MSc in Architecture, Urbanism and Building Sciences

Stand-alone Serviced Façade Panel

Master Thesis

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Abstract

This thesis focuses on the design and implementation of a flexible, adaptable, and modular integrated unitised façade panel. The panel integrates air-to-air building services technologies for ventilation and/or heating and cooling, driven by electricity, to enhance user comfort under different climate conditions. The primary objective is to develop a panel design capable of adapting to various climates in residential concrete tenement flats built post-war worldwide, due to the need of refurbishments of such residential buildings.

The thesis outlines a programme of constraints that define and determine key aspects for designing a building services integrated unitised façade panel. It also emphasizes the selection of efficient air-to-air technologies available in the market for heating, cooling, and ventilation, including heat exchangers that significantly decrease energy consumption in buildings while enhancing user comfort, regardless of the climate.

One of the challenges of the thesis lie in establishing the market acceptance of the proposed product design, ensuring feasibility and attractiveness to engineers, manufacturers, users, and architects. The design criteria also need to accommodate potential future changes, geometry adaptability and aesthetics flexibility. Additionally, the final product design will be simulated under two distinct climates to assess its feasibility for large-scale application.

The focus of this thesis will be on decentralised ventilation, heating, and cooling services to achieve substantial energy savings. Other technologies related to sun shading and energy generation will be considered regarding space and installation requirements but will not be part of the literature research.

In terms of comfort domains, the thesis will address indoor air quality (IAQ), thermal environment, and acoustics. The primary research question guiding the thesis is: “How can a façade design integrate building services for heating, cooling, and ventilation, and enhance user comfort in residential concrete buildings?” The methodology employed for this thesis follows a design-through-research approach.

Overall, this thesis aims to contribute to the development of an innovative building services integrated unitised façade panel that significantly improves energy efficiency while enhancing user comfort, and allows for adaptability for residential concrete buildings under different climates conditions.

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Acronyms

IAQ	Indoor air quality
AER	Air exchange rate
IEQ	Indoor environmental quality
DR	Design requirements
HP	Heat pump
D.B.	Design Builder
AHU	Air Handling Unit
BMS	Building Management System
ECM	Energy Conservation Measures
EMM	Energy modulation measures

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Chapter 1 | Introduction

1.1 Background

The built environment accounts for 40% of the annual global CO2 emissions. Of the total, 27% accounts for building operations, and the embodied energy of materials and construction accounts for 13% annually. (IEA, 2022). Let's consider that the population living in cities worldwide is expected to increase from 55% to 68% by 2050 (United Nations, 2018). This will directly translate into higher demand for the housing market stock. However, generating new building stock is one of the least sustainable solutions since it significantly contributes to the emission of CO2. Therefore, one of the challenges of the built environment towards 2050 is to deliver housing for cities at a fast pace while reducing the CO2 emissions of the industry.

In that sense, if the goal is to reduce the carbon emissions generated by the built environment, the more feasible and relatively rapid option is to refurbish pre-existing buildings and continue global decarbonisation. For instance, at a European level, the EU Renovation Wave aims to double the retrofit rate by 2030 (European Commission, 2011). In contrast, the Green Deal goal is climate neutrality by 2050, alongside buildings decarbonisation (Siddi, 2020). At an international scale, the Architecture 2030 and 2050 challenges aim for zero carbon emission on pre-existing buildings for 2030 and decarbonisation for 2050 (Architecture 2030, 2022). Unfortunately, according to the 2021 status report of the Global Alliance for Buildings and Constructions, the pace at which the building stock decarbonisation is being addressed is insufficient to meet the Paris Agreement goals. (United Nations Environment Programme, 2021).

A building renovation typically involves making significant changes or improvements to an existing building's structure, systems and/or finishes. The scope of a building renovation can vary widely from project to project, but some common aspects include structural repairs, MEP and interior finishes upgrades, and envelope replacement. Regarding MEP, the upgrades include replacing or updating outdated or inefficient systems such as HVAC, electrical, plumbing, and fire protection. The HVAC upgrades often require an intensive process, especially in time and space. In contrast, such buildings' energy is required to meet sustainable advancements in building operations, energy sources and electricity generation.

The world has experienced extreme weather conditions in recent years, and user comfort consumes increasingly high energy levels. Users around the globe have dealt with fluctuating temperatures on their own since they cannot control the indoor environment locally. For example, dwellers from the south of Europe have personalised their s with local ventilators to cool down the extreme heat during summer and have integrated local heaters for the cool winters. This shows the inherited need of the user to take over control of their building services to achieve their comfort. As a solution, renovations could be transformed into a more efficient and integrated process if the building services were integrated into the . However, the environmental assessment of building retrofits depends on different assumptions, such as the climate and user behaviour.

New technologies such as demand-driven ventilation and decentralised services have been shown to impact building energy savings and improve the user's comfort. Today, these different façade market products can be found primarily in Germany for integrating building services into the façade. However, incorporating building services in the façade has encountered setbacks in maintenance and aesthetics, to name a few.

1.2 Problem statement

Decarbonising the built environment and providing sustainable dwellings for 2050 are crucial challenges facing the construction industry. Refurbishing concrete buildings with a unitised can address these challenges since the panels could be replaced with integrated building services panels, making the refurbishment process more efficient while enhancing user comfort. The current façade panel designs with integrated services lack modularity, which makes it difficult to disassemble and maintain the technologies. There is a need for a modular panel design that enhances technology independence and is easy to maintain and disassemble. Furthermore, the panel design must be flexible enough to accommodate various technologies to meet the different climate conditions to ensure the system's adaptability and scalability at a larger scale. Thus, allowing to increase the retrofit rate worldwide.

1.3 Objective

1.3.1 General objective

This thesis aims to design a flexible, adaptable and modular unitised façade panel that integrates air-to-air building services technologies for ventilation and heating and cooling, driven by electricity to supply and enhance the comfort demands of the user under different climate conditions. The panel design is developed for its implementation in refurbishments for residential concrete tenement flats worldwide built post-war. Hence, the panel design can adapt and respond to different climates to provide comfort under similar architectural layout conditions.

1.3.2 Sub-objective

Generate a programme of constraints that defines and determines the key aspects to consider when designing a building services integrated unitised façade panel as well as the selection of the most efficient air-to-air technologies available in the market for heating, cooling and ventilation with heat exchangers that will have a considerable impact on decreasing the energy consumption of the buildings while enhancing user comfort, regardless of the climate.

1.3.3 Final product

One of this thesis's main challenges is determining the market acceptance of the proposed product design. It should be feasible and attractive to all; engineers, manufacturers, users, and architects. While the design criteria should meet possible future changes and adaptations. Moreover, the final product design will be simulated under two different climates to determine the feasibility of its application at a large scale.

1.3.4 Boundary conditions

In developed countries, HVAC systems and heating consumption represent around half of the 40% of the total energy consumed by buildings. In 2021, almost half of the buildings' energy demand was used for heating. Due to the hottest-ever recorded temperatures, the cooling demand represents 16% of the total energy consumption (IEA, 2022). As a result of the preliminary research based on UN reports and IEA reports, the focus of this thesis, in terms of services, will be decentralised ventilation, heating and cooling. This way, the end design result can have a more significant impact on energy savings. Whereas technologies to provide sun shade and to generate, energy will be addressed in the understanding that the panels design will consider the space and the needed installation for them but will not be part of the literature research. Regarding the comfort domains, indoor air quality (IAQ), thermal environment and acoustics will be addressed.

1.4 Research question

Main research question:

*"How can a **façade** design **integrate** building services for **heating, cooling and ventilation** and enhance **user comfort** in **residential concrete buildings**?"*

Sub-questions:

- To what extent have the state-of-the-art façades integrated building services?
- To what extent is integrating building services into a façade panel effective in meeting comfort demands?
- To what extent can decentralised building services technologies be integrated into a façade panel?

As mentioned in the general objective, the integrated façade panel aims to be a solution for refurbishments in residential concrete tenement flats built post-war.

1.5 Research approach and Methodology

1.5.1 Research team: execution, supervision and advisory board

This thesis is under the research themes of Façade Design and Building Services Innovation in the Department of Architecture Engineering & Technology of the Master Track Building Technology at the Delft University of Technology. The principal tutor is Dr Alessandra Luna Navarro, and the second is Prof. Dr. ir Atze Boerstra; their tutoring focused on design and engineering and building services, respectively. The delegate of the Board of Examiners assigned to this thesis is Ir. Maarten Meijs.

1.5.2 Research methodology

The methodological approach of the presented thesis builds on design through research. The research was done in six parts; introduction, design requirements, literature review, pre-design, final design, and final evaluation. Each one has a specific focus and contributes to the development of the following stage.

Part I (1 Introduction)

The introduction aims to give an overall comprehension of the thesis research. The selection of the thesis topic, the definition of the problem statement and the research question, followed by the sub-questions, are given in this part.

Part II (2 Design Requirements)

The design requirements was developed based on desktop research, static hand calculations in Excel and dynamic simulations on Design Builder based on an average apartment of 60 sqm. Part of the requirements was determined based on the case studies' country's (Mexico and the Netherlands) legislation, norms and guidelines. It provides all the design criteria for the integrated unitised façade panel based on five domains: architecture, user interaction, comfort, energy supply and fire safety.

Part III (3 Literature Review)

This part provides the theoretical framework of the research based on the literature review and state-of-the-art analysis. It is subdivided into two chapters; the first identifies the pre-existing s with integrated services, and the second focuses on the currently available technologies for façade integration. This last chapter also compares the technology's performance based on a KPI matrix and the Programme of Constraints.

Part IV (4 Pre-design)

This part is subdivided in the subchapters: pre-design and field validation. The unitised façade panel was pre-designed and assessed based on the program of constraints. It was developed using sketch tools, both physical and computational. The last subchapter is destined to the field validation. In order to enrich the design and test its reception in the façade field, five external meetings were held with different specialists, such as a façade product developer, a circularity expert, a building physics consultant, an architect, and a façade consultant.

Part V (6 Final Design)

Based on the feedback provided by the specialists and the simulation results, a final design application will be shown. The visualisations of the prototype were done in Rhinoceros with V-ray and Landscape. After, as an additional step simulations were run in Design Builder with Energy Plus to back up and test the energy efficiency of the building services integrated and the comfort levels.

Part VI (7 Final evaluation)

The last part includes an evaluation of the research and its main findings. This part is subdivided into conclusion, reflection and recommendations for future research.

Figure 1 exemplifies the research approach divided in six parts of the methodology and the workflow followed to fulfil this thesis. The timeline followed for this thesis can be found in Appendix A.

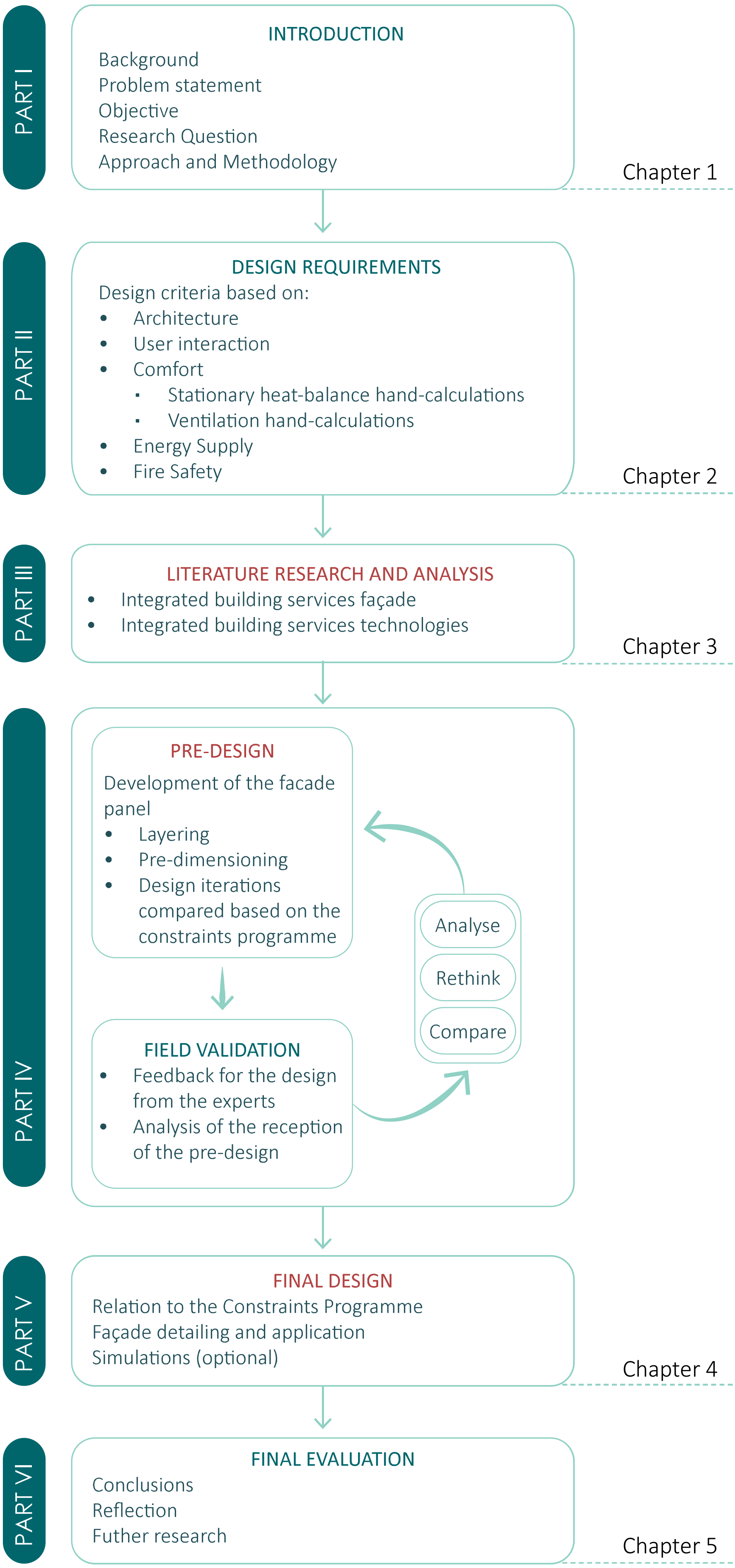


Figure 1. Thesis workflow and methodology.

Chapter 2 | Design Requirements

2.1 Requirements per domain

The design requirements were defined to determine the criteria for developing a unitised façade panel that integrates building services for heating, cooling and ventilation with filters. It aims to function as a document for the later stages of this thesis to help the designer choose the more suitable technologies, assess the pre-design iterations and the final integrated unitised façade panel design. Figure 2 shows the domains considered for elaborating the integrated panel along with the requirements per domain. The specification of the components, characteristics and design criteria per domain will be further developed in each table. Passive measures (ECM) such as improving the envelope Rc value, glazing u-value and the integration of overhangs were used to reduce the energy input required by the system for heating and cooling loads.

The requirements were first broken down by domain. In total, some five domains: architecture, comfort, energy supply and consumption, user interaction and fire safety, were considered, and each represents a part of the design to consider for elaborating the integrated panel.

Tables 1, 2, 3, 4 and 5 were developed for each domain considering the requirements, components, characteristics and design criteria to achieve.

Architecture

The architecture domain (Table 1) focuses on the characteristics that define the panel's geometry, the façade construction considerations such as tolerances and movements, and the interrelation between the parts to enhance the adaptability and flexibility of the unitised façade panel in different climates. The tolerances and movement criteria lead to the correct structural performance of the façade since the unitised system will be placed in-between structural concrete columns but in front of the slabs. Thus, the different movements between the façade and the building will be absorbed within the defined tolerances. The envisioned façade panel design will be implemented in massive concrete buildings of around ten floors. This is why the repetition of the panel has to allow for flexibility in terms of rhythm to enable the architects to enrich the façade design and avoid repetition in a monotonous way. The standardisation of the connections will allow for faster refurbishments and reduce the quality risk regarding the panel performance. Since the façade aims to integrate different HVAC systems, allowing easy maintenance and independency of the parts are vital aspects to consider within the design.

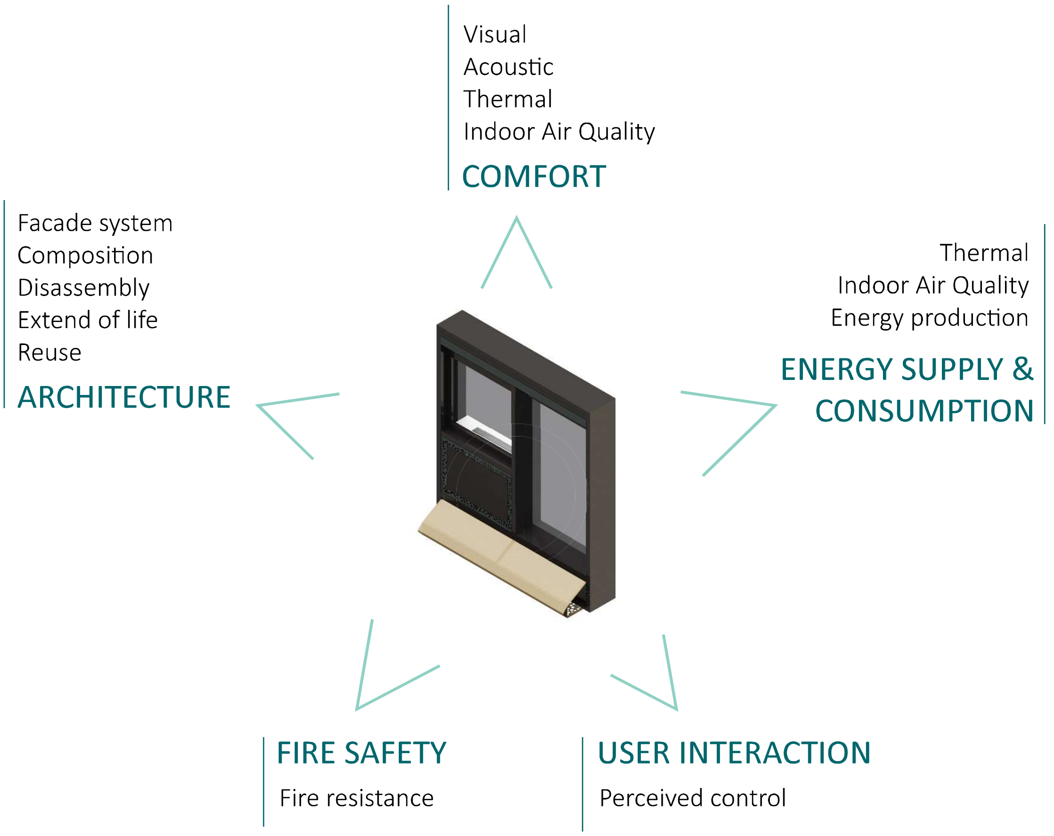


Figure 2. Design criteria showing the domains with components considered for the integrated panel.

Indoor Environmental Quality

The Indoor Environmental Quality Table (Table 2) focuses on the criteria required to achieve user comfort in terms of visual, acoustic, thermal and IAQ. To determine the values of these criteria, desktop research was done on the legislation, norms and guidelines per each case study country, Mexico and the Netherlands. More information on the requirements per country can be found in Appendix B. Considering that the building typology is residential, indoor comfort is more strict and can become a challenge regarding privacy and noise levels. For instance, the Netherlands have lower noise levels than Mexico (-5 dB(A)) for both private (bedroom) and social (living room) spaces. This is why in the design the values for the Netherlands are used. Dwellers aim to achieve more light transmittance and a WWR that enables them to have views of the outside while having the possibility to have privacy through inner blinds. This is why different values that allow the user to have visual comfort while not increasing the heat gains inside the apartment are defined, such as a 40%WWR. The thermal comfort varies per climate since Mexico City is a cooling demand zone and the Netherlands a heating demand zone. Therefore, different values are given for this part of Table 2. The IAQ of Mexico City is highly contaminated, so adding the filters specified in Table 2 is important to enhance IAQ. In addition to the criteria concerning the ventilation unit, the air flow rate and air velocity need to be carefully designed with the façade panel since they could lead to drafts within the different rooms.

Table 1. Architecture table description per requirement, component, characteristic and design criteria to consider for the panel design.

Architecture			
Requirements	Component	Characteristic	Design criteria
Facade system	Unitised panel unit	Mullion	2:1 proportion
		Transom	
		Depth	Adjustable, as thin as possible (<40cm without considering overhangs) to avoid decreasing the rentable space
		Modules max. (HxW)	3,0 x 2,50 m
		System	Simple for the user to understand, use and maintain
			Aim to use component for two purposes
	Structure	Tolerances	+/- 25 - 50mm
	Facade construction		+/- 1,5 mm < 1m (width)
			+/- 2 mm > 1m (width)
		Dimensions	Sizes and geometry fittable for the transportation in an average truck to avoid extra costs
	Structure and facade	Opennings integrity	> 6mm / 25mm
	Technologies	Thickness	<30cm
		Building physics	Integral airflow dynamics design
		Filters	Filters integrated in the units to enhance a good air quality for the interior spaces
		Maintenance	Easy access
Composition	Panel unit	Rhythm	Allow for small variation
			Avoid same module repetition
			Visually dynamic, rich
Disassembly	Connections	Easy de/installation of the façade panel	Standardised dry-connections
			Minimal number of connections
Extend life	Parts	Proximity between parts	Cluster the parts according to its function and maintenance period
		Independence between the parts	Different access to the parts without entaglement
		Easy maintenance	
Reuse	Unitised panel unit	Modular	Components with standardize dimensions that can be repeated within the project facade
		Flexibility	Clear interchangeable components modules in terms of location within the façade and integration of the different technologies
		Manufacture	Prefabricated unitised modules

Table 2. Indoor environmental quality table description per requirement, component, characteristic and design criteria to consider for the panel design.

