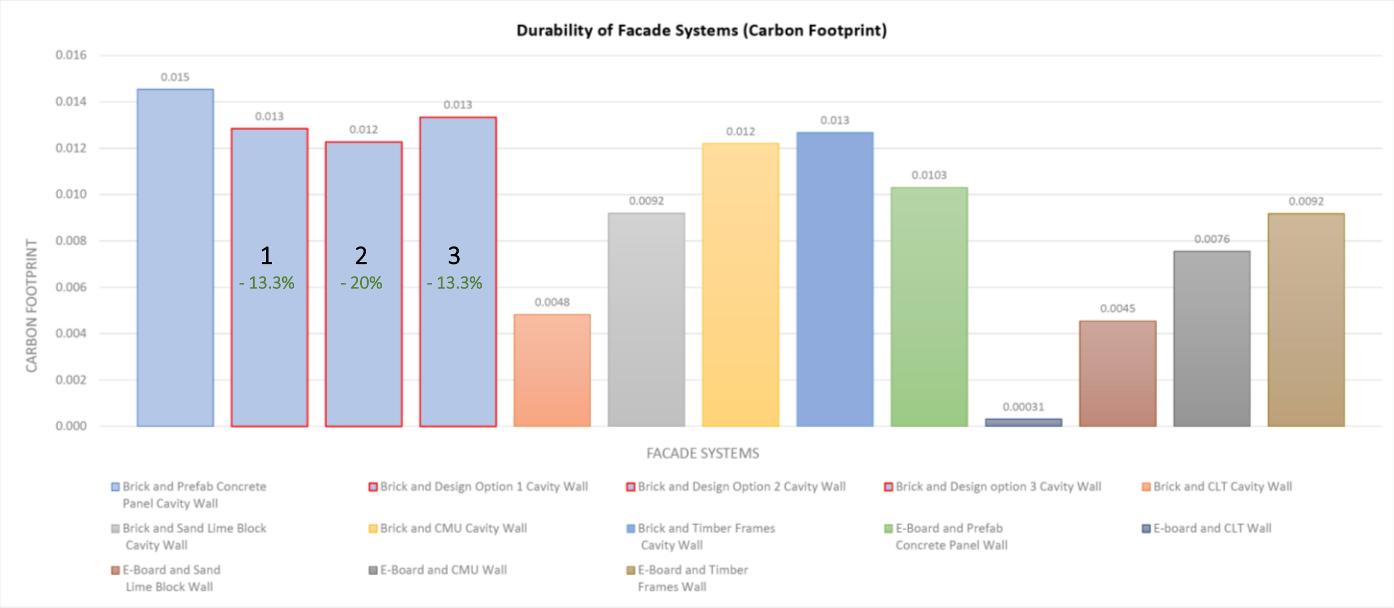
Acoustic Insulation vs Environmental Impact: Comparison





Durability: Comparison





Conclusion

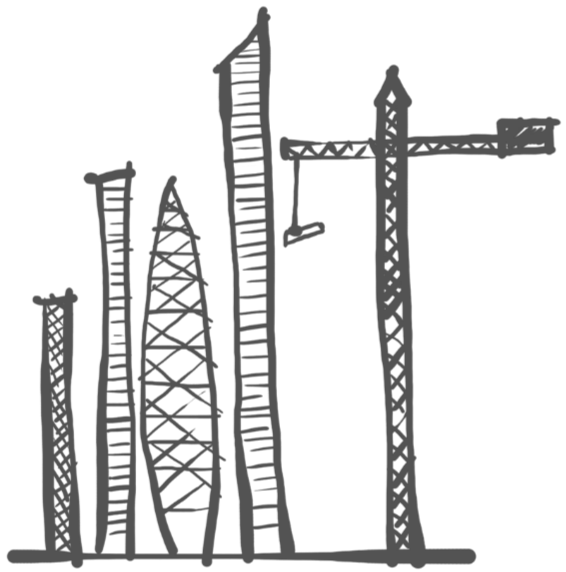
- The embodied energy and the carbon footprint are broadly understood parameters by designers and engineers. Therefore, a framework can be developed to measure the environmental impact of any product, component or façade system.

- Since facade components are normally measured in square meters (m^2), a good way of presenting the embodied energy and carbon footprint in a facade system is by measuring them in MJ/m^2 and $kgCO_2/ m^2$.

- The environmental impact can be related to any building parameter like the U-value and the airborne sound insulation, in order to assess any existing design and to obtain ideas on how to improve it.

- From the different conducted assessments it could be observed that the systems with the higher environmental impact in order to reach certain U-values or airborne sound insulation levels are the more massive systems. For this reason, optimizing these facades focusing on reducing the mass proved to be a good solution in order to reduce their environmental impact.

- → A way of quantifying the environmental impact of the materials in a facade system regarding the life-stages of **construction** and **use phases** can be taken into account
- → Other parameters can be taken into account in this tool to compare with the environmental impact, like **structural properties** or **cost**.
- → The assessment framework can be **scaled up** in order to evaluate not only facade systems, but **all the components in a building**.



Thank you!