Indoor Environmental Quality					
Requirements	Façade component	Façade characteristics	Design criteria		
				Mexico	Netherlands
Visual comfort					
Daylight	Double glazing	Light transmittance [VT]	≥ 75% [ideal 80%]	-	-
		SHGC	≤ 60%	-	-
	Sunshade	Light Reflectance [R]	≥ 70%	-	-
		Transmittance [Tvis] Fabric openness (Weave)	7% ≤ x ≥ 12%	-	-
		Emissivity	≥ 10%	-	-
	Window	Window area (min % in relation to the floor area)	WWR: 40 ≤ x ≥ 70	≥ 17.5 (%) [1]	≥ 0,5m2 + 10(%)
Acoustic comfort					
Sound	Integrated façade panel (bedroom)	Sound Pressure Level	≤ 25 dB(A)	≤ 30 dB(A) [2]	≤ 25 dB(A) [5]
	Integrated façade panel (living room)	Sound Pressure Level	≤ 30 dB(A)	≤ 35 dB(A) [2]	≤ 30 dB(A) [5]
Thermal comfort					
Thermal	Wall insulation	Reflectance	0,5	-	-
		Conductivity	0,2 ≤ x ≥ 0,9 W/m-K	-	-
		Density	1000 ≤ x ≥ 2500 kg/m3	-	-
		Rc value (minimal per norms)	-	≥ 1,10 m2K/W [3]	≥ 1,4 m2K/W [4]
	Sunshade	Conductivity	≤ 30%	-	-
		Positioning	Inside / outside	-	-
	Double glazing	SF/G-value	≤ 60%	-	-
		U-value	≤ 1,1	low-e coating exterior	low-e coating interior
	Heating & cooling	Operating temperatures	-10 ≤ x ≥ 35	20-25 (winter) °C [2] 23-26 (summer) °C [2]	16 - 22 (winter) °C [5] 23- 26 (summer) °C [5]
Indoor Air Quality					
Ventilation	Ventilation unit	Filter for fine Particulate Matter (PM 2.5 and PM10)	G3: with coarse 45%	-	-
			F7: with ePM1 75%	-	-
		Sensors	CO2 sensors	-	-
		Fresh air flow rate	≥ 36 m³/h per person	≥ 1,51 m³/h [2]	≥ 3,24 m³/h [4]
		Air velocity	-	< 0,16 m/s [2]	< 0,2 m/s [4]
		Room exchange per hour	= [(3600*36)/room volume]	-	-

1. Norma técnica complementaria para el Proyecto Arquitectónico en México

2. PROY-NMX-C-577-ONNCCE-2020

3. NOM-020-ENER-2011 https://www.dof.gob.mx/normasOficiales/4459/sener1/sener1.htm

4. Bouwbesluit

5. BKT-PGW-living-2022-01

Energy supply and production

The energy supply and production Table (Table 3) focuses first on characteristics of the technologies, such as high CoP efficiencies, units with an integrated heat exchanger, the power supply and most importantly, the heat transfer principle (air-electric) that will enable the façade units to be installed easily. Moreover, the minimum heating and cooling capacity is given based on the stationary heat balance calculations of an average 60 sqm apartment. From which the main bedroom was used to determine the capacities for Table 3. The calculations can be found in (subchapter 2.3). Regarding energy production, it focuses on efficiency, ideal tilt angles, energy production per square meter and best-suited orientations for higher energy production. This will inform the design for positioning the PV panels in the façade, selecting the best-suited technologies according to the heating and cooling capacity demands and the heat recovery ventilation performance for better energy performance of the integrated unitised façade panel.

User interaction

The user interaction domain Table (Table 4) determines how the user will control the façade components such as shadings, vents/windows, ventilation, heating and cooling technologies. Ideally, one device within the apartment to handle all the components would be handy. This Table shows how each component can be controlled independently, given that each technology has a different manufacturer, control strategies, and maintenance access types. For the components that allow for user-friendly app control, the user can have control of all components at once through a virtual assistant technology such as Alexa or Google by voice or in the app.

Fire Safety

The fire safety domain Table (Table 5) focuses on the façade characteristics of fire class, fire resistance time, fire stops and the compartments within the panel. The fire stops between the panels must be designed in cross-section and plan view since there will be a space between the panel and the building structure. The compartment criteria will help enhance the fire safety of the technologies and components of the façade panel and facilitate the maintenance of the parts. The materials chosen have to be under the thermal requirements as well as the fire classification of the building. Since the building is around 10 floors, the fire class is B.

Table 3. Energy supply and production table description per requirement, component, characteristic and design criteria to consider for the panel design.

Energy supply			
Requirements	Façade component	Façade characteristics	Design criteria
Temperature			
Thermal comfort	Heating & Cooling	CoP	≥ 3
		Heat exchanger	≥ 60%
		Power supply	230 volts - 1 phase - 50 Hz
		Heat transfer principle	Air-electric
	Heating	Heating capacity	≤ 110 W/m2
		Power consumption	≤ 600 W
		Energy class	≥ A
	Cooling	Cooling capacity	≤ 80 W/m2
		Power consumption	≤ 600 W
		Energy class	≥ A
Indoor air quality	Ventilation	Heat recovery	≥ 75%
		Power supply	230 volts - 1 phase - 50 Hz
		Energy class	≥ A
		Heat transfer principle	Air-electric
PV panels			
Energy production	PV-panels	Efficiency	≥ 20%
		Angle (case specific dependant)	30° - 90°
		Energy production per m2	≥ 154 -180 kWh
		Orientation	South, East and/or West

Table 4. User interaction table description per requirement, component, characteristic and design criteria to consider for the panel design.

User Interaction			
Requirements	Façade component	Façade characteristic	Design criteria
Perceived control	Shading	Control	Manual, bead chain/remote control
			Digital, user-friendly app
			Fixed shades, not movable on the outside
	Vents / window	Operable windows	Operable windows
			Handles are accesible
	Mechanical Ventilation, Heating and cooling system	Control	Manual, unit touch panel
			Manual, user-friendly app
			Digital, user-friendly app
	Technologies	Filters	Easy maintenance and understanding

>> Interface within Alexa/Google to handle all the components with one app
>> if automation and/or BMS are present, users receive information for further comfort optimisation

Table 5. Fire safety table description per requirement, component, characteristic and design criteria to consider for the panel design.

Fire safety			
Requirements	Façade component	Façade characteristics	Design criteria
Fire resistance	Materials	Fire class	B
		Resistant time	≥ 60 min
	Connections	Fire stops between panels	Firestop connection
		Compartments	Horizontal and vertical
			Per technology

2.2 Technologies integration workflow

Integrating building services driven by air and electricity for ventilation, heating and cooling into the panel requires a clear understanding of what the airflow should be through the technologies to meet indoor comfort demands and make the system more efficient. Figure 3 exemplifies the working principle that the air should follow from the outside, through the façade to the inside of the room. One of the main criteria to consider through the airflow is using filters before and after the technologies to enhance good air quality. Recirculation of the inside air through the heating and cooling technology is possible as long as an air filter is included in this part of the airflow.

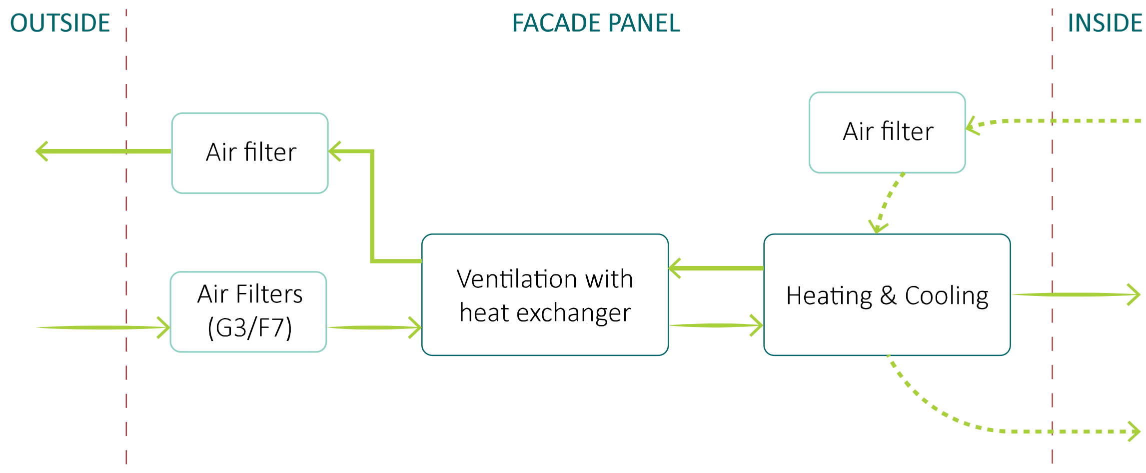


Figure 3. Ideal airflow diagram of the integrated services (ventilation, heating and cooling) in the façade.

2.3 Stationary heat balance hand-calculations

2.3.1 Case Study Design

The apartment building is located in the tenement flats of Centro Urbano Miguel Aleman in Mexico City. A complex with four types of apartments as shown in Figure 4. It was built in the early 50s and was inspired by the post-war tenement flats in Europe, the architect was Mario Pani. The structure of the building consist of a regular modular grid of concrete slabs and beams. For the similarities to a european post-war residential building and the concrete structure typology, this building is a suitable case study to analyse the heating and cooling demands required for an integrated unitised façade panel.

The case study apartment is of 60 sqm. It consists of two rooms, one dining room, a kitchen, one toilet, a walk-in closet and a tv-room. It represents an average apartment for a family of three people. Thus, the static heat balance calculations to determine the heating and cooling capacities for the design requirements were based on this apartment. For practical comparisons the same building was assumed to be in both case study countries, the Netherlands and Mexico City. Table 6 shows the architectural information required for the calculations, such as area, windows, volume, and height.

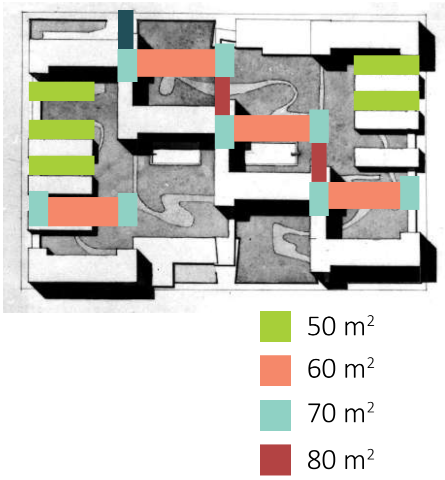


Figure 4. CUPA apartment typologies

Figure 5. Case study, Centro Urbano Miguel Aleman master plan with the chosen building to analyse highlighted in red

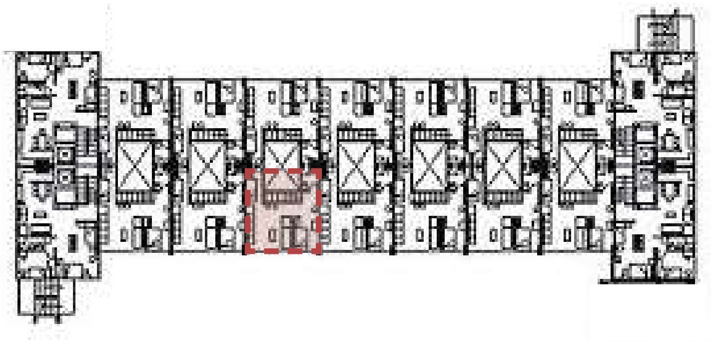


Figure 6. Lower level plan with the chosen apartment to analyse highlighted in red

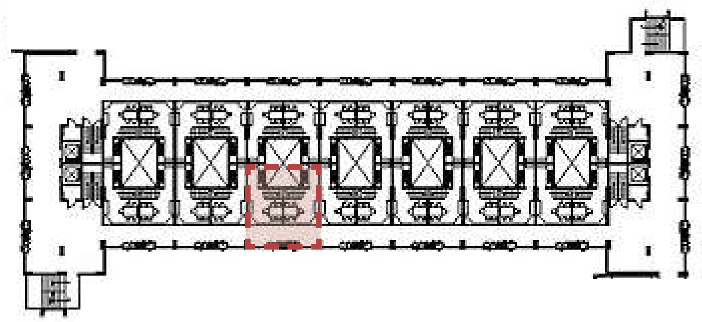


Figure 7. Upper level plan with the chosen apartment to analyse highlighted in red

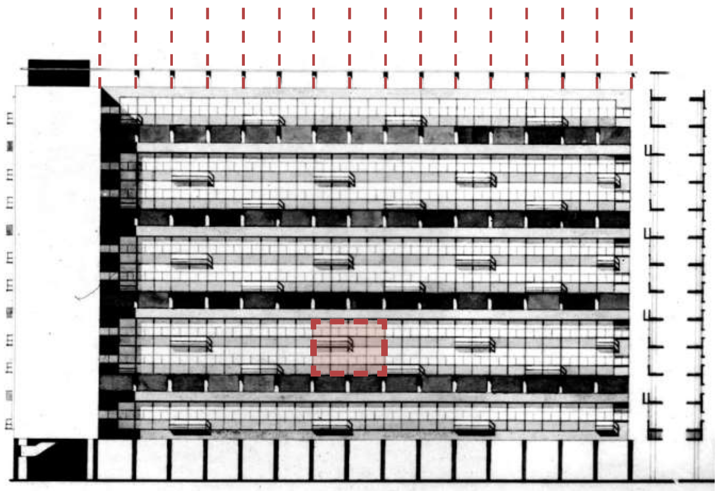


Figure 8. Façade elevation West/East with a cross section on the right side and the chosen apartment to analyse highlighted in red

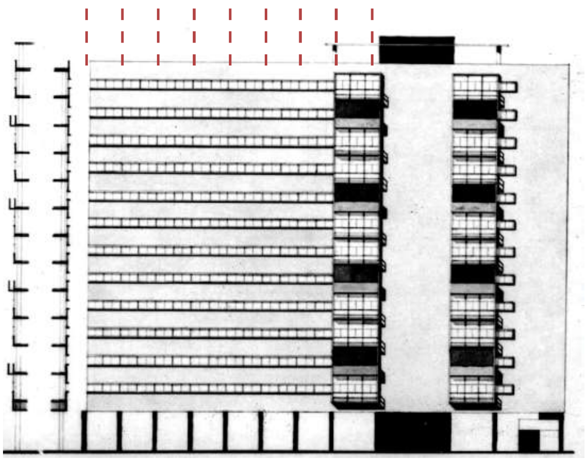


Figure 9. Façade elevation North

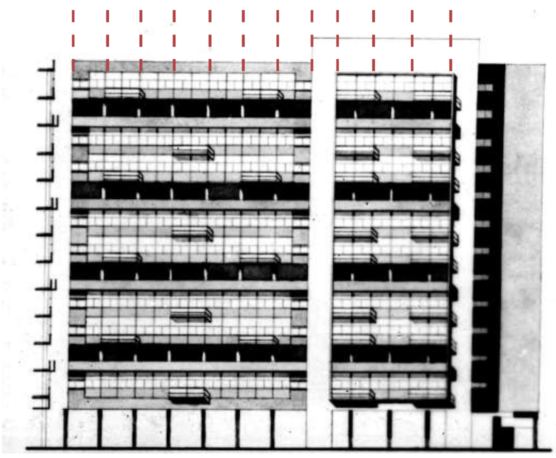


Figure 10. Façade elevation South

Table 6. Dimensions considered of an average 60m^2 apartment for the design requirements of the technologies capacity.

	Area [m2]	Window Height [m]	Volume [m3]	Naturally ventilated	Façade area [m2]	WWR [wall area]	WWR [window area]	Distance from the façade [m]	Height [m]	Free height [m]
Dinning room	8,9	0,9	23,2	Yes	4,7	**4,6**	**1,9**	2	2,6	1,9
Kitchen	4,0	0,9	10,3	Yes	4,7	**4,6**	**1,9**	2	2,6	1,9
Room 01	14,3	1	38,6	Yes	9,0	**8,5**	**3,6**	N.A.	2,7	2
Room 02	7,0	1	18,8	Yes	4,0	**3,8**	**1,6**	N.A.	2,7	2
Bathroom	3,9	1	10,6	Yes	5,0	**4,7**	**2,0**	N.A.	2,7	2
Walk-in closet	3,8	1	10,3	Yes	5,0	**4,7**	**2,0**	N.A.	2,7	2
TV-room	11,6	1	31,4	No	N.A.	N.A.	N.A.	N.A.	2,7	2

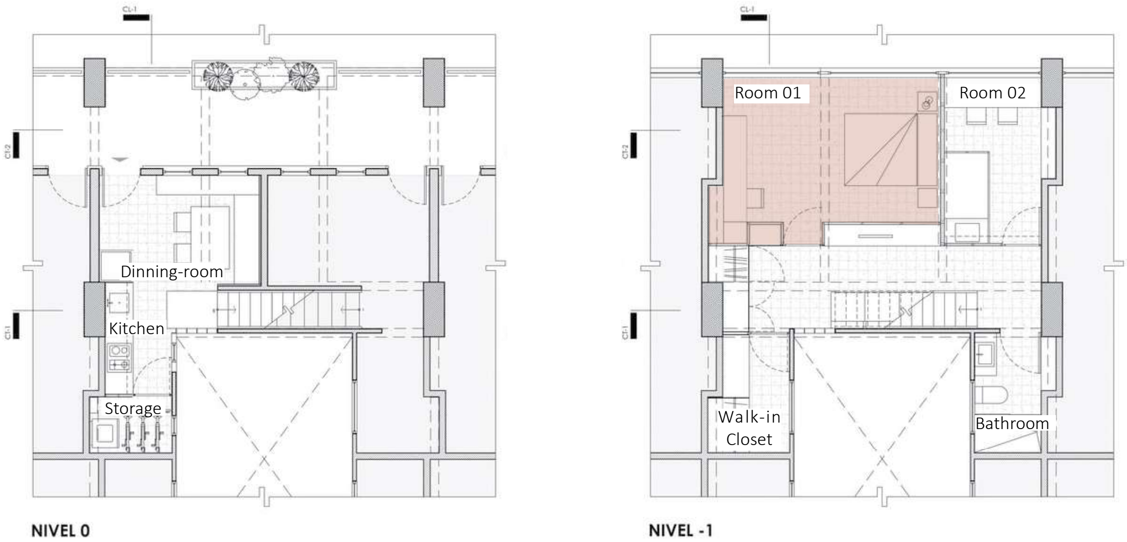


Figure 11. Case study architectural plan views

Figure 12. Case study section views

2.3.2 Stationary heat balance hand-calculations

As mentioned before, the same architectural layout was assumed to be in two different countries, Mexico and the Netherlands. From the apartment, two areas were not considered since they do not have a façade to the exterior; these were the tv-room and the walk-in closet. The results from room 01 were used for heating and cooling capacities for the design requirements. The stationary heat balance was calculated using the equations 1, 2, 3, 4 and 5 shown below. Table 7 shows the parameters considered for the hand-calculations, there are values that depend on the climate and country, therefore a diference is made on the values in properties such as the wall and glazing u-value, qsun and operative temperatures. The temperature and envelope insulation values were retrieved from the norms and guidelines of each country. In the case of Mexico City, the design category considered was CAI II from the norm NMX-C-577-ONNCCE-2020. The qsun was calculated from the epw file from each country using the software Climate Consultant. The solar graphs used to determine the qsun value can be found in appendix C. For the air properties and person heat production, standard values were considered. In addition, the simulated days were the hottest and coldest of summer and winter, respectively. The calculations tables for Mexico City are 8 and 9 whereas Tables 10 and 11 are for the Netherlands.

Stationary heat balance method:

$$Qcool = Qtransmission + Qventilation + Qsun + Qintern \quad \text{Eq. 1}$$

Qtransmission

$$Qtrans = (Uglass\ Aglass\ \Delta T) + (Uwall\ Awall\ \Delta T) \quad \text{Eq. 2}$$

Qventilation (Energy loss through ventilation)

$$Qvent = \frac{\rho c n V \Delta T}{3600} \quad \text{Eq. 3}$$

Qsun

$$Qsun = qsun\ abs\ t\ A \quad \text{Eq. 4}$$

Qint

$$Qint = \sum appliances \quad \text{Eq. 5}$$

Table 7. Data base considered for the stationary heat balance hand-calculation in Mexico City and the Netherlands.

		Mexico	Netherlands
Wall properties			
WWR		40%	
Wall area		60%	
Wall U value [W/(m2K)]		0,5	0,16
Glass properties			
Glass LT [%]		0,75	**0,8**
Glass SF/SHGC/g-value [%]		0,6	
Glass Ug-value [W/(m2K)]		1,2	1,1
Energy			
Person heat production [W]		80	
qsun summer [W/m2]		130	200
qsun winter [W/m2]		280	120
Air properties			
c (Specific heat capacity) [J/kgK]		1006	
n [m3/h]		1	
Temperature			
Outside temperature [°C]	Summer	29	28
	Winter	3	-10
ρ (Air density) [kg/m3]	Summer	1,16	
	Winter	1,28	
Inside temperature [°C]	Summer	23	25,5
	Winter	20	18
Temperature difference [°C]	Summer	6	2,5
	Winter	-17	-28

Table 8. Cooling demand stationary heat balance calculation for Mexico City.

	SUMMER					
	Qcooling [W]	Qtransmission	Qventilation	Qsun	Qint	**Qc [W/m2]**
Dinning room	459,3	27,3	45,0	147,0	240,0	51,5
Kitchen	274,2	27,3	19,9	147,0	80,0	69,4
Room 01	565,7	51,3	74,8	279,6	160,0	39,6
Room 02	265,6	23,1	36,4	126,0	80,0	38,2
Bathroom	283,7	28,4	20,5	154,8	80,0	72,4
Total energy demand	**1848,5**					

Total cooling demand/m2 **44,2 [W/m2]**

Table 9. Heating demand stationary heat balance calculation for Mexico City.

	WINTER					
	Qheating [W]	Qtransmission	Qventilation	Qsun	Qint	**Qh [W/m2]**
Dinning room	257,1	-77,2	-140,8	316,6	240	28,8
Kitchen	257,1	-77,2	-62,4	316,6	80	65,1
Room 01	382,4	-145,5	-234,2	602,1	160	26,8
Room 02	172,0	-65,6	-113,9	271,5	80	24,7
Bathroom	268,5	-80,5	-64,3	333,3	80	68,5
Total energy demand	**1337,0**					

Total heating demand/m2 **32,0 [W/m2]**

Table 10. Cooling demand stationary heat balance calculation for The Netherlands.

	SUMMER					
	Qcooling [W]	Qtransmission	Qventilation	Qsun	Qint	**Qc [W/m2]**
Dinning room	491,9	7,0	18,7	226,2	240,0	55,1
Kitchen	321,5	7,0	8,3	226,2	80,0	81,4
Room 01	634,5	13,3	31,2	430,1	160,0	44,4
Room 02	295,1	6,0	15,2	193,9	80,0	42,5
Bathroom	334,0	7,3	8,6	238,1	80,0	85,2
Total energy demand	**2077,0**					

Total cooling demand **49,7 [W/m2]**

Table 11. Heating demand stationary heat balance calculation for The Netherlands.

	WINTER					
	Qheating [W]	Qtransmission	Qventilation	Qsun	Qint	**Qh [W/m2]**
Dinning room	686,1	-78,5	-231,9	135,7	240	76,9
Kitchen	396,9	-78,5	-102,7	135,7	80	100,5
Room 01	952,4	-148,5	-385,8	258,0	160	66,6
Room 02	451,0	-67,0	-187,6	116,4	80	64,9
Bathroom	410,9	-82,2	-105,8	142,8	80	101,2
Total energy demand	**2897,3**					

Total heating demand **69,3 [W/m2]**

Case study: Mexico City

The first case study is in Mexico City in Mexico. The climate is Cwb (Oceanic Subtropical Highland Climate) according to the Köppen Classification. According to the hand-calculations for the stationary heat balance of the 60 sqm apartment the overall cooling demand is 1.848,5 W. whereas the heating demand is 1.337 W.

Case study: The Netherlands

The second case study is the Netherlands. The climate is Cfb (Marine West Coast Climate) according to the Köppen Classification. According to the hand-calculations for the stationary heat balance of the 60 sqm apartment the overall cooling demand is 2.077 W whereas the heating demand is 2.897,3 W.

Heating and cooling design capacities

As shown in Figure 13, the results for both countries performed as expected. Mexico City has higher cooling demand and lower heating demand than the Netherlands. The exact opposite performance was shown in the Netherlands with higher heating demand. Based on both countries' stationary heat balance calculations, an average **design capacity** was calculated considering **70%** of the total energy demand required for the integrated façade panel deisgn since the days used for the calculations were the extreme temperatures recorded during winter and summer. The values from the chosen room named "Room 01" were used for this exercise and are shown in Table 12.

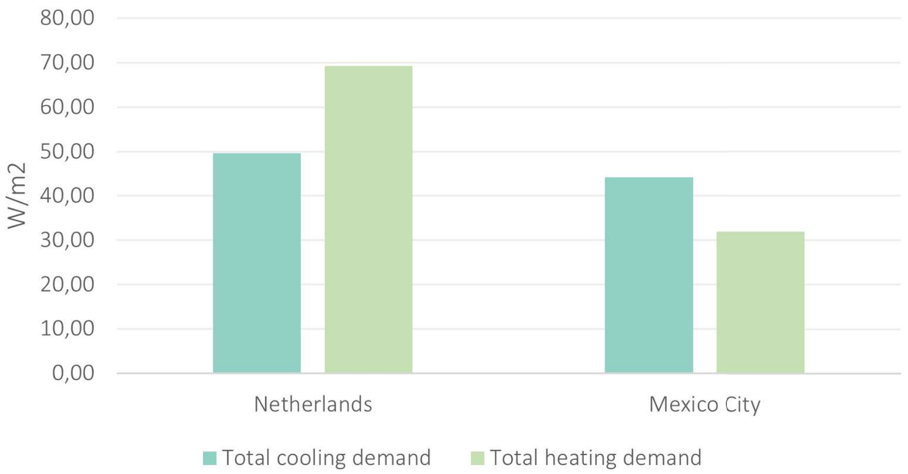


Figure 13. Heating and cooling demand comparison hand-calculation results for the cases of Mexico City and the Netherlands

Table 12. Heating and cooling design capacities per country.

Design capacity Room 01			
	Units	Mexico	Netherlands
Q cooling [70%]	[W]	565,7	634,5
	[W/m2]	39,6	44,4
Q heating [70%]	[W]	382,4	952,4
	[W/m2]	26,8	66,6
Room 01 area	[m2]	14,3	14,3

2.3.3 Ventilation calculations

The same apartment layout used for the stationary heat balance calculations was used for the ventilation—a 60 average sqm residential apartment. To determine the required ventilation for the Design Requirements, the calculation was based on the architectural layout's most significant rooms: the dining room and room 01. The minimal ventilation requirements were retrieved from the norms and guidelines of each country. However, in the case of The Netherlands, a higher fresh air supply of 10 was considered instead of 7. In the case of Mexico City, the category considered was CAI I from the norm NMX-C-577-ONNCCE-2020.

VENTILATION DESIGN CAPACITY

For Mexico, the ventilation requirements for the fresh air supply per person in the rooms is 72 m3/hr and 144 m3/hr for the living room. The air exchange rate per dwelling varies per country. For Mexico, the dining room requires 35 m3/hr, and the main bedroom 58 m3/hr. For The Netherlands, the dining room requires 75 m3/hr, and the main bedroom 125 m3/hr.

Table 13. Minimum requirements from each country norms.

	units	Mexico	Netherlands
Air exchange	[m3/(h per m2)]	1,51	3,24
Fresh air supply	[l/s]	10	10

Table 14. General architectural values from the case study layout for a 60 sqm apartment.

	Area [m2]	Height [m]	Volume [m3]	No. of people
Dinning room	8,9	2,6	23,2	4
Kitchen	4,0	2,6	10,3	2
Room 01	14,3	2,7	38,6	2
Room 02	7,0	2,7	18,8	2
Bathroom	3,9	2,7	10,6	1
Walk-in closet	3,8	2,7	10,3	1
TV-room	11,6	2,7	31,4	4
Total area	**41,8**			

Table 15. Air exchange rate per dwelling and fresh air supply per person requirements for a 60 sqm apartment.

	Air exchange rate per dwelling [-/h]		Fresh air supply per person [m³/h]	
	AER = Room fresh air supply / Room volume		= (# people * fresh air flow * 3,6)	
	Mexico	Netherlands	Mexico	Netherlands
Dinning room	6	6	144	144
Kitchen	7	2	72	72
Room 01	2	2	72	72
Room 02	4	4	72	72
Bathroom	3	3	36	36
Walk-in closet	4	4	36	36
TV-room	5	5	144	144

2.4 Conclusions

This chapter solves the sub-research question: "To what extent is integrating building services into a façade panel effective in meeting comfort demands?". Integrating building services into a façade panel can fully meet the comfort demands of the interior space of a 60 sqm apartment under two different climate conditions; Cwb and Cfb. To conclude this, design requirements broken by five domains; architecture, comfort, energy supply and consumption, user interaction and fire safety were developed. This design requirement also gives the designer a clear guideline on the criteria to follow for designing an air-to-air integrated façade panel.

The architecture criteria defines the panel geometry in height, width and depth. This will be key when choosing the technologies later since it will constrain the technology's dimensions. Characteristics such as modularity, flexibility and easy maintenance will lead to the order of the components in the façade panel, the search for simplicity in the design, and a low number of technologies are linked to easy maintenance. The building physics aspects of the location of the technologies within the façade panel concerning the interior space will allow for design flexibility and enhance indoor comfort through accurate airflow dynamics. The type of façade system (unitised), the connections (dry), the structural characteristics of the components (brackets connections to the building), tolerances and movements (absorbed by the unitised system) are strictly linked to the concrete structure of the building since they are required to be designed in combination. Moreover, this criteria considers preliminary dimensions for easiness in the panel transportation after manufacturing them at the factory.

As expected, the comfort demands vary according to the climate and country. This is proved by having two case studies, Mexico City and the Netherlands. However, similar comfort levels are sought in both countries in terms of visual and acoustic comfort and indoor air quality (IAQ). The definition of the design criteria for IEQ was based on regulations and guidelines per country, static hand calculations on the hottest and coldest day of the year, case specific, and hand calculations for the ventilation demands in each country. More importantly, passive measures are defined first to enhance the lowest possible energy demand required to meet comfort levels with the technologies. This means that values are given per country for the façade characteristics of sunshade systems, namely roller blinds, window-to-wall area, Rc values for the walls, and glazing specifications such as u-value and g-value.

Given that the technologies are driven by electricity and use air as a medium, a design requirement domain table on energy supply and production was done. To ensure an energy-efficient façade panel, the façade characteristics of CoP, the integration of heat exchangers in the ventilation unit, the heat-transfer principle (air), the energy class of the units, power consumption and heating and cooling capacities are essential characteristics to consider when choosing the technologies. For instance, the CoP of the technologies is critical to achieving good performance with less possible energy. That is why the CoP requirement is set to a minimum of 3. Regarding the PV panel's energy production, the tilt angle and orientation are dependent on the climate and location of the building. However, optimal orientations are defined (south, east and west), and a minimum of 154kWh per sqm is recommended.

Regarding fire safety, integrating technologies in a façade panel increases the risk of fire spread. That is why designing compartments for the technology units and using suitable cladding materials for class B is recommended in the DR. It can become a complex situation regarding user interaction since the number of technologies implemented can be directly proportional to the number of control devices the user will require to make the façade function. This is why it is adviced that the technologies chosen have an app access that can later be linked to a 'main' app, namely Google or Alexa, through which you can control all devices in one through WiFi.

The hand calculations show an expected performance in heating and cooling seasons per climate in the chosen case study Sout-East oriented; for practical reasons, it was assumed to be located in both the Netherlands and Mexico City to compare the two countries heating and cooling loads. This means that in the case scenario of Mexico City, the cooling loads are higher than the heating loads. In contrast, the heating loads in the Netherlands are higher than the cooling loads. Overall, an energy consumption of 70 W/m2 was achieved for the heating season in the Netherlands and 45 W/m2 during the cooling season in Mexico City. The cooling and heating capacities required for the design considers 70% of the calculated demands since the calculations were done for the hottest and coldest days of the year. The ventilation calculations were done with a higher fresh air supply than the considered by the norms in the Netherlands (10 l/s). This value was used for both scenarios. Thus, the ventilation design capacity was the same for both countries, given that they have the same volumes and values for the calculation. As mentioned before, the calculations are linked to the comfort demand requirements, and they function as a measurement tool to define the feasibility of the technologies, heating and cooling, and ventilation capacities for the façade panel design.

Chapter 3 | Literature Review

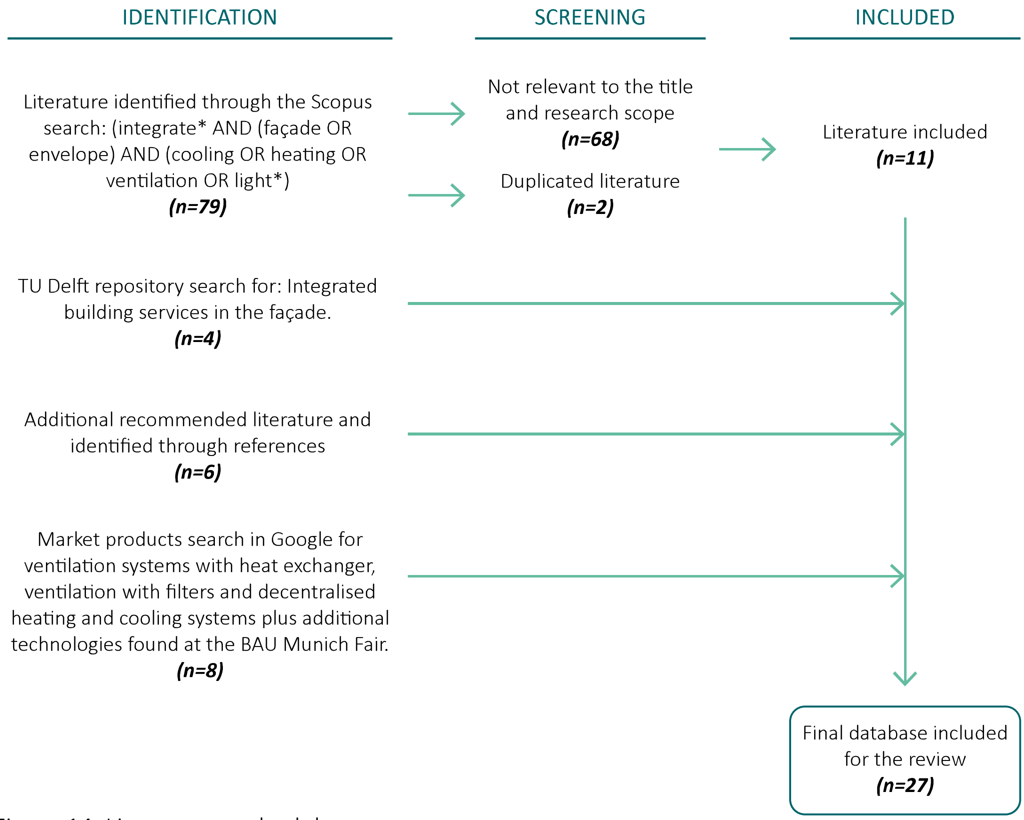


Figure 14. Literature methodology

3.1 Literature methodology

The literature was conducted to analyse the state-of-the-art building services façades and the potential building services technologies for the implementation in the integrated services façade panel design.

The literature search for the façade integrated technologies was based on four sources: Scopus, TU Delft repository, recommended literature and market products. The search string in Scopus was: integrate* AND (façade OR envelope) AND (cooling OR heating OR ventilation). The recommended literature were research papers and PhD dissertations. The database results from Scopus was filtered on their relevancy to the thesis scope depending on the title and the abstract and the removal of duplicates. The market products were found based on a Google search with the keywords: decentralised ventilation units, stand-alone heat pumps, and ventilation units for polluted cities. As well as a field trip to the Munich BAU fair, one of the world's largest and most important trade fairs for architecture, materials, and systems. The different ventilation systems were seen first-hand and technical information was gathered regarding the units' performance. The Scopus and TU Delft database, the recommended papers, the Google search, and the field trip left a final database of 27.

This literature selection process is exemplified in Figure 14. The sources are mostly journal articles, followed by articles, doctoral theses, company websites, and journals.

3.2 Overview of literature results

The literature review confirmed the knowledge gap from the integrated services façades in residence buildings, the few technologies suitable for this purpose compared to central systems and the need for studies done in an oceanic subtropical highland climate (Cwb). In this sense, most of the case studies for façade integration focus on building retrofit for office buildings, whereas residential buildings are overseen (Figure 16). The suitable technologies for façade integration are categorised as heating and cooling, cooling, energy generation and solar control. At the same time, the case studies climates from the literature are hot and warm temperature (Figure 15). This is because the technologies are solar-driven, and their performance can be better shown in those scenarios. However, this chapter is an overview of the found literature, and it does not aim to assume that these technologies can only be applied in the before mentioned climates. For instance, using solar cooling façade systems is feasible for almost every climate region and orientation if the cooling demand is controlled by passive measurements first, which is strictly linked to the potential of making it a self-sufficient concept (A. Prieto Hoces et al., 2016). Solar technologies' potential is also higher when used in a temperate and hot-arid context, depending on the orientation and climate extremity. In this sense, the best-suited orientations for cooling technologies are East and West (A. I. Prieto Hoces et al., 2018).

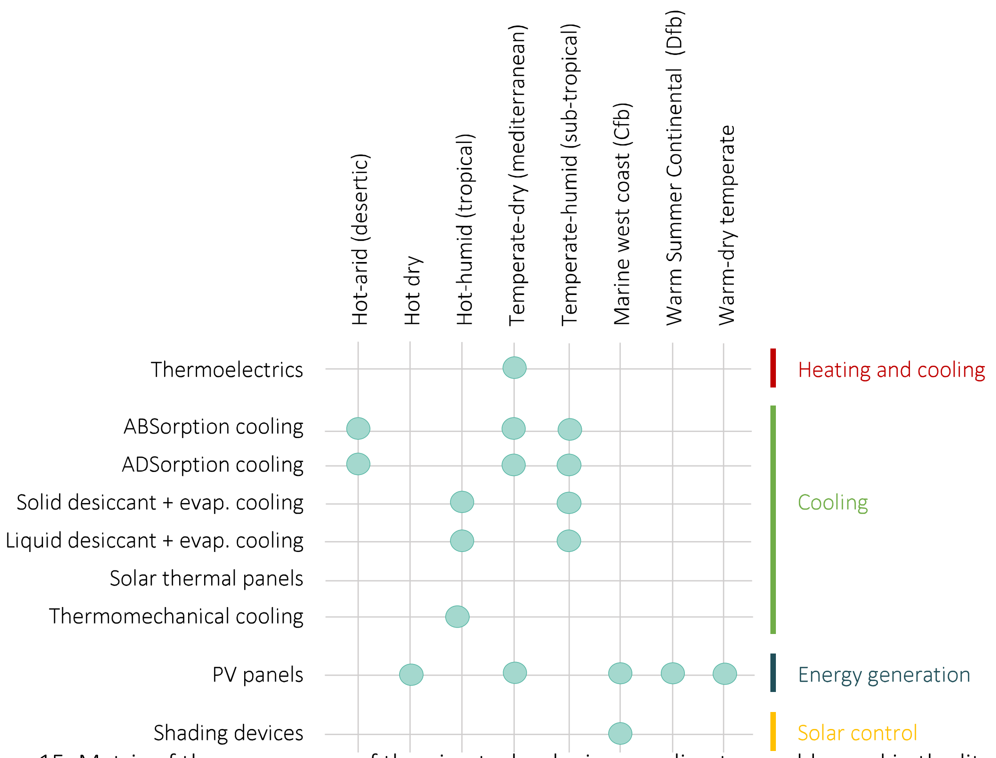


Figure 15. Matrix of the appearance of the nine technologies per climate as addressed in the literature review. The technologies are divided by technology use; heating and cooling, cooling, ventilation, energy generation and solar control

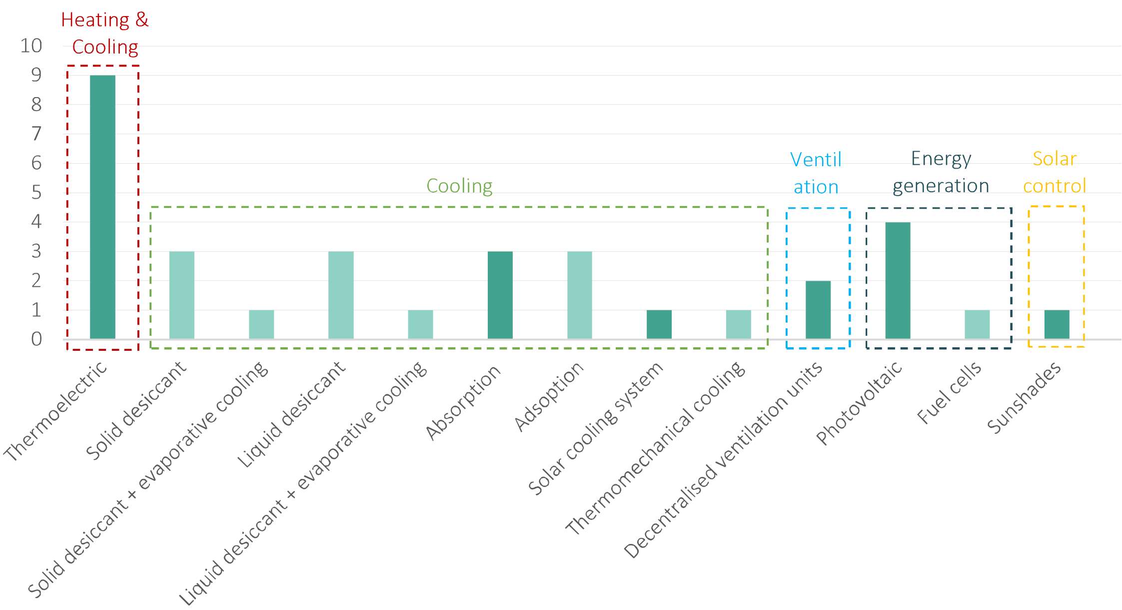


Figure 16. Number of papers where the integrated façade technologies found in the literature review are mentioned. They are shown divided per technology use; heating and cooling, cooling, ventilation, energy generation and solar control

3.3 State-of-the-art building services façades

As part of the literature review process shown in Figure 14, seven novel concepts of building services façade integration were found. All of them were designed to be applied in office buildings and no integrated façade panel was found for dwellings. Thus, this confirms a gap in knowledge that this thesis aims to contribute to and the found state-of-the-art buildings will work as inspiration for this thesis purposes. The building services integrated into the found façades are decentralised ventilation, heating, cooling, lighting, sunshade systems, and PV panels. Most of the services that produce heating and cooling are air to water and, therefore, require water-pipe connections, making it unsuitable for a stand alone serviced façade. The buildings found started their operation between 2003 and 2018 in Germany, France and the United Kingdom.

Several researchers and companies agree that decentralised systems can be implemented without additional costs due to installation savings such as equipment, ducts, and cables. The investor can increase the rent area by saving up to 12% on floor height since installing a service floor is no longer require. (Schuler, 2005) According to measurements done by the Energy Research Center of the Netherlands (ECN) for the Smartbox unit, the energy demand of the building is reduced by 50% by adding improved insulation, smart sun shading, and daylight admittance combined with energy-efficient heating, cooling, and ventilation (de Boer, 2008). Whereas the manufacturers of the E2 façade mention that the primary energy requirements for heating, cooling and ventilation can be reduced by up to 50% compared with the 2009 German Energy Saving Decree 2009. (https://www.stylepark.com/en/news/the-intelligent-façade OR https://www.schueco.com/com/). Prieto et al. (2017) also mentions that such façades have benefits on several fronts, like cost savings for the main stakeholders and even improving users' comfort. The flexibility and local control of the decentralised system allows for the identification of local demands and therefore are more energy efficient while the perceived indoor comfort undergoes improvements. (A. Prieto Hoces et al., 2017)

TEmotion façade – Hydro Building systems

Wicona developed the TEmotion façade. The design consists of a two-glass skin façade with a ventilated air chamber in which all functional systems are located. The façade has a total depth of 45cm. It is the only panel with all building services integrated: decentralised ventilation, heating, cooling, lighting, sunshade systems and PV panels. It aims to achieve a high level of self-sufficiency and room-conditioning. (Oebbeke, 2009) (Djairam, 2008)

Between the issues, we find the materiality of opaque panels, water pipes and cables from the room inside into the façade construction and the lack of design flexibility. This last one had a direct negative effect on the architect's acceptance. However, the product was found to be two of the only ones designed with circular principles and to have a factory manufacturing process. ("Wicona Temotion, Most Innovative Façade System at the Fair BAU 2011," 2011)

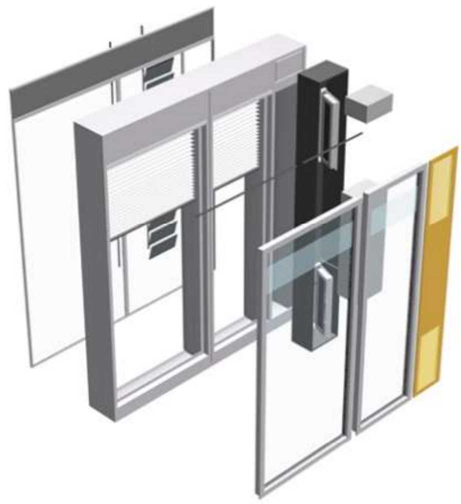


Figure 17. TEmotion façade exploded view

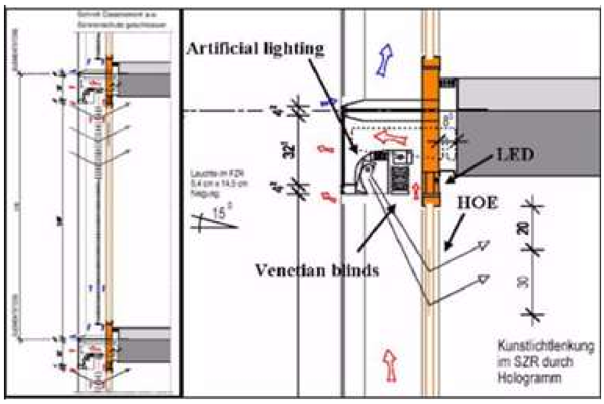


Figure 18. TEmotion façade section

E2 façade

Schüco developed the E2 façade. The design consists of a single-skin façade that is cantilevered with unique arms. It is a combination of a curtain wall and a structural glazing system.

The system's location is in front of the slab, and whereas this could be an aesthetically accurate decision, it is not in terms of maintenance.

This product stands out from the others in its design concept. The company has different modules that can be added, shuffled, and complemented with each other. This way, the E2 façade is based on four functional, flexible modules that allow individual solutions to complete a system. These modules are made from automatic opening units, solar shading devices, decentralised ventilation and solar (photovoltaic) modules. On top of this, the system can be integrated into a building management system (BMS). (Schüco E2 Façade, n.d.)

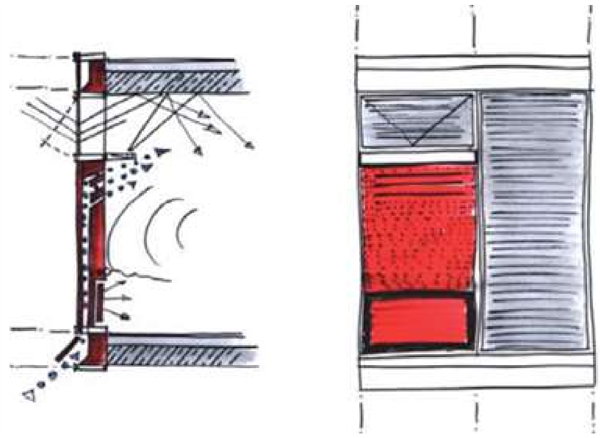


Figure 19. Building services integration in the E2 façade

I-module

Schossig and Gatermann developed the i-module. The design consists of a single-skin unitised cladding panel. The total dimensions are 2.7x3.35m with 20cm depth. Its functionality requires an external power source and cold and hot water supply. Between the limitations, we find that it is conformed with opaque panels and needs water pipes and cable connections from inside the building. Apart from the ventilation module location that obstructs the views to the outside. (Klein, 2013)

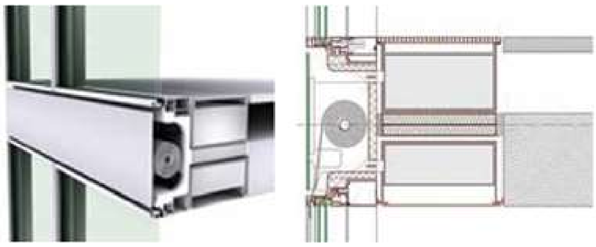


Figure 20. Building services integration in the I-module

Post Tower

Helmut Jahn Architects developed the post tower. The design differs from the other façades analysed because it is not a module; it involves a unitised double-skin curtain wall façade. It requires a connection for its functioning through an air intake nozzle. This innovative system allowed the architect to have one more floor of renting space instead of a service floor. (Schuler, 2005)

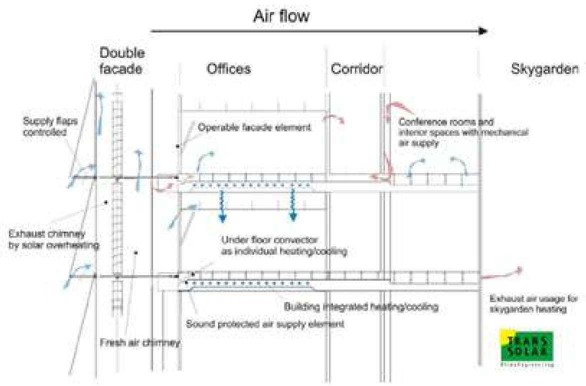


Figure 21. Post Tower section drawing

Smartbox Energy Façade

The Smartbox unit implements decentralised ventilation, heating, cooling, lighting, sunshade systems and PV panels. However, this product stayed at a prototype level. The dimensions of the design are 40x40x110cm. (Klein, 2013)

Figure 22. Impression of the smartbox integrated in the fron of the slab

Breathing Window

This project was developed to provide good air quality ventilation and a healthy indoor climate, with minimal energy loss, for housing. The design consists of an installation box of standardised space next to the window frame. Here, the required services can be stored. Ventilation can be achieved through an operable window. (De Boer - 2008 - Dynamische Zonnegevel..Pdf, n.d.) However, a decentralised ventilation system can also be added inside this box. Figure 23 below represents an example of possible concept scenarios. The first scenario exemplifies a situation in which the heating load is low. Therefore the existing radiator can be used, and an operable window can function as a natural cooling and vent during the day. In this case, the box is left empty. The second scenario exemplifies a higher heating and cooling demand climate. Mechanical ventilation with heat recovery is located inside the box. (Ebbert, 2010) (De Boer - 2008 - Dynamische Zonnegevel.. Pdf, n.d.) (Fiwihex BV, 2005)

Cellia - Interactive cell

This façade panel is a compact system that integrates the stem, wiring and energy production, external sun shading, motorised blinds and internal and external lighting (see Figure 24). The HVAC system is integrated through a heat pump developed in coordination with Mitsubishi Motors and requires a water connection. One of the main attributes of this system is that it allows higher building energy efficiency levels in terms of operating costs and environmental impact. Moreover, this was the only example found to integrate a plug&play modular concept (Figure 25) with prefabricated panels that overcome the barriers of quality and integration in integrated services façades. Regarding façade construction, it requires mini-cranes instead of tower cranes and scaffoldings, in new buildings. The concept's strengths are the increasing building value while maintaining active work operations regarding building services. The panel was developed in Milan, Italy, by the company Focchi in partnership with Progetto CMR and Mitsubishi Motors. (Explore R2M Cellia Fuori Salone 2022 in 3D, n.d.)

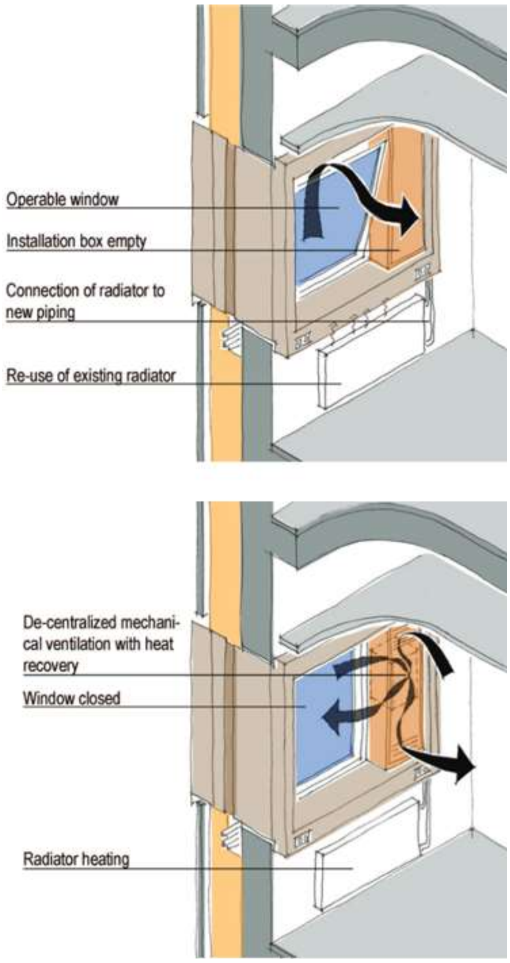


Figure 23. Building services installation as a box concept

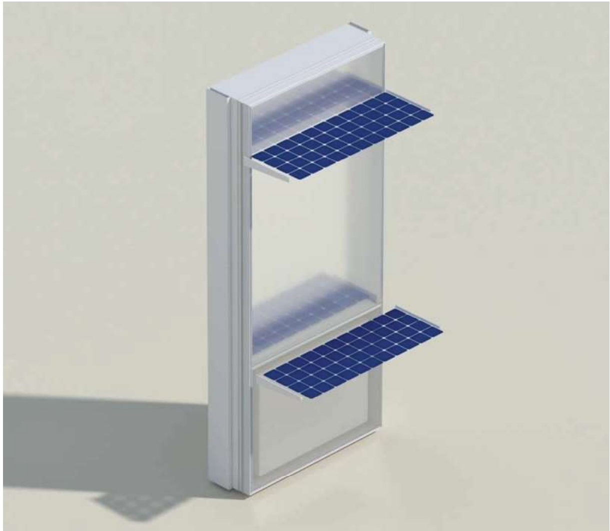


Figure 24. Visualitation of the Cellia interactive cell

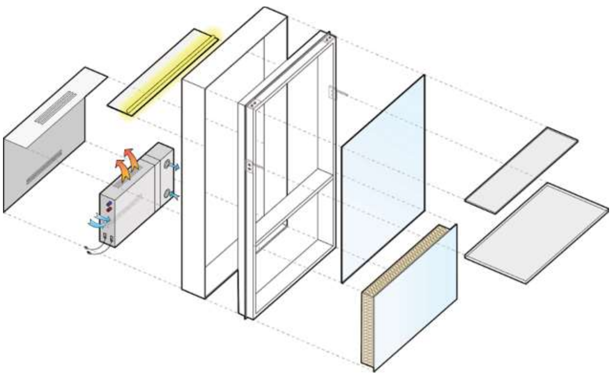


Figure 25. Cellia interactive cell exploded view of the parts

Table 16. State-of-the-art building services façades comparison.

Product name	**cellia interactive cell**	**TEmotion facade -Hydro Building Systems**	**E2 facade**	**i-module (Capricorn Haus)**	**Smartbox Energy Façade**	**Breathing window**	**Post Tower**
Company	Focchi & Progetto CMR	Wicona	Schüco	Schossig and Gatermann	ECN, cepezed, et al		Helmut Jahn Architects
Year	2021	2018	2007	2007	2006	2004	2003
Location	Italy	Germany, France, UK		Düsseldorf, Germany	Prototype level	Netherlands	Bonn, Germany
Operable windows	No	No	Yes	Yes		Yes	Yes
Descentralised ventilation	Yes	Yes	Yes. Cooling and heating air in the system. They have 5 different concepts, with and without heat recovery. (C4). The air enters through the ceiling, the outging air leaves my a ceiling device for heat recovery.	Ventilation (fresh air enters through a closable gap).	Yes	Yes	Yes
Heating	Yes	Yes. There are ducts for piping and wiring.	Heat recovery?	Heating + heat recovery (needs an external power source and cold and hot water supply)	Yes	Yes	Pre heated air
Cooling	Yes	Yes	No - the blinds reduce the cooling load by aprox. 50%	Yes	Adiabatic cooling (water supply needed)	Yes	Pre cool air
Lighting	Yes	Yes	No	Yes (ligh shelf)	Glass spandrels with vacuum insulation	No	No
Sunshade	Yes	Yes	Yes - CTB(Concealed Toughened Blind) sunshading system. Solar shading and anti-glare protection. Design consists of micro louvre. It is not visible because it is located in the are between floors.	Yes - Venetian blinds in the cavity of the boxed windows.	Yes - Retro reflective interior blinds	No	Yes
Solar integration	Yes	Yes	Yes (Thin PV films tech). Facade integrated photovoltaic module. Highly efficient component for solar energy generation. Meets **requirements** of thermal insulation, weather resistance and sound reduction. Different tyes of solar cells, transparent included.	No	Yes - PV panels in semi-transparent glass	No	No
Acoustics	Not given	Not given	Not given	Sound insulation	Not given	Yes	No
BSM (Building Services Management) Control	Not given	Yes, user can control it too.	Uniform automation of opening units, solar shading and decentralised veintlation. This allow automatic night-time cooling and opening individual windows.	Not given	Not given	Not given	Not given
Circular design	Modular	Yes	Modular	No	No	No	No
Manufacture process	Factory	Factory					
Location on the facade	Panel in front of the building structure.	Transparent section for sunshades and natural lighting improvement elements. Opaque section into which building services and slar cells are integrated.	In front of the slab. Therefore, homogeneous, highly transparent and stylish facades. 'Max. Architectural freedom'	Units behind the facade. Dimensions of 2.70m x 3.35m	Smartbox goes in front of the floor edge. Therefore, there is room to different panel combinations. measures 40 x 40 x 110 cm	Next to the window	Floor slab behind the facade. Only connection is an air intake nozzle.
Design	A single compact façade panel unit integrates an HVAC system that provides energy production, sunshade systems, and internal and external lighting. Is adaptable to the existing inter-storey height. Suitable for new buildings and retrofits. According to the designer, it is energy efficient.	**Two glass skin** comprising a ventilated air Chamber which houses all functional systems. ventilation, heating and cooling have been combined in one element produced by Trox/FSL. The size of this element is 0.30 m x 0.40 m x 1.30 m TOTAL DEPTH of the facade 45cm	Concealed in front of the intermediate floor within the **single-skin façade** construction, combination of curtain wall and structural glazing system. All building services components are located in a designated space between the floor slab and the façade. For this reason, the façade is cantilevered with special arms. Services components by Trox.	**Single-skin façade**, Unitised cladding panels (20cm depth). Requires an external power source and cold and hot water supply. Integrating building services in the façade, increased available area and the flexibility of the interior without any major refurbishment work. Module is 104,9 cm X height is 1065 mm Services components by Trox.	The Smartbox unit is positioned in front of the floor edge as an integrated part of the façade. This leaves room to combine the various kinds of panels. decentralised system can save room for installations such as suspended ceilings, and can save up to 12% floor height and façade costs.		United curtain wall. **Double skin facade.** System installed on the floor slab directly behind the facade.
Issues	It requires a water pipe connection for the HVAC unit.	The use of pre existing products equalled big dimensions. Lack of design possibilities, therefore was not embraced by architects. Opaque panel, water pipes and cables in the facade construction from the inside.	In front of the slab.	Opaque panel, water pipes and cables in the facade construction from the inside. The ventilation modules are in the facade.			

3.3.1 State-of-the-art integrated façade comparison

As mentioned before, seven building services are currently being integrated into the façade panels; decentralised ventilation, heating, cooling, lighting, sunshade systems and solar generation. Some products like the TEmotion façade and the Smartbox Energy Façade have developed a product that integrates them all. From the façades found during this research, a conclusion can be made that the building services that all products implemented are decentralised ventilation, heating, and sunshades. Three of them (TEmotion façade, E2 façade and i-module) implement ventilation, heating and cooling through a compact element produced by Trox. The positioning of the integrated services varies depending on the product; it can be in front of the slab, in the slab, on the window side, and within the glazing part of the window. Figure 16 show the found building services position in the integrated serviced façades. Whereas Table 16 shows what services each product integrates, what type of manufacture process they followed, whether it is modular or not, a design brief of each concept and the main issues found on each.

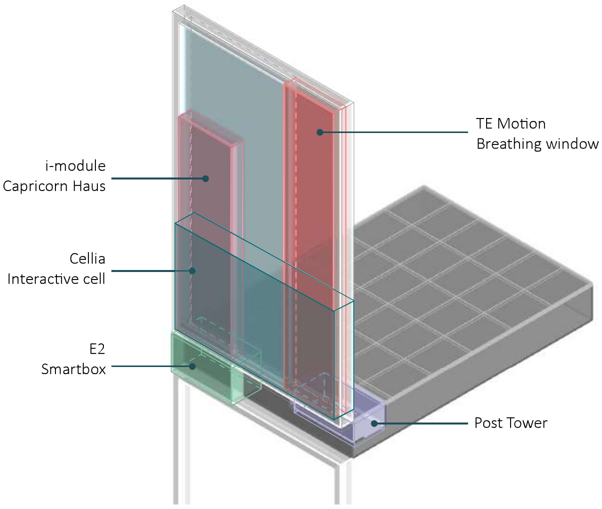


Figure 26. Arrangement of the different building services components in the façade according to the analysed examples

3.3.2 Barriers to the integrated services façades

Several authors have addressed the barriers to integrating building services, from market introduction to integrating active systems into the façade. The authors mentioned that aesthetics, functionality, economy (initial and operational) and flexibility are relevant issues for integrating this type of system. (A. Prieto Hoces et al., 2017).

The application of surveys has been a valuable tool for evaluating the possibilities for façade integration. The surveys were applied to professionals with experience in façade systems development, from the design and construction process. Between the authors, we can find Ledbetter (2011), Klein (2013) and Zelenay et al. (2011). The first author focused on the design stage problems. The decisions made during it that limited the specialists' actions, and the packaging led to operation problems due to the lack of coordination between contractors. At the same time, the author Klein (2013) mentions that stakeholder coordination and interaction during the design and construction process can be crucial to the success of an integrated system. Finally, Zelenay et al. (2011) divide the survey results into three stages: design, construction, and operation. The barriers during the first stage involve professionals, clients, and economic issues; the second focuses on the lack of specialised installers and installation issues; the third involves the system's cost-effectiveness and consecutive monitoring and maintenance requirements to ensure occupant comfort.

A recent study conducted by Prieto et al. (2018) gives a relevant overview of the findings of an exploratory survey to determine the barriers to an integrated façade system. The survey was sent to the professionals involved in the field worldwide through a Central Europe-based network. The knowledge background of the respondents was engineering, architecture, other or not specified, and materials science. Being the professionals with an engineering background, the biggest group. This type of system has already been implemented worldwide, thus the respondents declared to have worked on projects based mainly in Germany, The Netherlands and the UK, followed by the USA and the middle east (UAE).

The gathered data was based on the design, production, and assembly stages. At all process levels, these stages have problems related to coordination, knowledge, logistics, cost, and responsibilities. At a product level, the most mentioned problems are technical feasibility, physical integration, durability and maintenance, performance, and aesthetics. The issues that affect all three stages are coordination issues, lack of knowledge and the need for rigorous supervision, high costs, physical integration of the design due to the number of different parts, the size and, therefore, weight of the components, as well as the lack of tolerances. In Table 17, a

Table 17. Design barriers in the integration of building services into the façade

Responsibilities for interfaces between components	Problems caused by separation of components
Warranties in case of malfunction	
Lack of feedback between contractors	
Lack of **Coordination** between designer/facade consultants and building services specialists	Design
Knowledge	
Lack of tools for accurate prediction of long term **performance** during early stages.	
Need for more empirical information to validate theoretical or numerical simulations for the assessment of integrated technologies, considering diverse climates and regional contexts.	
Cost: prove that the higher costs are a return of the investment in the long term.	
Aesthetical quality	
Physical integration. No integral vision ruling the development process (building phsyics, building services, construction principles)	
Building enclosure: air tightness, thermal resistance.	
Lack of variety in terms of design solutions and available building systems	
The size of the components that need to be integrated VS the available space.	
Compatability of the integrated technologies in terms of connections to be solved.	
Lack of technical experience from supplier	
Coordination: Lack of proper communication channels between designers and manufacturers. Struggles with subconstractors and subsuppliers	Production stage (prototyping and manufacturing)
Responsibility refrain from facade contractors due to fear of risk	
Lack of qualified technical staff	
Logistics: Lack of flexibility within the production and supply chain (strong quality control required and mid-production testing)	
Cost and physical integration	
Size and modular components (standardised dimensions facilitates integration)	
Multiple connections and different materials	
Compatibility between the system and facade component	
Need for new working models to assist the development of new integrated facade concepts.	
Activities on site: physical integration, multiple not standardised conections and lack of well trained workforce on site.	Assembly stages
Lack of prefabricated unitised modules. Lack of tolerances.	
Coordination closely linked to logistics.	
Construction: physical integration of the components and systems	
The number of different trades and suppliers. Integration of technical, service, building, systems, facade and time.	
Knowledge: Better prefabricated integrated components assembled off site under rigorous supervision.	
Weight of the facade units	
Connections should be design considering the **number of components** different materials and easiness of construction. The less number of components the better.	
Better low number of steps: **Plug&Play** Concept	

(Prieto Hoces et al., 2017)

summary overview of the main findings of the research paper analysed is exemplified. Integrating building services in the façade appears to have a high potential for implementation. However, the issues mentioned before need to be solved to see the implementation of such a system, especially the issues related to the process. Amongst the solutions is the generation of a modular design that could solve the primary physical integration of the parts and the compatibility of the connection and will lead to an industrial manufacturing process which would take out of the equation all the issues related to the need for well-trained and knowledgeable people on site for the assembly stages and physical integration while reducing the construction mistakes. The design requires a clear understanding of the parts that compose the façade panel. Failing this could directly translate into significant and costly issues during the product operation. A clear overview of the communication workflow and an understanding of the whole system is essential to achieve coordination and make the professionals in the field feel comfortable using the product. Finally, the numerical validation through empirical proof could potentially lead to the acceptance of the product in the market at a large scale.

3.3.3 Conclusion state-of-the-art building services façade

This chapter addresses the sub-research question: "To what extent have state-of-the-art façades integrated building services?" The findings reveal that current state-of-the-art façades primarily cater to office buildings and incorporate six types of building services: decentralised ventilation, heating, cooling, lighting, sunshade systems, and PV panels. Façades integrating heating and cooling systems require water pipe connections, which render them unsuitable for plug-and-play façade panels. Among the novel concepts discovered, only two designs, the TEmotion façade by Wicona (2018) and the Cellia interactive cell by Focchi & Progetto (2021), are based on modular panels and encompass all the mentioned building services. However, neither of them addresses acoustic comfort, though they represent the most advanced integrated façade panels in the office building sector. This creates a knowledge gap for this thesis, as the aim is to design a façade panel integrating air-to-air technology systems for large-scale residential refurbishments. Nevertheless, the aesthetic solutions of the panels, with a width of less than 40cm, meet the design requirements, and the box concept of the breathing window provides a basis for compartmentalizing technologies to meet fire safety standards. The reviewed concepts indicate that the location of technologies can compromise other aspects of the façade, such as ease of maintenance for aesthetics. The concepts primarily apply to office buildings and require empirical evidence to gain industry trust, or they may remain in the conceptual phase, like the case of the Smart box. On the other hand, the ventilation box offers a potential user-friendly solution for residential dwellings.

An important observation from this subchapter is that the reviewed novel concepts were developed between 2003 and 2018, with a significant gap from 2007 to 2021. Barriers encountered by product developers, including bulkiness and efficiency of technologies, as well as overall costs, have limited further development of such concepts during that period. Integrated façade services find more practical application in office buildings, where companies can make larger investments in acquiring the technologies.

Perceived barriers to implementing building services façades can be categorized into three stages: design, production, and assembly. Common issues across these stages include coordination challenges, lack of knowledge, the need for rigorous supervision, high costs, physical integration complexities due to the multitude of components, size and weight constraints, and tolerance limitations. These issues have been integrated into the design requirements within the architectural domain of this thesis, except for costs and weight, which are beyond its scope due to their numerous limitations. Most of the perceived barriers identified by industry professionals can be overcome through modular designs that address physical integration, connection compatibility, and factory manufacturing processes. Thus, the TEmotion and Cellia façades serve as leading examples for this thesis design. Additionally, the panel design's crucial aspect has been included in the design requirements. Survey results emphasize the significance of industry collaboration to assess the feasibility of implementing and developing building serviced façades, ensuring the launch of well-designed and carefully integrated façade panels.

3.4 Building services technologies

Building services are the core system operation of a building. They are essential for the correct building management and, at the same time, they represent a positive impact on the user's day-to-day life, health and comfort. They are usually located in the core of the building, from where they distribute the resources to the rest of the building (centralised system). However, it is also possible to integrate decentralised building services such as decentralised ventilation units, lighting, PV panels, fuel cells, heating, and cooling (Khaled Saleh & Vitaliya S., 2016).

This research focuses on determining the feasible technologies to integrate heating, cooling and ventilation in the façade without water pipes. In order to determine the most optimal technologies for façade integration without water pipes, they will be compared and assesed based on the KPIs exemplified in Tables 18 and 19 for heating, cooling, and ventilation, respectively. The KPIs for heating and cooling technologies are divided into four categories: unit design, energy, comfort and overtime performance. Whereas the ventilation technologies' KPIs are subdivided into unit design, acoustics, ventilation, heat exchanger, filters, user control, electrical data, and overtime performance.

Table 18. KPI's for heating and cooling technologies

H&C Technologies KPI's	[Units]
Unit design	
Dimensions (LxWxH)	[m]
Area	[m2]
Number of parts	-
Connections	-
Energy	
Cooling capacity	[W]
Heating capacity	[W]
Efficiency (COP)	-
Comfort	
Supply temperature	[°C]
Sound power	[dB(A)]
Air supply quantity	[m³/h]
Over time performance	
Maintenance period	

Table 19. KPI's for ventilation technologies

Ventilation Technologies KPI's	[Units]
Unit design	
Dimensions (LxWxH)	[m]
Area	[m2]
Number of parts	-
Connections	-
Acoustics	
Sound insulation	[dB(A)]
Sound pressure	[dB(A)]
Sound power	[dB(A)]
Ventilation	
Air exchange capacity	[m³/h]
Fresh air flow rate	[m³/h]
Night cooling	
Heat exchanger	
Operating temperatures	[°C]
Heat recovery	
Intake and exhaust	
Filters	
Air filter	
User control	
Type	
Electric data	
Supply voltage	[V AC/DC]
Power supply	[W]
Energy efficiency class	
Over time	
Maintenance period	times per year

3.4.1 Decentralised ventilation technologies

Decentralised ventilation systems are standalone units that supply natural air into different rooms separately with different air regulations. Between the advantages, we can find the flexibility for future changes, user comfort optimisations and an overall decrease in energy consumption compared to standard systems, namely centralised ventilation. Moreover, this type of technology can represent lower operating and construction costs. Reduced service areas and less space required between floors translate into higher storey heights. (Schüco E2 Façade, n.d.) According to Prieto et al. (2017), decentralised systems can also offer better indoor user comfort. A positive effect of installing decentralised ventilation systems is that it does not require lengthy and expensive supply shafts and ducts; this results in better supply air quality and elimination of the air re-circulation, lower transport energy consumption and construction costs. In addition, a decentralised air supply simplifies the maintenance and replacement of the parts, whereas the quality standards can be guaranteed and controlled through a manufacturing pre-fabrication process. (Khaled Saleh & Vitaliya S., 2016).

However, natural ventilation can have a negative effect on the indoor temperature. It can lead to higher energy demands due to temperature differences and discomfort due to drafts. Mechanical ventilation with heat recovery solves these issues since the incoming air can be pre-heated or pre-cooled, avoiding high-temperature differences in the incoming air (Ebbert, 2010). Most ventilation technologies that provide heat recovery and air conditioning by heat exchangers are often connected to hot water and chilled water circuits, making them unsuitable for the design goal of this thesis. However, the market has developed products that contain air-to-air heat exchangers with the potential for façade integration. Nevertheless, the space required in the façade is often more than 300mm. Hence, they are more commonly used in low-rise buildings. (van Roosmalen et al., 2021).

Amongst other barriers of a decentralised ventilation system, we find noise and draft when the air flows are high (Silberberger, 2008), the façade wind pressure and outdoor temperature might affect the functionality of the equipment, the difficulty for maintenance is also considered as a barrier to this system implementation.

A recent case study by the TU Dresden, where 50 retrofit integrated façade cases were compared, concluded that except for one building, all the decentralised HVAC applications were in offices. In contrast, insulation improvements such as renewable energy storage (RES) and renewable energy generation (REG) were primarily applied in residences. (van Roosmalen et al., 2021).

The cutting-edge technologies in Table 20 are the state-of-the-art market products of decentralised ventilation systems with heat exchangers apt for water-pipe free window integration.

Decentralised ventilation with heat recovery

It is an air-to-air exchange system technology that reduces energy consumption with the possibility of adding air filters, CO2 sensors and low noise levels. Between the market products available, we can find the VentoTherm Twist by Schüco in partnership with Renson, the Aeromat VT WR by Siegenia with similar dimensions and geometry and the FreshBox E-100 with a more cuadrangular geometr. The Rhinocomfort 160RF by Vantubo and the HRC 05 by Innova differ from the previously mentioned technologies in size and geometry. This one has a tubular shape that connects the outside with the indoor environment. All five products' technical information can be found in Table 20.

The rectangular prism shape products (see Table 20, columns 1, 2 and 3) are manufactured in modular shapes; these are 1.00m, 1.25m, 1.50m, and 2.00m lengths and comparable widths and heights, 0.35m and 0.11m respectively. The unit is compact and feasible to install horizontally and vertically next to the window profile. Sound insulation levels range from 32-47dB when opened to 41-50dB when closed; sound pressure levels vary from 22.8 dB(A), the more silent, to the loudest 50 dB(A). The airflow rates depend on the number of fans added to the units with heat exchanger; the 1m length unit can go from 24 m^3/h to 48 m^3/h, depending on the brand.

All of these systems feature a night cooling mode, which further reduces energy consumption during the summer. Additionally, they offer a range of heat recovery percentages, ranging from 62% to 98%. Furthermore, they can integrate a filter system to choose from: G3 filters, commonly used in ventilation and air conditioning systems and F7 filters which are specifically designed to eliminate fine dust particles, such as soot, pollens, mold spores, and bacteria. Notably, the FreshBox E-100 model goes a step further by giving the option of accomodating H13 filters, known for their high efficiency in removing airborne particles as small as 0.3 microns, including dust, pollen, mold, bacteria, and other contaminants. Such filters are commonly employed in hospitals to ensure clean and healthy air quality. ((Bag Filters F7 and F8 to BS EN779- Ace Filtration, n.d.) (Filter Media, n.d.) (US EPA, 2019)

It is worth noting that the inclusion of filters does result in a reduction in the fresh air supply. However, the integration of these advanced technologies offers various methods of control, including CO2 sensors, touch control interfaces, and WiFi connectivity. These control options provide users with flexibility and convenience in managing the system's performance and ensuring optimal air quality for their specific needs.

The tubular shape products (see Table 20, columns 3 and 4) are manufactured in fixed depths; this is 0.28m and 0.24-0.53m, and the same width and height, 0.19m and 0.16m, respectively. The unit is compact and feasible to install horizontally in a wall in contact with the exterior. The sound pressure levels vary the most from 18-27 dB(A), the more silent, to 32-38 dB(A), the loudest. Depending on the brand, the airflow rates can range from 24-50m³/h or 28-68m³/h. All of them count with a night cooling mode with a minimum flow rate, translating into energy consumption during night cooling. The heat recovery percentage goes from 77%, the lowest, and 90%, the highest. All of them can integrate G3 filters. Controlled by remote control and WiFi.

All these technologies count with a pressure compensation regulation that activates automatically when significant pressure differences exist on the façade. Figure 27 and 28 exemplify the heat exchanger working principle of the Ventotherm Twist technology and Freshbox E-100, respectively. This was done to understand and analyse the feasibility of the airflow connection of the ventilation technologies with the heating and cooling devices. Figures 27 show that the Ventotherm Twist unit has an interchangable heat exchanger that mixed the air current during its operation making it complex to connect to another unit. Whereas the Freshbox E-100 (Figure 28) has a traditional heat exchanger with a linear airflow.

A decentralised ventilation system with air filters can be found in Table 21. This technology provides an adequate fresh air supply without opening the windows; the maximum air supply can be manually limited and includes pollen protection and sound reduction to improve user comfort. For example, the VentoFrame product developed by Schüco is installed in the outer upper horizontal frame profile. The ventilators can be altered to a required essential depth. When high wind speeds occur, the outer ventilator flap automatically regulates the incoming air to avoid draughts, enhancing user comfort. The noise levels vary from up to 33 dB(A) when opened and 43 dB(A) when closed.

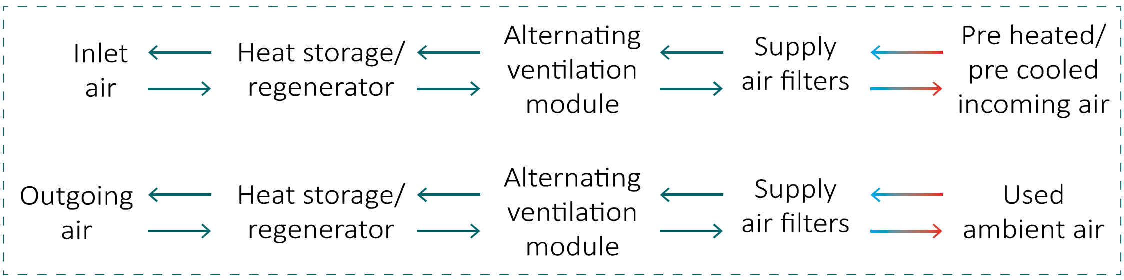


Figure 27. Ventilation system (Ventotherm Twist) with a two-way heat exchanger working principle

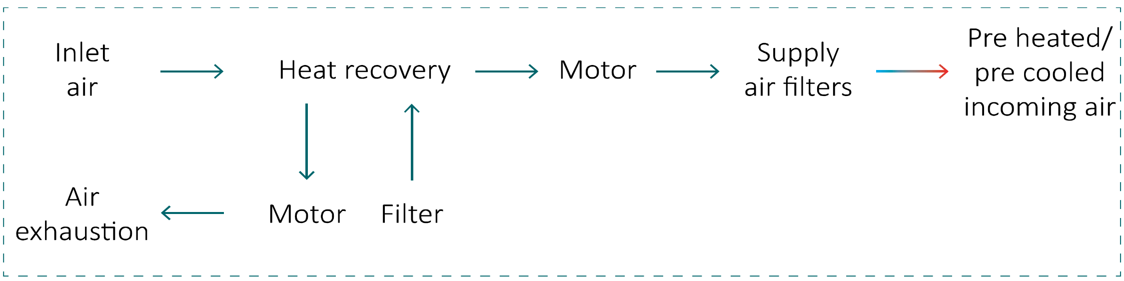
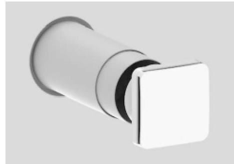


Figure 28. Ventilation system (FreshBox-E100) with a conventional heat exchanger working principle

Table 20. Ventilation technologies with heat exchanger comparison

		AIR BASED				
						
	Company:	**Schüco + Renson**	**Siegenia**	**Vantubo**	**Innova**	**Blauberg**
	Model:	**VentoTherm Twist 2x2**	**AEROMAT VT WR 1000 smart**	**Rhinocomfort 160RF**	**HRC 05 - ElectronicMaster**	**Freshbox E-100 WiFi**
Technologies KPI's	[Units]					
Unit design		also 1.25 length				
Dimensions: Length	[m]	2,00	1,00	0,28	0,24 - 0,53	0,59
Dimensions: Width	[m]	0,35	0,32	0,19	0,16	0,20
Dimensions: Height	[m]	0,11	0,10	0,19	0,16	0,69
Area	[m2]	0,70	0,32	0,28	0,20	0,12
Number of parts / location	-	1	1	2	2	1
Connections		1 - electric	1 - electric	1 - electric	1 - electric	1 - electric
Acoustics						
Sound insulation	[dB(A)]	32 [open] 41[closed] dB	47 [open] dB	-	-	10mm insulation
Sound pressure level	[dB(A)]	40 [open] 50[closed] dB	24 / 36 / 43	27 / 32 / 38 [1,5m]	18 / 26 / 32 [1,0m]	33 [3,0m]
Ventilation						
Fresh air flow rate	[m³/h]	48 [1m] / 72 [1.25m]	60	28 /48 / 68	24 - 50	75
Night cooling		Yes	Yes	airflow rate 15m3/h	airflow rate 10m3/h	Not given
Heat exchanger						
Operating temperatures	[°C]	-15 to 45	-15 to +40	Not given	Not given	-20 to +40
Heat recovery		Yes [≤80%]	Yes [62%]	Yes [90%]	Yes [77%]	Yes [98%]
Intake and exhaust		Yes	Yes	Yes	Yes	Yes
Filters						
Air filter		G3 (coarse 45%) + F7(ePM1 75% - poor outside air quality)	F7 (supply) + G3 (exhaust)	2 x G3 (insects, fibres, sand, larger ash, larger pollen, cement and dust)	G3	G4 & F8 (PM2.5 > 75 %) or H13 (PM2.5 > 99 %)
User control						
Type		BMS/Demand driven + CO2 sensor	DDV + IAQ / touch control / WiFi	Control remote	WiFi	WiFi
Electric data						
Supply voltage	[V AC/DC]	15 V DC	230 V DC / 50 Hz	230	230 / 1 / 50 V/ph/Hz	230 V / 50 Hz
Power supply	[W]	230 VAC +- 10%/50 Hz	24	2/6,6	4 or 6	23
Energy efficiency class		A	B	-	-	A
Over time						
Maintenance period	times per year	1 (fans) 2 (filters)	1 (fans) 2 (filters)	1 (fans) 2 (filters)	1 (fans) 2 (filters)	1 (fans) 2 (filters)
Source		*https://www.schueco.com/de-en/architects/products/ventilation-systems/ventilation/ventotherm-twist*	*https://www.siegenia.com/nl/products/comfort-systems/window-ventilators/aeromat-vt-system*	*https://vantubo.nl/air/rhinocomfort-wtw-.html*	*https://www.climazon.net/amfile/file/download/file_id/824/product_id/3617/ P. 27*	*https://blaubergventilatoren.de/uploads/download/bl_freshbox_100_2022_05_en.pdf*

Decentralised ventilation systems with multi-stage air-cleaning filters are ideal for buildings located in large cities or polluted metropolitan areas. The product VentoLife developed by Schüco in partnership with Renson, is a controllable decentralised ventilation with an integrated activated charcoal multi-stage air-cleaning filter that efficiently frees the air by 99.5% of all pollutants and particulate matter 2.5 (PM) that jeopardise the health, both small and big particles. At the same time, it can eliminate smells, bacteria and toxins. It can be used for room air filtering when circulating the air too. This way, indoor pollutants would be cleansed. A sensor-controlled valve injects outer air on demand to ensure indoor air quality. The installation can be done vertically on the side of the window frame. Finally, this product has a low power consumption of 14 Watts per hour. During the BAU fair in Munich, Germany, the product developer of Schüco mentioned that this product is no longer being produced for sale in the market, given that the people did not acknowledge the importance and added value of having healthy indoor air quality through integrating this unit in the façade. However, it is still possible to manufacture it.

Overall, the water tightness and condensation-free properties are the advantages of these technologies. As well as the compact size dimensions make all three products an almost invisible add-on component for the façade panel while enabling more views to the outside and assuring daylight entrance. One of the disadvantages is the filters' maintenance period frequency, which varies from six to nine months, depending on the use.

Table 21. Decentralised ventilation technologies with filters

	Company:	**Schüco**	**Schüco**
	Model:	**VentoFrame**	**VentoLife**
Technologies KPI's	[Units]		
Unit design			
Dimensions: Length	[m]	0,50 - 0,75	0,90
Dimensions: Width	[m]	0,44	0,20
Dimensions: Height	[m]	0,28	0,11
Area	[m2]	0,33	0,10
Number of parts / location	-	1	1
Connections		1 - electric	1 - electric
Acoustics			
Sound insulation	[dB(A)]	28 [open] 36[closed] dB	
Sound pressure	[dB(A)]	42 [open] 52[closed] dB	Transmission 38dB
Sound power	[dB(A)]	Not given	25-40
Ventilation			
Air exchange capacity	[m^3/h]	40,6	60
Fresh air flow rate	[m^3/h]		60
Night cooling		N.A.	Auto silent mode
Heat exchanger			
Operating temperatures	[°C]	-20	N.A.
Heat recovery		No	N.A.
Intake and exhaust		Intake	Yes
Filters			
Air filter		Pollen + particulates	Clas 12 particulate filter and activated carbon
User control			
Type		Air volume flow on demand	Sensor control based on IAQ
Electric data			
Supply voltage	[V AC/DC]	Not given	230 V
Power supply	[W]	Not given	14
Energy efficiency class		Not given	Not given
Over time			
Maintenance period	times per year	1	2
Source		*https://www.schueco.com/de-en/architects/products/ventilation-systems/ventilation/ventoframe#techInfo*	*https://alukoenigstahl.md/en/blog/products/schuco-ventolife/* *https://www.winincomedesign.com/store/ventilation-system/ventilation-system-ventolife/*

3.4.2 Heating and cooling technologies

During building retrofit, energy conservation measures (ECMs) and energy modulation measures (EMMs) can reduce the heating and cooling demand. The ECMs can considerably reduce the energy demand by preventing excessive heat transmittance produced by specific processes, technologies, or facilities in the building by implementing insulation, window improvements, window-to-wall ratio, and air tightness. The EMMs modulate energy consumption through passive heating and cooling technologies and are often climate-specific (Sarihi et al., 2021). The thermal performance optimisation of the façade is crucial in reducing the energy demand for the technologies (A. Prieto Hoces et al., 2016). Therefore, it will be considered for the façade panel design but not addressed in the literature review.

This subchapter consists of an overview of the research and the state-of-the-art technologies for only cooling, heating, and cooling. It is divided into two: solar technologies and heat pump technology. Table 22 shows the technologies subdivided depending on their applicability. Absorption cooling and TEM are solar technologies, while the monoblock unit is an air to air heat pump technology.

Solar technologies

In recent years, the potential of solar-driven cooling technologies to lower indoor temperatures using renewable energy has gained attention. Their cooling processes are environmentally friendly and represent an alternative to conventional centralised air-conditioning systems in warm climates. During the literature research five cooling technologies suitable for façade integration were found: TEM, absorption cooling, adsorption cooling, solid desiccant cooling and liquid desiccant cooling. These systems at a big scale can be divided into those using gas, like air, as a medium (TEM, solid desiccant and liquid desiccant) and those using a liquid as a medium (absorption and adsorption cooling). Even though the systems using liquid as a medium performs with higher efficiency, they require pipe work and are less suitable for a standalone façade. (van Roosmalen et al., 2021) However, the medium these technologies work with differs when applied at a smaller scale. Recent studies show that absorption cooling and TEM (heating and cooling) are the only solar technologies with the potential for a façade integration since it does not require a water pipe connection at a small scale. (Prieto et al., 2019) (A. I. Prieto Hoces et al., 2018)

Overall, the barriers and restraints to the widespread application of solar cooling in façade integration are process related rather than the final product itself. The performance of solar technologies still requires more development in terms of testing compact systems to increase and rely on COP values. The coordination of different professional areas and the lack of technical knowledge during the design and assembly stage have represented major setbacks. During the production and assembly stages, the physical integration of the parts is a challenge. During the operability stage, durability and maintenance are a concern. In comparison, the technology's lack of variety and aesthetics represent a constraint at an architectural level. Finally, costs and lack of warranties throughout the overall process have also been considered barriers by the authors. (A. I. Prieto Hoces et al., 2018)

Small absorption units for cooling applications can be found on the market with dimensions of 1,50x0,40x0,90 m. The bulkiness and weight of the technology represent significant drawbacks, generating doubts regarding the feasibility and potential for decentralised applications. (Prieto et al., 2019).

The units comprise seven parts: the vapour compression system (condenser and evaporator), the heat-driven generator, the absorber, an integrated pump, the heat rejection system, the input heat from a solar array and the hot/cold storage unit. As mentioned, it is the only solar technology with an electric connection and without pipes. The cooling capacity of the technology is amongst the lowest when compared to the rest of the solar technologies (1440 W). The same applies to its COP with a range of 0,27-0,36. However, the operating temperature is among the heights with a range of 80-110 C (Prieto et al., 2019).

It involves complicated maintenance, whose primary focus is the operation of the correct fluid. The pipes require periodical maintenance to avoid leakages, and the vacuum must be checked over time (Prieto et al., 2019).

Thermoelectric modules (TEM) is a technology still in early research and development, mostly applied at a small scale for refrigerators and camping gear. The technology is based on the Peltier effect, which was discovered in the early 1800s. It consists of directly converting energy between heat and electricity. (Prieto et al., 2019)

The composition consists of three main parts: the thermoelectric module, the heat dissipater (hot side) and the cooling component (cold side). When the operative temperature is reached, the operation may cease. Therefore, all thermoelectric modules require a heat sink to dissipate the generated energy absorbed at the two junctions for cooling and heating applications. It is advisable the use fans for heat rejection to increase the efficiency of the TEM. For its standalone performance, the TEM require a connection to the PV panels and a battery for electricity storage. (Prieto et al., 2019)

TEM modules are considered a promising technology for implementing integrated building components. Liu Z et al. (2015) consider that, shortly, TEM driven by PV will significantly contribute to zero-energy buildings by reducing fossil fuel consumption and protecting the environment (Liu Z et al., 2015). According to Ma et al. (2019), the advantages of TEM air conditioning are no refrigerant requirement, no periodic replenishment, minor maintenance, very compact unit, lightweight, no mechanical moving parts, therefore no noise or vibration, except for the fan when added, long life span, high reliability compared to current HVAC systems, and environmentally friendly. Moreover, it can be powered by direct current electric sources like PV cells without needing an AC/DC converter. While it is also capable of performing heat recovery ventilation when used in the heating mode. (Ma et al., 2019)

The same study proposed different novel integrated thermoelectric systems for heating/cooling and ventilation and the reuse of heat waste produced during the cooling mode for drying or DHW services. The examples are more relatable to this thesis scope consist of a system integrated of three components: the TE modules (TE unit), the finned encapsulated PCM and a high-power heat sink or a microencapsulated phase change slurry heat dissipating, transportation, and storage system (PCS system) (Ma et al., 2019). The positioning of the finned encapsulated PCM is attached on one side (the side face to the room) of the TEM as a heat dissipater and a heat storage of extra cooling/heating energy output from TEM stores thermal energy that will be used in the night-time (when driven by PV) or high peak electricity period (when driven by main power).

A prototype developed by Gibson consisting of coupling 85W-PV panels and a 72W-cooling TEM showed that the heating side of the TEM module affects the performance of the TEM. Alternatively, the PV modules that supply energy to the TEM can emit heat into the wall's inner layer via a radiant aluminium panel. This prototype is based on TE Peltier cells but filled with air as a cooler ((ZhongBing, 2014). Another study showed that 20 Peltier cells in a façade module with dimensions 1.2m*1.8m*0.25m have a power of 1000W. (Ibáñez-Puy et al., 2015).

Monoblock heat pump technologies

A monoblock heat pump system is a type of air-source heat pump that consists of a single unit installed in a wall with a direct connection to the outside with a dual power function that allows to achieve the required temperatures in the shortest possible time. In contrast to a traditional split system heat pump, where the compressor and heat exchanger are located in separate outdoor and indoor units, the monoblock heat pump has both components in a single unit. The system works by extracting heat from the outside air and using it to heat the indoor space or reversing the process to provide cooling (Figure 29)

The main advantage of this technology is that it is quieter than a split system; it allows for a decentralised heating and cooling system in one compact unit without requiring pipes connections between the indoor and outdoor units, avoiding complicated maintenance. Moreover, it is a relatively easy technology to install.

The cost and the incompatibility with extreme outdoor temperatures are between the main barriers and limitations. For example, Table 22 shows the most aesthetic and slim monoblock heat pump unit currently available. It was developed by the company Innova Expert. It uses the R32 refrigerant gas. R32 stands out as an environmentally friendly refrigerant with a significantly lower global warming potential (GWP) than many other HFC refrigerants, approximately one-third that of R410A. Its excellent thermodynamic properties enable efficient heat transfer and superior performance in heat pumps, offering higher cooling capacity and improved energy efficiency by up to 10% compared to alternative refrigerants. It is important to note that R32 is classified as mildly flammable (A2L), necessitating careful installation and maintenance to ensure safety and mitigate potential risks. (R-32, The Most Balanced Refrigerant, n.d.). The

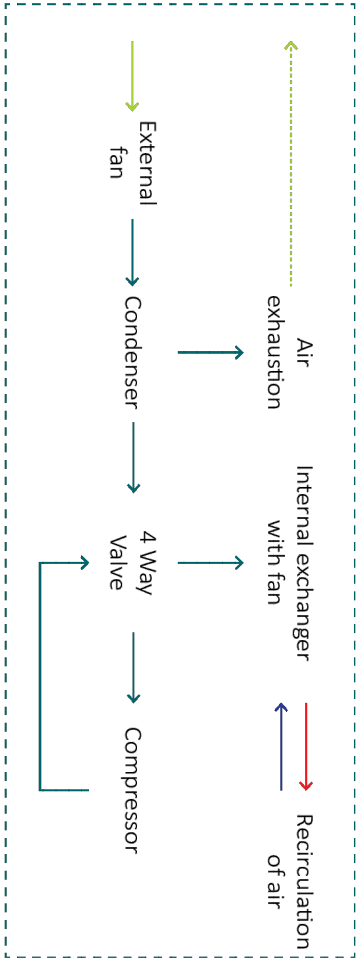
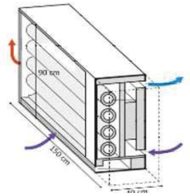
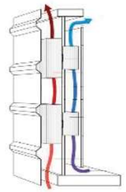


Figure 29. Monoblock heat pump (2.0 mini- Innova) working principle

Table 22. Heating and cooling technologies for stand-alone façade integration

		Cooling	Heating & Cooling	
				
Technologies KPI's	[Units]	**ABSorption**	**TEM**	**monoblock heat pump unit**
Unit design				
Dimensions: Length	[m]	1,50	0,04	0,17
Dimensions: Width	[m]	0,40	0,04	0,81
Dimensions: Height	[m]	0,90		0,55
Area	[m2]	0,6	0,0016	0,13
Number of parts / location	-	7	6	1
Connections		1 - electric	1 - electric	1 - electric
Weight	[kg]			39
Energy				
Cooling capacity	[W]	1440	63	-700 ≤ x ≥ -2350
Heating capacity	[W]	N.A.	126	750 ≤
Efficiency (COP)	-	0,27-0,36	cooling: 0,9-2,0 (market) heating: 3,0 (market)	3,15
Comfort				
Operating temperature	[°C]	80-110	50-100	-10 ≤ x ≥ 43
Sound power	[dB(A)]	N.A.	N.A.	27
Nominal sound pressure	[dB(A)]			39
Air supply quantity	[m³/h]	N.A.	45	240-320 (min), 300-360 (average) , 360-430 (max)
Over time				
Maintenance period		Periodical (complicated)	Time to time (fans specific)	once a year
Source		*https://doi.org/10.1016/j.rser.2018.11.015*	*https://doi.org/10.1016/j.rser.2018.11.015*	*https://www.innova.expert/index.html*

installation consists of making two holes in the wall for the air inlet and outlet; the weight of the smallest unit is 39 kg. The system functions outside; therefore, no noise nuisance is present indoors. The maintenance period is shallow, as well as the energy consumption, 570W power during cooling and 540 during heating. The power supply is 230 Volts – 50Hz. For both heating and cooling scenarios, the energy class is A. (Expert, n.d.)

3.4.3 Technologies suitability assessment

Hand-calculation was made to determine the most energy-efficient and suitable technologies for façade integration. The calculations can be found in Table 23. The heating and cooling loads were based on “Room 01” from the case study used to calculate the design requirements in Chapter 2. The analysis was done based on loads of the room, the power energy consumed to meet the room loads, the heating and cooling capacities of the technologies, and the area required. The heating loads were based on the Netherlands scenario and the cooling loads in Mexico.

Figure 30 show the results of the calculations in terms of energy consumption per technology for cooling and heating. TEM technologies require higher energy given their low COP (1) and the

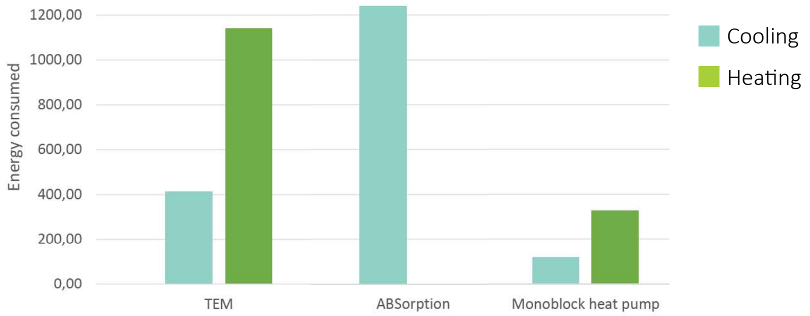
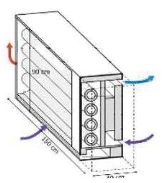
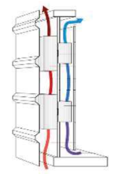


Figure 30. Technologies comparison based on the energy consumed to meet the comfort demands

Table 23. Hand-calculations to determine the most suitable technologies according to the heating and cooling loads, energy consumed per unit to meet the loads and required area.

Demands Room 01 loads		
Q cooling [70%] Mexico scenario	[W]	371,75
Q heating [70%] Netherlands scenario	[W]	1027,94
Parents room area	[m2]	14,29
Wall area	[m2]	2,688
Façade length room	[m]	4,48





Technology information from research	*units*	**TEM**	**Cooling ABSorption**	**Monoblock heat pump**
Cooling capacity	[W]	50	1440	2640
Heating capacity	[W]	50	N.A.	2640
COP range		0,9-2,0	0,27-0,36	3,15
COP choosen		0,9	0,3	3,15
Unit area [LxH]	[m2]	0,1000	1,35	0,48
Length	[m]	0,30	1,50	0,80
Width	[m]		0,40	0,17
Height	[m]	0,30	0,90	0,60
Design requirements cooling				
Calculated required cooling Power	[W]	413,05	1239,15	118,01
Units required based on the technology capacity and room loads	[unit]	250	0,26	0,14
Area required in the façade	[m2]	25	1,35	0,48
Design requirements heating				
Calculated required heating Power	[W]	1142,16		326,33
Units required based on the technology capacity and room loads	[unit]	691	N.A.	0,39
Area required in the façade	[m2]	69		0,48

highest amount of façade area (25 sqm for cooling and 69 sqm for heating). The absorption cooling technologies require a feasible façade area (1,35 sqm); however, the unit consumes the highest energy of the three, and it can only be used for cooling, which would mean adding another device into the façade for heating demands. The monoblock heat pump unit gives the best energy performance and a non-invasive area space (0,48 sqm). This was expected based on the literature review and the compatible COP of 3.

3.4.4 Conclusion building services technologies

This subchapter answers two sub-research questions: "To what extent can decentralised building services technologies be integrated into a façade panel?'' and "To what extent is integrating building services into a façade panel effective in meeting comfort demands?". The first sub-research question was answered by reviewing the market products and literature on technologies suitable for façade integration. The second sub-research question has already been answered in the design requirements chapter. However, in this subchapter, calculations and comparisons based on the technologies KPIs were done to determine the more suitable units to use in the design based on the design requirements.

The technologies were categorised for their analysis into four, (1) decentralised ventilation, (2) solar technologies and (3) monoblock heat pumps. They all require an electric connection for their functioning and they use air as a medium. None of the found technologies integrated only heating; however, heating was always combined with cooling (TEM and monoblock heat pump). In comparison, there was one technology suitable for only cooling; this was absorption cooling. Overall, the technologies in the literature research have low efficiencies compared to the market products found through the Google search and the field trip to the BAU Fair. The absorption cooling has the lowest CoP compared to an average heat pump system (of COP 3) by twelve times which will translate into a higher energy input demand from the system to operate.

Regarding decentralised ventilation, the technologies were divided into two categories (1) ventilation with heat exchanger and (2) ventilation with air filters. In the first category, we find two types of ventilation systems with heat exchangers based on shape; rectangular prism and tubular. The tubular systems present up to 98% heat recovery, whereas the rectangular prism can achieve up to 80% heat recovery. Rectangular prism shape technologies represent higher sound pressure levels (above 40dB(A)). As expected, adding filters (G3 and F7) to the ventilation systems directly impact the airflow rate, reducing it to a point where another fan might be required to meet the thermal comfort requirements set by the DR. Ventotherm Twist (Schüco&Renson) can control the systems via CO2 sensors that are already integrated in the ventilation unit, positively impacting the user's comfort and health. Both systems, tubular and rectangular prisms, represent a non-invasive addition to the façade wall since the installation can be done on top, bottom or side of the window frame; in the case of the rectangular prism and the wall under the window, for the tubular shape. The operating temperatures are feasible for extreme climates (-15°C to 35°C).

The ventilation with air filters found, VentoFrame and VentoLife, are optimal for façade integration due to the compact size whose height does not exceed 0.30m and lengths compatible with window size (0.80-0.90m). VentoLife technology has a relatively lower sound pressure level (38dB) than the Vento Frame (42dB). The advantage of the former is the capacity to intake and exhaust the air and the high-class filters integrated (Class 12 and carbon activated). The latter only has intake air and integrates average ordinary filters used in ventilation systems (against pollen and particulates). However, during the field trip to the BAU fair in Munich, the product developer of Schüco mentioned that the VentoLife technologies are no longer in the market due to a lack of acceptance from the market. The users did not recognise the importance of having good indoor air quality. Despite this, according to Schüco Nederland, it is still possible to order this technology unit. Moreover, from the conversation with the product developer from Schüco, it is possible to upgrade the Ventotherm Twist with a higher efficiency filter ventilation system. Nevertheless, adding these filters will lead to bigger units because fans with more power would be required.

As stated in the design requirements, before adding building services technologies on the façade panels, the building requires the implementation of ECM to reduce the heating and cooling demand to its minimum. Regarding solar technologies, they are based on a sustainable energy source. Unfortunately, their low efficiency represents a significant setback. For instance, in absorption cooling, the efficiency, its applicability to cooling only and its bulkiness mean two significant setbacks for façade integration. The TEM's main issue is low efficiency which is six times more inefficient than an average central heat pump system with a CoP of 3. Moreover, it requires several modules to meet the different room heating and cooling demands. However, it is possible to increase the efficiency by connecting it to the DHW system, but this would lead directly to incompatibility with the façade system goal. Among the advantages of the TEM, we find that it allows for the integration of all HVAC functions; ventilation, heating and cooling in one unit, apart from the easiness of a direct connection to a PV panel system for its functioning and integrability to a façade panel due to its compact size.

Regarding the advantages of a monoblock heat pump unit technology for heating and cooling, we find high COP efficiency compared to the other decentralised technologies. This COP is comparable to a traditional centralised heat pump system in the market, making it a viable and competitive solution in terms of investment and energy consumption.

The best combination for the integration of technologies to provide heating, cooling and ventilation is decentralised ventilation with heat recovery that integrates air filters to enhance the indoor air quality and the integration of a monoblock heat pump system with a competitive COP that covers heating and cooling demands despite the time of the year in the same unit, and if necessary, the integration of a high-tech air quality filter technology system that ensures the elimination of the particulate matter and smog from the outside air. In this sense, the market products chosen for the integrated façade panel are the VentoTherm twist, developed by Schüco, the FreshBox E-100, developed by Blauberg and the 2.0 mini monoblock heat pump unit, designed by Innova.

The FreshBox E-100 unit allows the integration of one type of highly specialised filters to choose from: G4, F8 or H13, for high air standards such as hospitals. For the design, the F8 was chosen given that they have a 75% efficiency and are designed to remove very fine dust particles from the air including soot, pollens, mold spores, and bacteria. However, the unit does not comply with the ventilation requirements for a living room, only for a bedroom. Therefore, this unit is proposed for its use in the bedroom areas. For the living room area, the VentoTherm twist with F7 filters was chosen for the same reasons as why the F8 filter. The decision of choosing to different ventilation units for the same appartment implies inconveniences in terms of maintenace since it will require different contractors and it increases the complexity for the user to understand the system. However, given that the purpose of this integrated façade panel design is to enhance user comfort, the decision had to be made to choose two different AHU to meet acoustic and fresh air supply set by the DR. It is certainly possible to integrate two FreshBox E-100 to meet the air flow demand of the living room, however, the price of buying two units would be the double of buying one Ventotherm Twist with a higher air flow rate capacity and that is an unnecessary investment for the dwellers. Those are the reasons why it was chosen to use two different ventilation units depending on the area.

Adding the VentoLife product when the case study requires it is possible. However, as mentioned in the DR, the fewer parts, the better. Either way, the VentoTherm twist and the Freshbox E-100 technologies already have a good air quality filtering process, best than not having filters which is the current situation, at least in most dwellings in Mexico City.

For both ventilation units, the parts are integrated into one package, which meets the design requirements of fewer parts for the façade. Also, the noise levels of these AHU does not meet the bedroom DR by 8dB(A) and the living room requirements by 10dB(A). Therefore this topic will need to be further analysed and solved during the design stage.

Regarding the heating and cooling demand, the same technology unit, a 2.0 mini monoblock heat pump unit, will be used for both the living room and the bedrooms since it meets the design requirements of the heating and cooling capacities of the 60 sqm apartment building.

Chapter 4 | Product design

4.1 Pre-design

This subchapter shows the design process followed to achieve the most optimal façade integration design idea to develop further. The pre-design iterations stage lasted over a month and was developed based on the information gathered from the two previous chapters; design requirements and literature review. In addition, meetings were held with professionals from the field of architecture, specifically product developers, façade designers, building physics consultants, zero energy professors, architects and marketing manager, to see their perspectives and input on the design.

4.1.1 Design iterations

An overview of all the design iterations and how they are related can be seen in Figure 32. The design iterations was done at four levels; panel and building structure, technologies, façade and technologies, and details solutions.

Design iteration 00_ Panel sizes

The first approach, shown in Figure 31, was to address the panel dimensions by analysing the possible subdivisions. This was done considering the DR of easiness of transportation in a standardtrailer dimensions. The preliminary panel was not meeting the tansportation requirements (a and b), moreover it was not possible to have residential window opennings of 2.7x1.5m. Therefore, the subdivision ended in three panels of 2.7x2.4m which at the same time were subdived into panels of 1.2m width which meets the requirements (c).

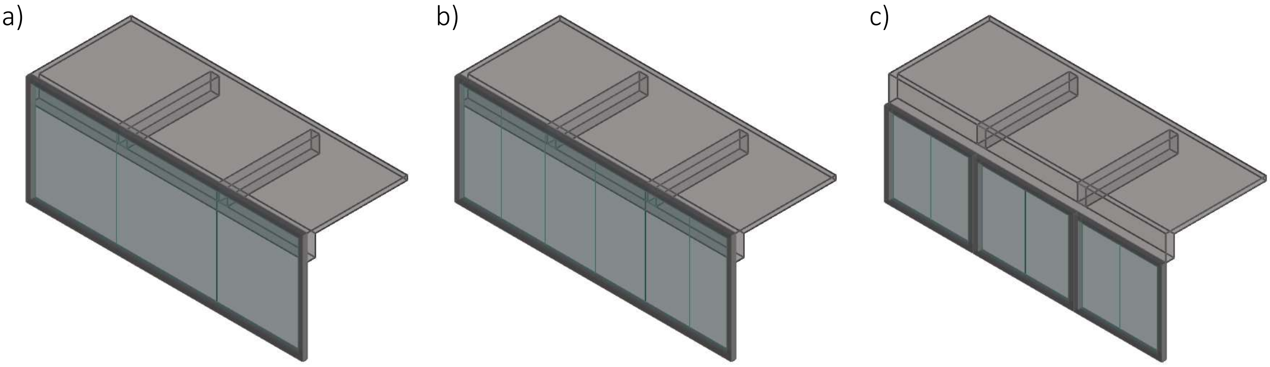


Figure 31. Iteration 00: panel sizes and subsidivisions in accordance with the structure. "a" represents no subdivisions, ''b'' glazing subdivisions, no frames, ''c'' panel subdivision with two parts per panel.

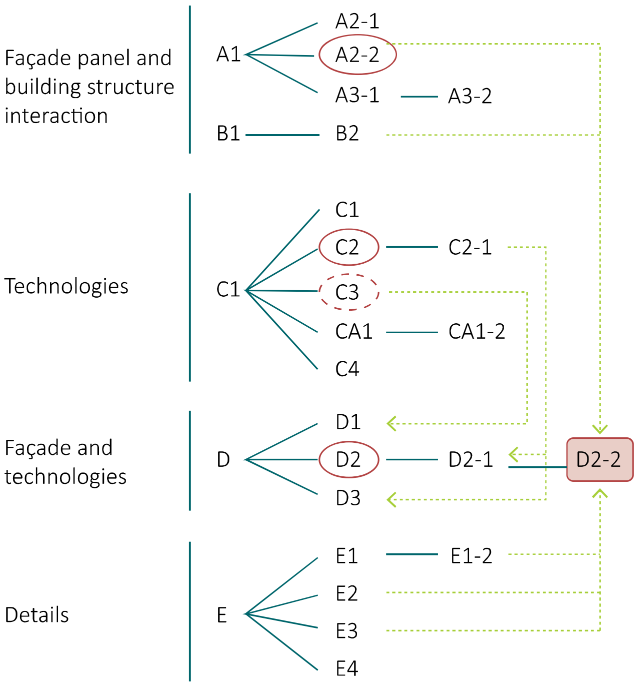


Figure 32. Iterations matrix divided per level; panel and building structure, technologies, façade and technologies, and details.

Design iteration 01_ Unitised façade system sections

Here the approach was to analyse the interaction between the façade, the building structure and the technologies. In Figure 33, we can first see an assessment of the location of the technologies. In terms of maintenance and installation, Option A1 presented greater complexity compared to B1. This was due to the design of the technologies being situated in front of the slab, making access difficult and user control less convenient. Although the concept of incorporating a tilted glass panel was considered, it was ultimately rejected because it did not enhance comfort performance in relation to sunlight radiation, while also introducing complexities regarding operable windows and structural elements. Three options were considered for positioning the unitised system to the structure. Based on the idea of having the technologies in front of the slab (A1), the unitised panel could be connected at the top of the beam (A2-1) or the bottom (A2-2). The attachment of the façade partially inside and partially outside is shown in B2; it represents a significant complexity compared to the A's options since it requires two different structures to move together. Thus, generating extra critical structural points in the façade. Therefore, based on the anchoring of A2-2, a less complex and independent system, the variants A3-1 and A3-2 were generated. A3-1 is a passive approach that has an air inlet in front of the slab and a double cavity façade to pre-heat the air during winter and air filtering before the air exhaustion. A3-2 has the same concept but without a cavity because a technology system was already included in front of the slab. From this first set of iterations, A2-2 was chosen to further develop given the structural simplicity in terms of connections and moves.

Design iteration 02_ Technologies integration

From Chapter 3, the current best technologies for heating and cooling are the monoblock heat pump 2.0 mini developed by Innova, for ventilation the VentoTherm Twist produced by Schüco in conjunction with Renson and the FreshBox E-100 WiFi produced by Blauberg.

The airflow design for the technologies is illustrated in Figure 34. In these iterations, the VentoTherm

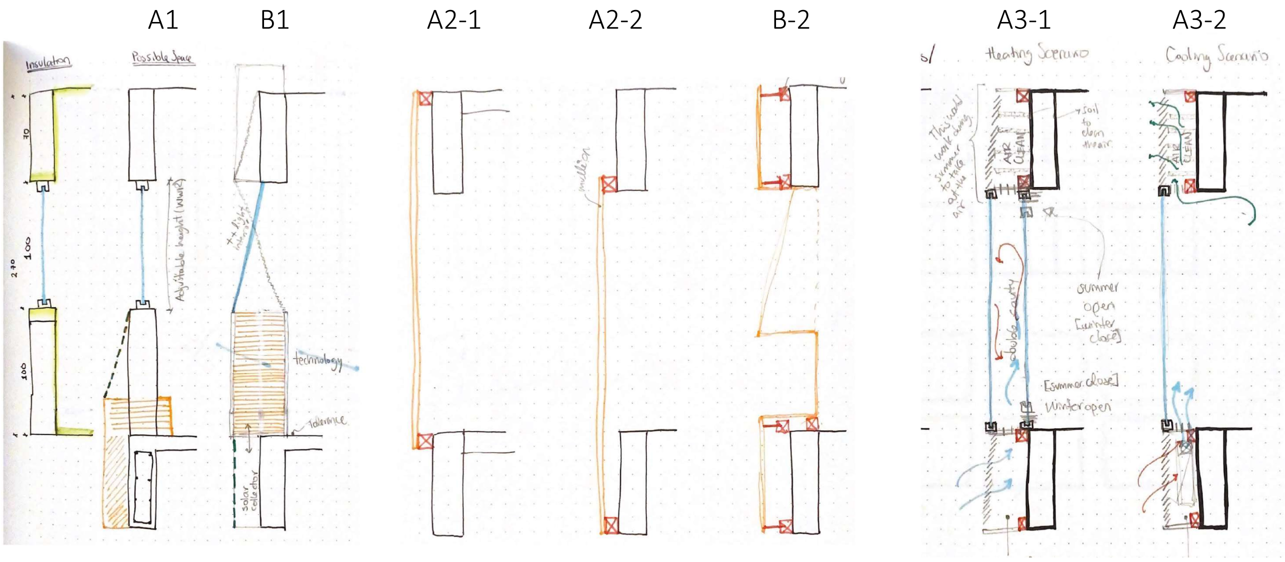


Figure 33. Façade panel structure and building structure interaction

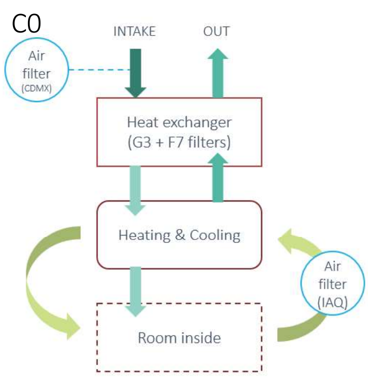


Figure 34. Ideal technologies airflow

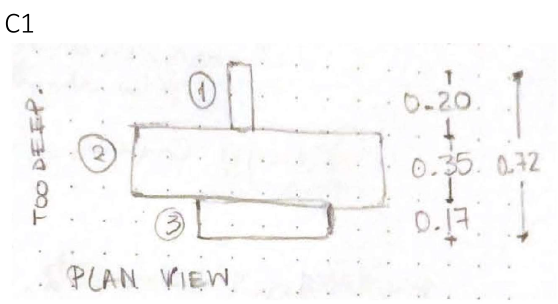


Figure 35. Composition of technologies following ideal airflow

Twist technology was chosen for ventilation due to its visually appealing façade integration, the ability to add filters, and its efficient heat exchanger performance. Figure 35 shows iteration C1, a hypothetical situation where each technology is positioned one after the other, without tolerances or space. This showed that by grouping the technologies, they have a thickness is 72cm, which do not meet the architecture DR, chapter 2.

Figure 36 shows the iteration C2, which positions the technologies at the bottom of the window inside a box that can be taken out. For this iteration, the ventilation unit, VentoTherm twist, was positioned at the bottom and the monoblock heat pump on top of it in the opaque space. This intended to allow the air to heat or cool as it goes up the wall immediately. The main ideas from this iteration were to analyse the building physics of the airflow with the design and to determine the possibility of a technology box that you can take out from the façade. This iteration proved to have potential to further develop since it met the DR of easy maintenance.

Figure 37 shows the design iteration of a vertical technology duct (iteration C3). The possibility of compartmentalising the duct for each technology with horizontal ducts connections within the duct to allow the airflow to go through. The goal of this idea was to reuse the heat exhausted from the heat pump and to achieve an integration of the technologies medium instead of them working separately. As in the previous iteration (C2), the duct was also considered to be designed as an operable furniture that could be removed from the ducts to perform the respective maintenance. However, this option was complex regarding maintenance and the risk of non-operability of the system when one of the technology units would require maintenance. Apart from the unsuitabilitty of mixing the exhausted air from the HP which will be further addressed in the iteration CA4.

C2

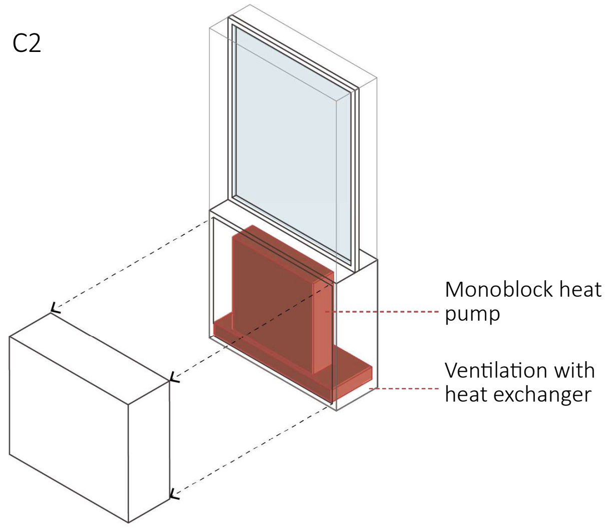


Figure 36. Technologies located at the bottom of the panel

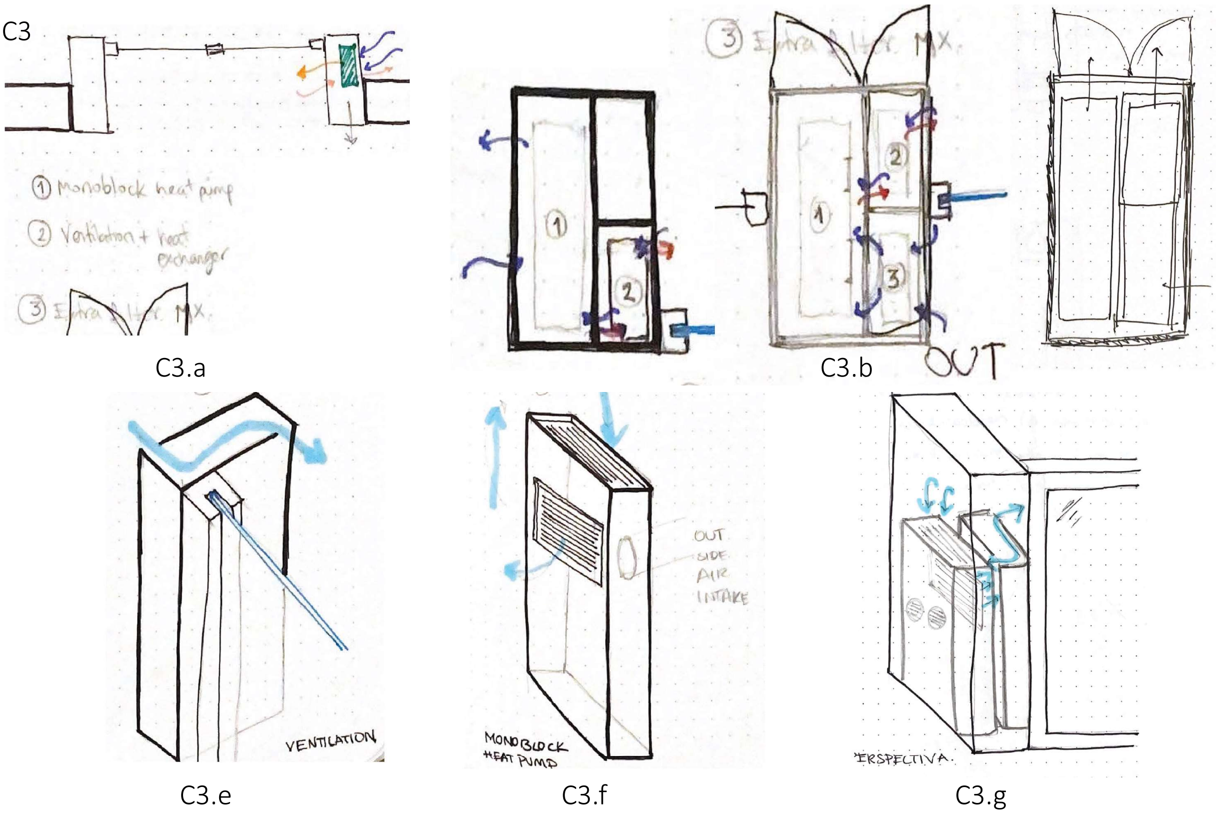


Figure 37. Technologies location in a vertical duct compartment. A floor plan view of the technologies and a lateral air inlet crossing towards the inside (C3.a). Floor plan with the technologies located in compartments inside the duct (C3.b). Air flow in technology duct (C3.c). Air flow in a vertical monoblock heat pump (C3.f). Air move between technologies in the duct (C3.g).

Figure 38 shows two ideas that are based on the A1 iteration. CA1-1 represents the heat pump technology in front of the slab, with the ventilation unit under the window frame on top of the slab. The CA1-2 has the same concept, but this time a sunshade was added at the bottom of the heat pump unit to give shade to the apartment below. The technologies positioning resulted in complex access through the outside of the façade and given that they need maintenance at least twice a year due to the filters, they were not further develop.

Figure 39 shows iteration C4, a development of airflow integration within the technologies. This iteration was developed using the technologies of FreshBox E-100 and the monoblock heat pump 2.0 mini. The goal was to test if by reusing the exhausted air from the heat pump for the ventilation unit, the system performance could be further improved in terms of energy. However, it was found out that during winter time, the exhausted air by the HP is colder than the outside temperature whereas during summer time, the exhausted air is higher than the outside temperature. If the exhausted air were to be combined with the air inlet for the ventilation technology it would translate into a higher energy demand than if the ventilation unit only used the outside air. This iteration was not further developed since the aim is to reduce the energy input required for the technologies not to increase it. Thus, it was decided to integrate the technologies separately in the façade panel. Added to this, the pipe system behind the technologies would have created a thicker unitised façade panel unit than what is allowed by the design requirements (<50cm).

Design iteration 03_ Façade and technologies

Figure 40 shows the iterations D1, D2 and D3 that involve the interaction between the façade and the technologies. All three include the integration of horizontal PV panels to generate shade and produce electricity and the addition of PV panels in the concrete columns of the building. D1 is based on the vertical duct idea (C3). D2 is based on the wall integration of the technologies (C2). D3 is a combination of D1+D2 since it combines the option to have the ventilation technologies in a vertical duct and the heat pump in the wall. The main issues for D1 and D3 were the columns' thickness and their predominance in the façade view. It jeopardised the views to the outside and the aesthetics of the façade since the vertical ducts were around 2 meters apart. Iteration D3 made the vertical ducts and the wall slimmer since less space was required. However, the extra weight of the duct plus the wall was not optimal for a façade panel, apart from the repetition of these elements along a large façade that made it look bulky and massive. From this iterations

CA1-1 CA1-2

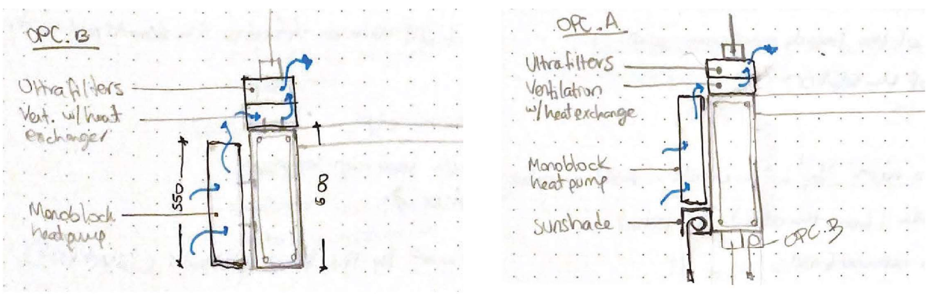


Figure 38. Technologies located in front and on top of the slab

CA4

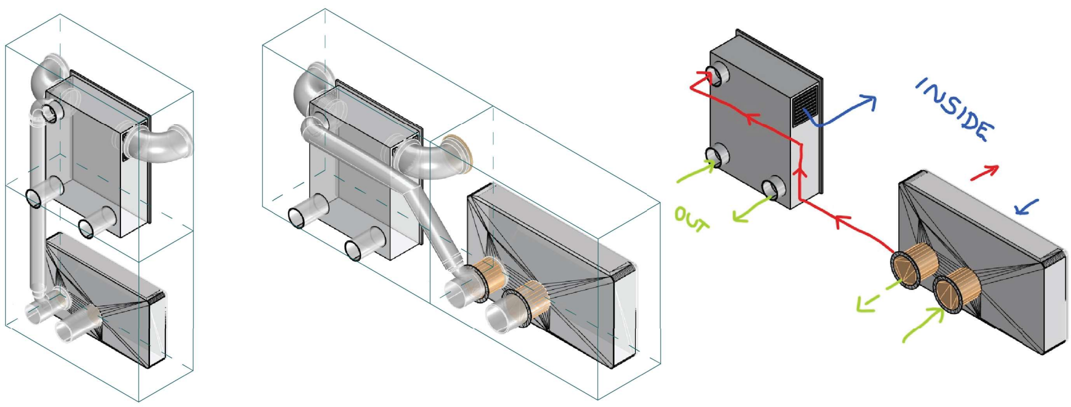


Figure 39. Technologies located within the façade panel. Reuse of the heat waste from the heat pump to the ventilation system

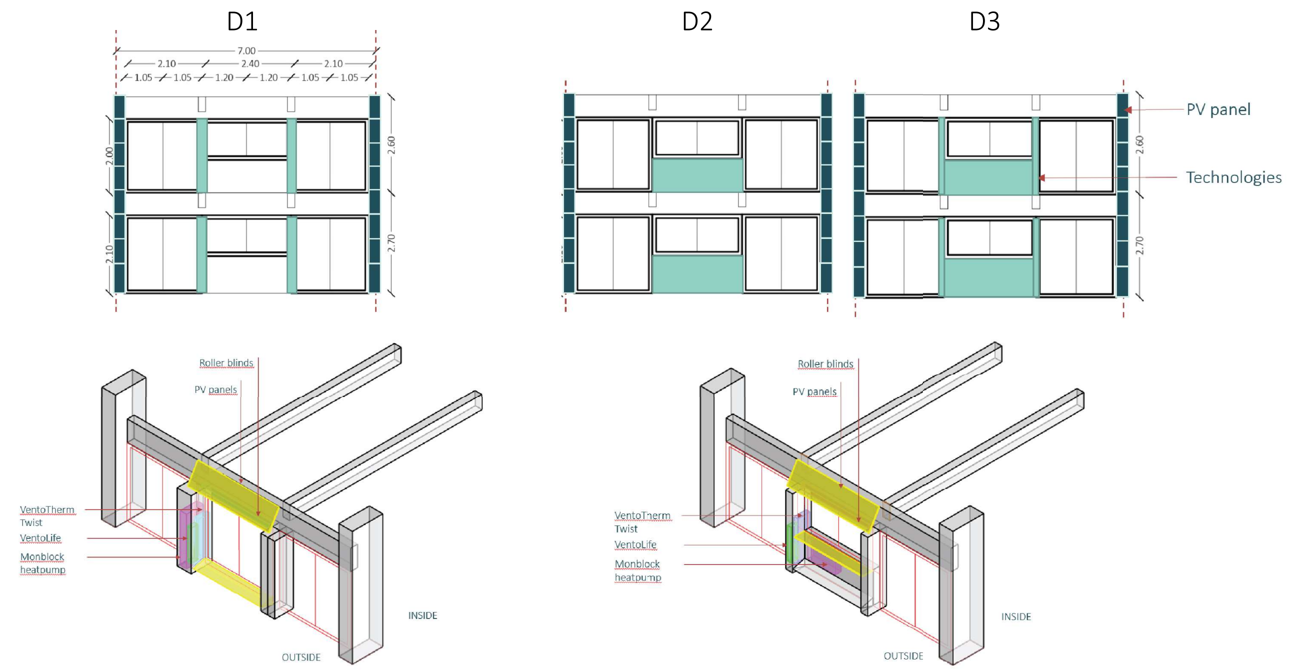


Figure 40. Visualitations of how the technologies can be located in the façade along with a proposal for pv panels and horizontal sunshades

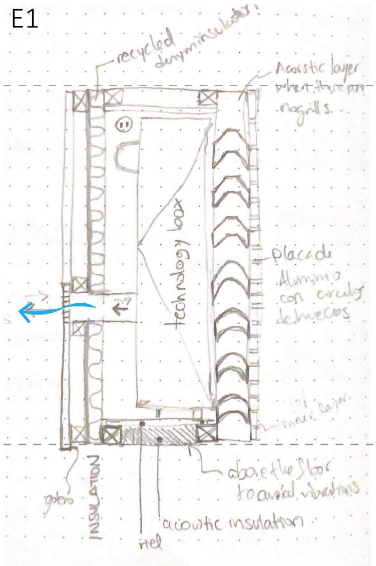
group, the best option for further development was iteration D2 since the thickness aligns with the architectural DR, it allows for WWR adjustments and the positioning of the technologies are easily accesible from the interior of the appartment.

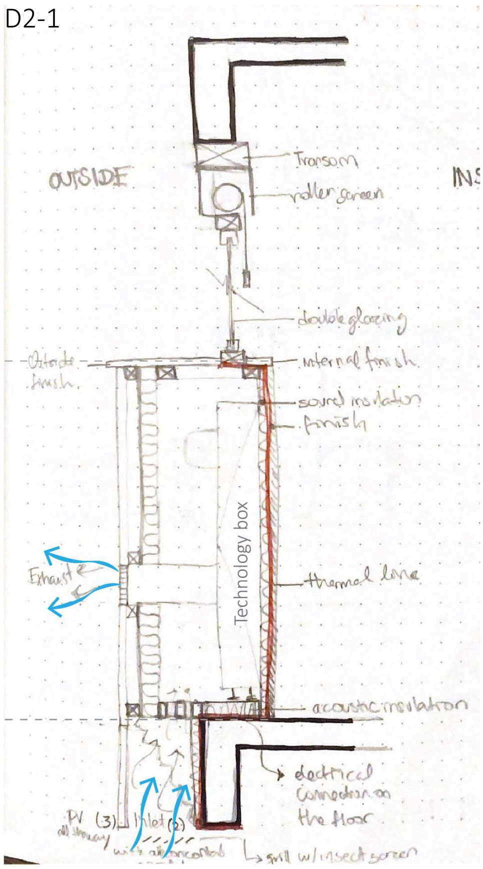
Figure 41 shows the iterations D2-1 and D2-2. These iterations consider the detailed location of the technology vs the building concrete structure. They are based on the first iteration ideas (B1 and B2). Iteration D2-1 considers a façade panel that is outside the limits of the building for the air inlet, but the rest remains inside the structure. This idea was not unitised. Thus, it did not meet the design requirements and was not further develop. D2-2 is a unitised system that allows for easy construction in front of the existing concrete structure of a building. It is divided into two parts. The unitised façade panel is installed from the outside and the technology box is installed from the inside (Figure 42). This approach allows for the façade panel to have a depth under 50cm which meets the DR, it has the thermal line on the outside of the building (see Figure 42), and the technologies are located in a fireproof compartment installed in the interior of the building attached to the façade. This last characteristic allows for an easy plug-and-play system since even when the climate changes over the years, there is a possibility for upgrading the technologies or even replacing them with another without interfering with the façade panel. Moreover, it lowers the fire risk compared to its integration inside the panel. It also allows the existing mansory wall to stay, if needed. The façade panel integrates the technologies and components such as the air inlet, air outlet, and an interior roller blind. For these reasons, the D2-2 iteration was chosen to develop further in the architecture façade panel design.

Design iteration 04_ Details

The detailing iterations were done based on the final chosen iteration: D2-2. The purpose was to solve technical aspects that did not met the comfort DR in terms of technologies and the design.

The first detail study is represented by E1 which shows the technology compartment box with an extra acoustic layer to reduce the noise emitted by the unit and an acoustic grill air inlet integrated into the box door. From Chapter 2, we concluded that the ventilation units did not meet the noise level requirements set by the DR. Therefore, this had to be addressed to enhance user comfort.





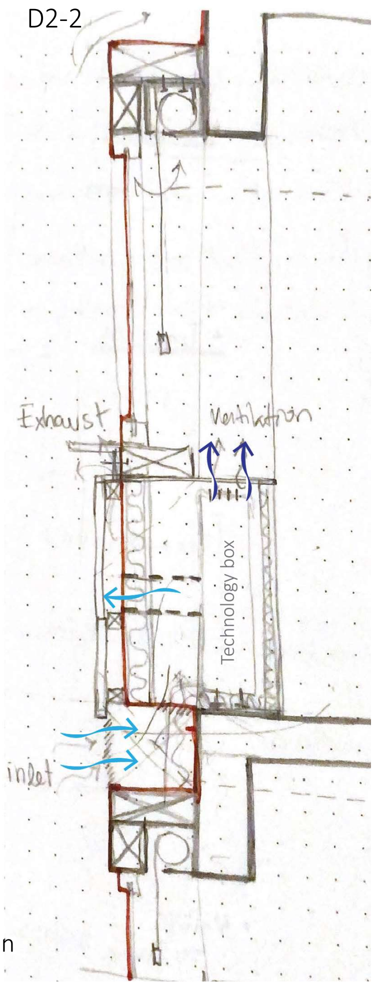


Figure 41. Detailed visualisation of the integrated serviced façade panel in cross section

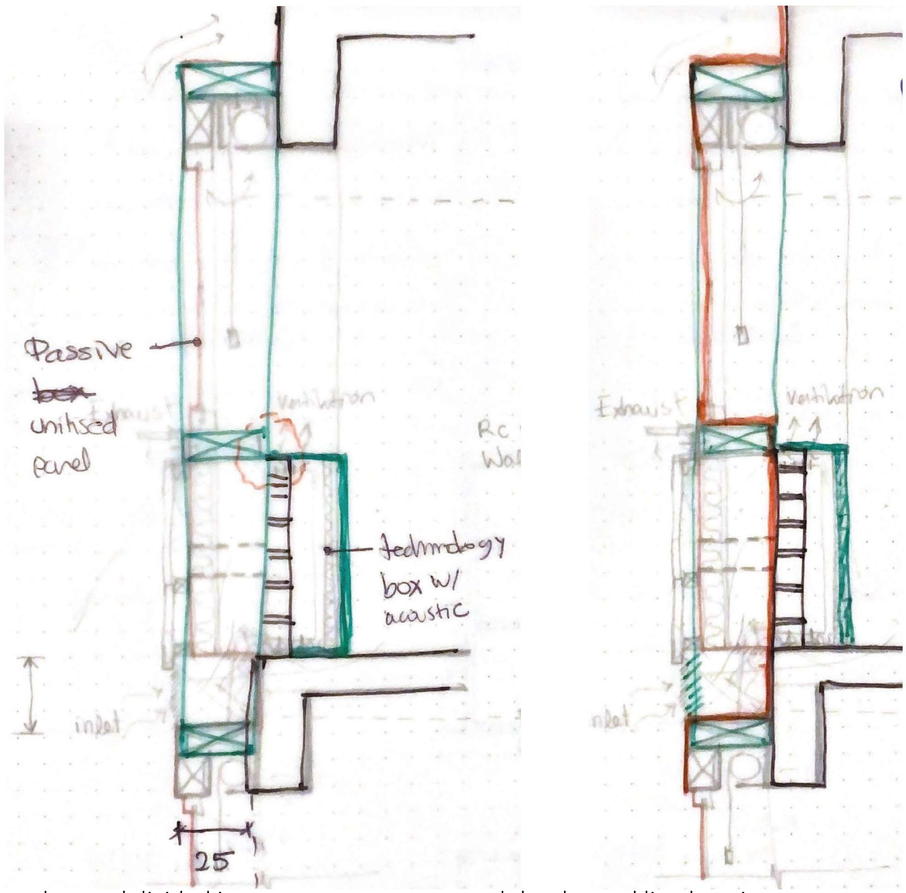


Figure 42. Visualisation of the façade panel divided into two parts concept and the thermal line location

E1-2, shown in Figure 43, represent a design option for the acoustic grill air inlet from the ventilation unit Freshbox E-100. This grill could be with dots or horizontal or vertical lines imprinted in the finish of the technology box.

E2 is exemplified in Figure 44. It shows the idea further developed in the architecture design of the façade panel by adding an overhang with a PV panel on top long enough to cover the sun angle during summer time. At the same time, this overhang would function as the air inlet for the technologies. This way, the overhang would be meeting the DR of multiple uses per façade part.

Figure 45 shows the electricity solution for the panels (E3). It was based on the vertical duct iteration (C3). The concept consists of having vertical lines running through the façade to supply the technologies with energy. Each floor has an overhang through which these electricity lines will go through and, at the same time, connect to the PV panels. We can also see that the PV panel has a perforated aluminium frame around it. This is to allow the air outlet from the technologies to cool the PV panel in their way out and, this way increasing their efficiency.

Figure 46 showcases the E4 iteration, which represents a theoretically passive concept utilising PCM (Phase Change Materials) for indirect cooling and heating. While this concept had the potential to reduce the reliance on heat pumps integrated into the façade panels, it ultimately posed limitations due to its passive nature, which heavily relies on the specific climate conditions. As the design goal of this thesis is to create a standardised solution applicable across diverse climates and contexts with minimal aesthetic variations, further elaboration on this concept was not pursued.

E1-2

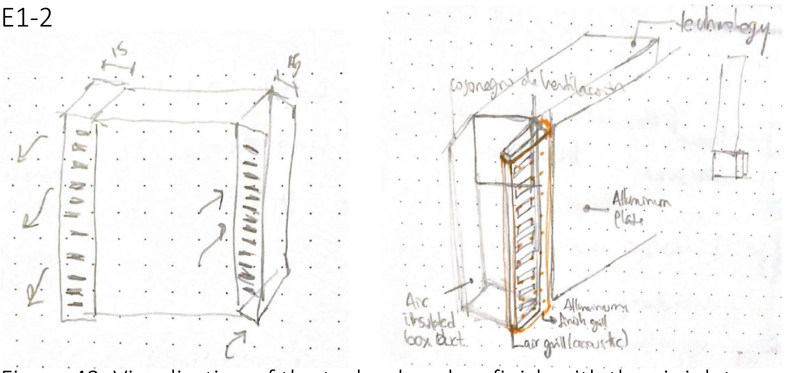


Figure 43. Visualisation of the technology box finish with the air inlet through an acoustical grill

E2

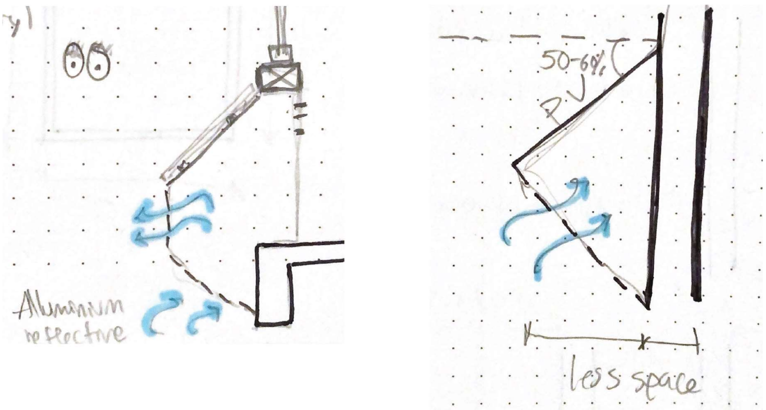


Figure 44. Overhang air inlet ideas integrated with PV panels tilt angle

E3

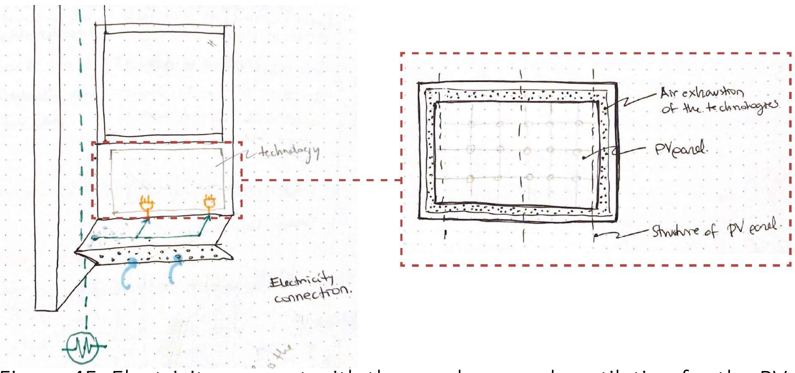


Figure 45. Electricity concept with the overhang and ventilation for the PV panel from the back (air coming from the technology exhaustion)

E4

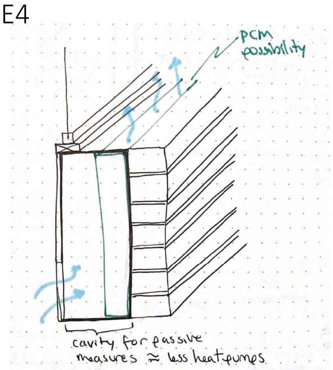


Figure 46. Possible addition of passive measures within the façade panel cavity

4.1.2 Contact with the industry

The industry contacted for feedback on my pre-design were façade designers, building services product developers, circularity experts, building physics consultants, architects, façade designers and marketing manager. As well as a field trip to BAU Munich, a World's Leading Trade Fair of Architecture, Materials and Systems, to corroborate gathered data during the desktop-research of the technologies and discuss first-hand the technologies and their feasibility for façade integration with the product developers. As well as have a physical review of the latest innovations in façade systems to implement in my design regarding aesthetical building materials, solar technologies, light/smart building, and glass. Appendix E gives detailed information on the proffesionals with whom the interviews were done. Table 24 exemplifies the main findings and conclusions of the interaction with the industry. The information gathered at the fair is part of the Product developer's row in the same table.

The main positive impacts are that the technologies chosen are the leading cutting-edge products in the market nowadays, and the integration of building services in the façade raises interest and has potential in the façade sector. Moreover, the pre-design developed during the talks with the industry was considered ambitious, attractive, new and aesthetically flexible. It was proved that the design requirements are a valuable document with the suitable characteristics to fulfil a well-designed integrated façade panel. Moreover, the document improved with the feedback from the proffesionals of the industry, in terms of design integration, fire safety, air flow design and façade panel installation.

The main concerns of the industry are the electrical connection solution, the need to avoid drafts, reduce noise levels, the isolation of the parts for fire safety achievement, easy maintenance, the life span of the components vs the life span of the panel, as well as the possibility to enhance the richness and dynamism of the façade.

Amongst the consideration for the development of the architectural design façade panel are the technologies lifespan, the technologies location in the façade compared to the room for optimal airflows to avoid drafts, the thermal lines designed to avoid thermal losses, the approach of the façade panel design in terms of architecture (whether it aims to reinterpret or preserve the façade), the fire-safety measurements, panel sizes for transportation, the façade maintenance periods, the energy savings evaluation and cost risks.

These three areas were merged and considered for the further development of the architectural design façade panel. The feedback between the talks was applied within the next week of the meetings to allow the pre-design to develop faster. In this sense, the previously shown design iteration considers some of the recommendations made by the professionals from the field, such as the thermal line design, the compartmentalisation for fire safety reasons, the integration of different uses for one part component such as the overhang, the thickness and sizes of the façade panel, as well as the electrical connection solution. In the following subchapter, a formal application of what has been learned until now will be implemented and translated into an integrated façade panel design.

Table 24. Main conclusions from the talks with the industry in terms of possitive feedback, main concerns and things to consider in the next steps of the final design.

	Positive feedback	Concerns	Things to consider
Product developers (façade and building services)	The HVAC units chosen are the latest **cutting-edge technologies** in the market. There is **interest** in developing an **integrated serviced** façade at a company level.	The **noise** levels of the units. The VentoLife unit is no longer available in the market due to a lack of demand for it.	The possibility of developing a new HVAC technology is a recommendation for further research in the market. The **technologies lifespan** depends entirely on their use. An approximation of 50 years can be assumed under normal conditions. However, these conditions have yet to be tested in real life since the technologies have been used for less than 20 years.
Circularity expert	The characteristics within the design requirements of modularity, disassembly, flexibility and independence between the parts are a positive addition to the panel design.	The components added to the façade have many **critical materials**, making it hard to achieve sustainability. Other concerns were the **electrical connection** from the facade to the technologies and the need to avoid dependency between the panel frames, the window and the technologies compartments.	The manufacturer is responsible for addressing the after-life use, but this matter could be a thesis. It was recommended to consider **evaluating** the concept in terms of **cost and energy**. Adding design aspects leading my design in the design requirements, such as slim technologies.
Building physics consultant	Addressing indoor air quality is good for people's health. Using the façade cavity from the design is possible as part of the solution. A recommendation was made to reach out to the product developers to see if they had a similar concept undergoing in their companies.	To avoid **drafts**. The **noise** levels needed to be considered not only from the technologies (especially the heat pump) but also from the urban space—a recommendation to especially be aware of the lower frequencies by using mass inside.	The **technologies' position** in relation to the space, orientation and location of the building, noise levels, thermal lines and aesthetics of the design. The **thermal lines** must be designed carefully and thought through since, for instance, if I decided to go for the duct column, that would directly impact the elements next to it.
Architects	The design process is a clear simultaneous approach to the composition of the façade at a building and panel level. The façade design reinterprets the current geometry but gives a new and fresh technological aesthetical look.	The **richness and dynamism** of the original façade need to prevail. The **electrical connection** to the technologies needs to solve.	It would be interesting to see the technologies being part of the expression of the façade and whether the aim is to **reinterpret or preserve the façade** with this design. There is **more to be integrated** rather than plug&play with the technologies. For instance, the technology box can work as a shading device.
Façade designers	The concept is **ambitious, attractive, new and with potential for flexibility in terms of finishes** and technologies' location. It addresses a facade integration that professionals are not daring to take. Implementing a unitised system is logical and congruent with the goals. Using the overhang for multiple purposes was an accurate decision. The cavity in the facade panel design could allow for implementation of **greenery** and generate an **urban element**.	The **fire safety** solution where the technologies are should be **isolated or compartmentalised**. The **facade panel thickness** can go as long as 30 to 40cm thick—**easy maintenance** of the technologies, especially regarding filters and user interaction. Integrate **fewer technology units** possible to avoid the system working for a couple of years, not to mention the higher **maintenance** investment **costs—**the **lifespan** of the technology vs the facade panel. **Avoid** the **on-site** panel **assembly** process. **Noise** levels are a concern.	The design requirements for **fire safety** were addressed to achieve a 60min fire-resistant façade. Evaluating the risk, cost and energy savings could be interesting. Regarding **cost**, it probably would be best to look into long-term savings since the initial costs would be high. Regarding the design, three window **panel grid sizes** would allow the architects to implement different combinations to enhance freedom and flexibility. This, at the same time, would result in less assembly time—consideration of the truck sizes for the panel, as well as the **facade maintenance** exterior through a rope attached to a substructure.
Salespersons	The design concept has potential since the **governments** are **investing in building refurbishments.**	-	A **cost analysis** would be required to decide whether or not such a product is feasible to be launched in the market.

4.2 Architectural façade panel design

4.2.1 Sun analysis

The stereographic sun paths shown in Figure 47 and 48 represent the sun altitude for the case study in Mexico City and the Netherlands, they were retreived from the online software Andrew Marsh. The sun altitude angles will be key afterwards for the panel design of the overhang.

The PV solar disk shown in Figure 49 represent the efficiencies of the PV panels according to the orientation and tilt angle used in the Netherlands. This information will be key to define the dimensions and form of the overhang in the Netherlands scenario. The orientation at 45° South-East with a 10° tilt angle can represent between 90-95% efficiency whereas a 90° tilt angle (like a vertical PV panel cladding) can represent a 60-70% efficiency. For the case of Mexico City such graph was not found. However, it is known that the ideal tilt angle for the installation of PV panels there is of 30°

4.2.2 Materiality

The Rc-value achieved with this proposal meets the design requirements for both, the Netherlands and Mexico City which is above 1,1. The u-values differ from each case study, Figure 50, given that in the Netherlands a better insulation is required due to its colder winters (0,16 for Mexico and 0,56 for the Netherlands). The thermal performance of the façade panel proposed was based on calculations run the online calculator tool called Ubakus. The different material u-value iterations done to determine the best insulation for both case studies can be found in Appendix F.

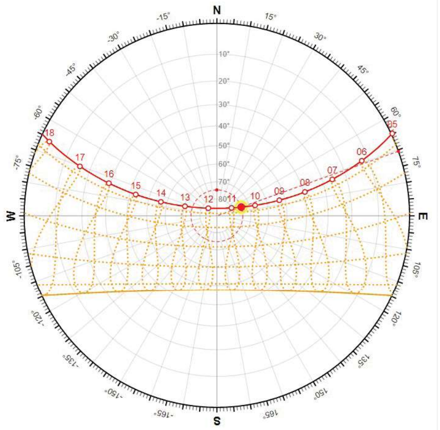


Figure 47. Mexico City stereographic sun path. June 21st, sun altitude of 74.71°

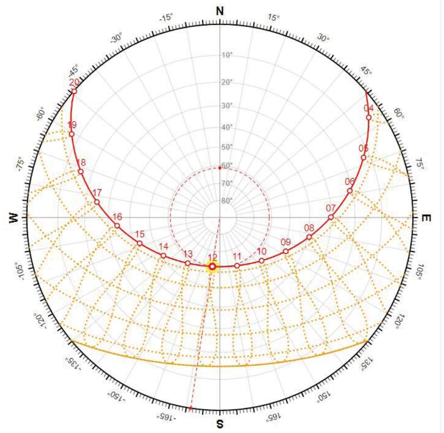
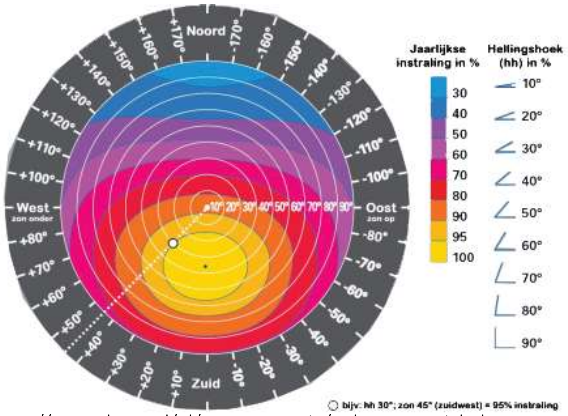


Figure 48. Netherlands stereographic sun path. June 21st, sun altitude of 61.23°



https://www.dgem.nl/nl/zonne-energie/opbrengstvariabelen-zonnepanelen

Figure 49. Netherlands PV solar disk (PV zonneschijf).

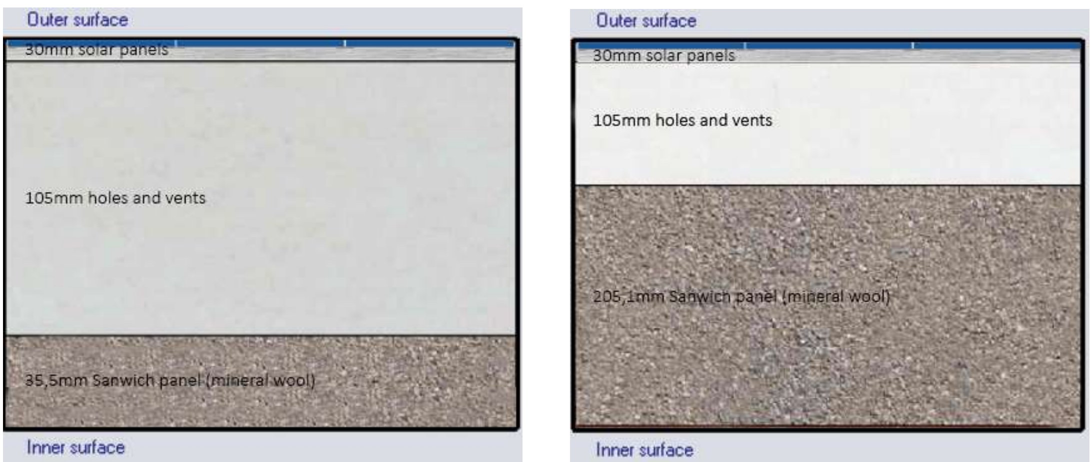


Figure 50. Calculated U-value of the façade panel case of Mexico City: 0,16 (left) and Netherlands: 0,56 (right)

4.2.3 Technologies selected

According to chapter 3, the ideal technologies for the façade integration are the monoblock heat pump 2.0 from Innova for heating and cooling, the Freshbox E-100 WiFi from Blauberg and the VentoTherm Twist from Schuco&Renson for ventilation. According to the hand calculations, two units are required per apartment zone. Figure 51 exemplifies the combinations of units needed per zone. The living room requires a combination of the VentoTherm Twist and the monoblock heat pump 2.0. The rooms require a combination of the Freshbox E-100 WiFi and a monoblock heat pump. These combinations are due to the airflow capacity of the ventilation systems and the noise levels. For more information on the calculations, please refer to the design requirements in chapter 2.

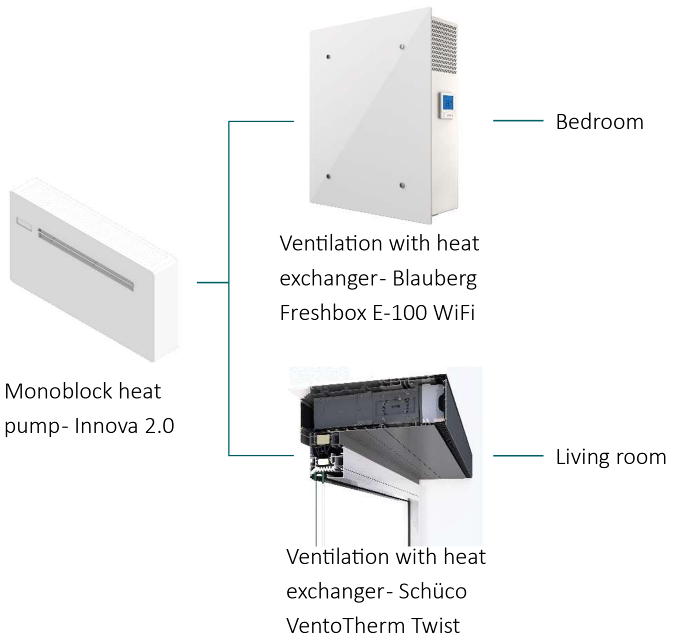


Figure 51. Combination of technologies depending on the apartment room

4.2.4 Services integrated

As subchapter 4.1 pre-design mentions, the integrated façade panel design is based on iteration D2-2. The design consists of a unitised façade panel attached to a concrete structure. The panel concept goes as follows; it is divided into two parts when a pre-existing masonry needs to be kept or just one when it is possible to remove the masonry wall. The integration of the technologies includes monoblock heat pumps 2.0 mini, ventilation units with heat exchanger, ventotherm twist and freshbox E-100 with their respective air inlet and outlet, exterior sunshades and interior roller blinds, PV panels and the electrical installation for the panel to function. Unless mentioned otherwise, all the visualisations in this subchapter represent the design panel with a brick wall between the unitised façade panel and the interior.

Figure 52 shows the location of the PV panels in the façade. They are located on top of the overhang and possibly as cladding for the wall. Figure 53 shows the horizontal outside shade system generated by the overhang where the electric duct and air inlets are. This overhang protects the window from the sun’s radiation during the hottest days of the year in summer. Figure 54 shows the location of the heat pump and the respective part of the overhang where the air inlet and outlet are positioned. Figure 55 shows the same concept as the heat pump but is now applied to the ventilation with the heat exchanger.

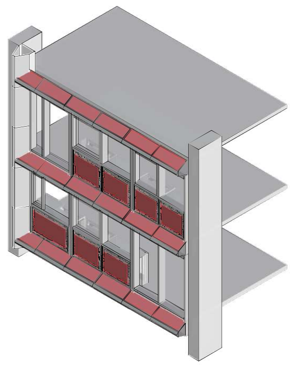


Figure 52. Electricity generation

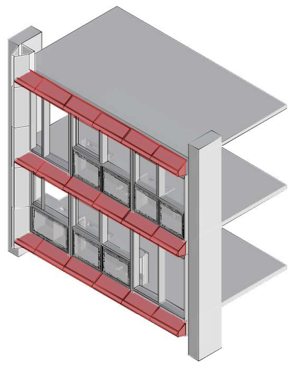


Figure 53. Horizontal sunshades and internal roller blinds

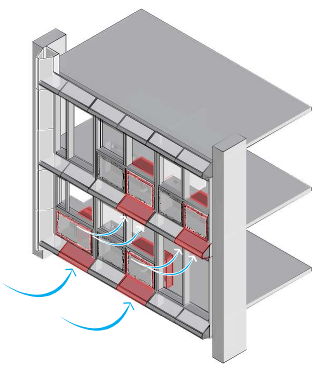


Figure 54. Heat pump integration (horizontal scenario) with air inlet through the façade

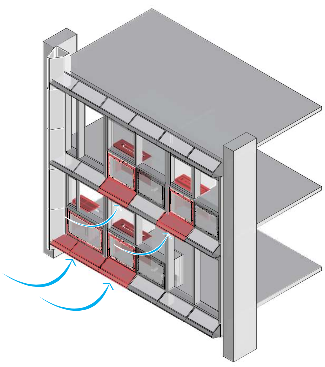


Figure 55. Ventilation with heat exchanger integration (horizontal scenario) with air inlet through the façade

4.2.5 Technologies location

The flexibility of the design relies on the positioning of the technologies in the façade according to the demands of the architect and the climate.

Figure 56 shows the situation of a living room and the different location possibilities for the technologies. These zones' limitations are the air changes per hour according to the volume. Therefore, the ventilation unit has a restriction of 2m in width, meaning that the living room panel has to be at least 2.10m in width or height. The heat pump unit remains horizontally located under a window. An advantage of this panel is that it allows the user to have more views to the outside which is usually preferred in the social area of the dwelling.

Figure 57 shows the different possibilities for the location of the technologies for the bedroom. The variations are horizontal, vertical and a combination of vertical and horizontal. With an upright positioning of the technologies, the views to the outside are lower, which is why for the development of the integrated façade, a horizontal layout was chosen for the rooms.

Figure 58 illustrates the optimal airflow arrangement suitable for an oceanic subtropical highland climate such as Mexico City, where higher cooling demand is necessary. In this climate, it is favorable to position the ventilation and heat pump unit at the bottom of the panel to generate drafts, which are desirable. On the other hand, Figure 59 showcases the ideal positioning of the technologies for a marine west coast climate like the Netherlands, where drafts need to be minimized, and there is a greater need for heating.

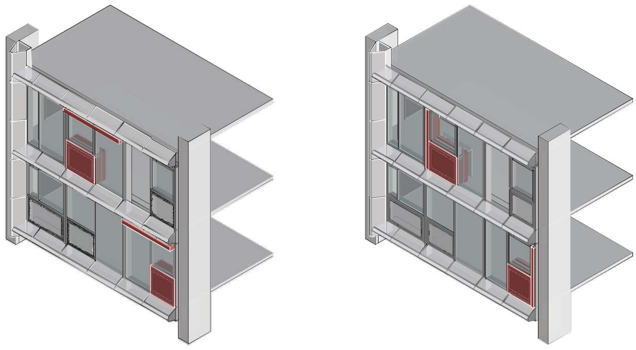


Figure 56. Possible location of the technologies in the living room (horizontal above the window or vertical).

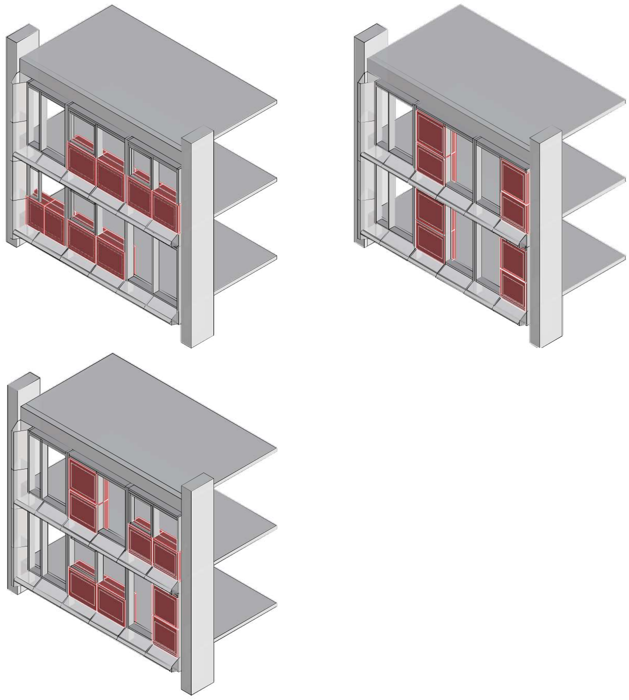


Figure 57. Possible location of the technologies in the bedroom.

Figure 58. Air flows in Mexico City (cooling demand climate).

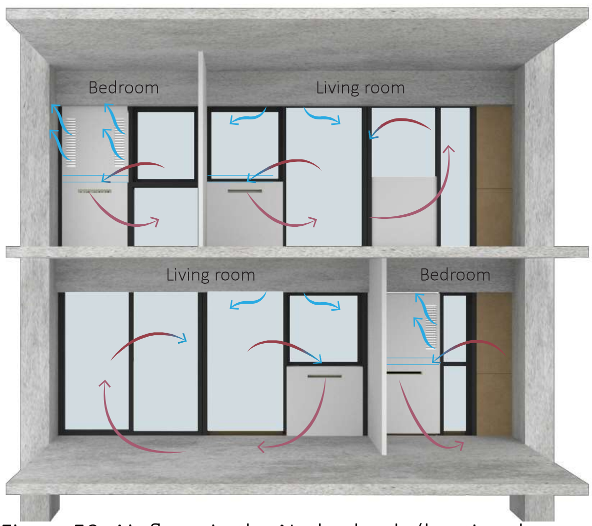


Figure 59. Air flows in the Netherlands (heating demand climate).

Figure 60 illustrates the positioning of air inlet and exhaustion ducts for both the ventilation and heat pump units. The heat pump unit requires a taller duct due to its top-mounted duct entrances, while the ventilation unit necessitates a shorter duct as its openings are located at the bottom. In this figure, the PV panels on the overhang are retrieved to provide a clear view of the inlet duct connecting the perforated plate of the overhang to the respective unit.

Moving on to Figure 61, it demonstrates the path of exhausted air from the ventilation unit through a duct to a cavity located behind the PV panel. From there, the air is expelled to the outside through the perforated perimeter of the cladding. This arrangement aims to cool the PV panel from behind, as recent studies suggest that this method can enhance its efficiency. The same principle applies to the heat pump system.

Figure 62 exemplifies the connection of the air inlet from the lower part of the perforated overhang to the cavity within the integrated façade panel. If present, the inlet may traverse the masonry wall to reach the heat pump ventilation unit. After being pre-cooled or pre-heated, the air enters the room for recirculation. This concept applies similarly to the ventilation system.

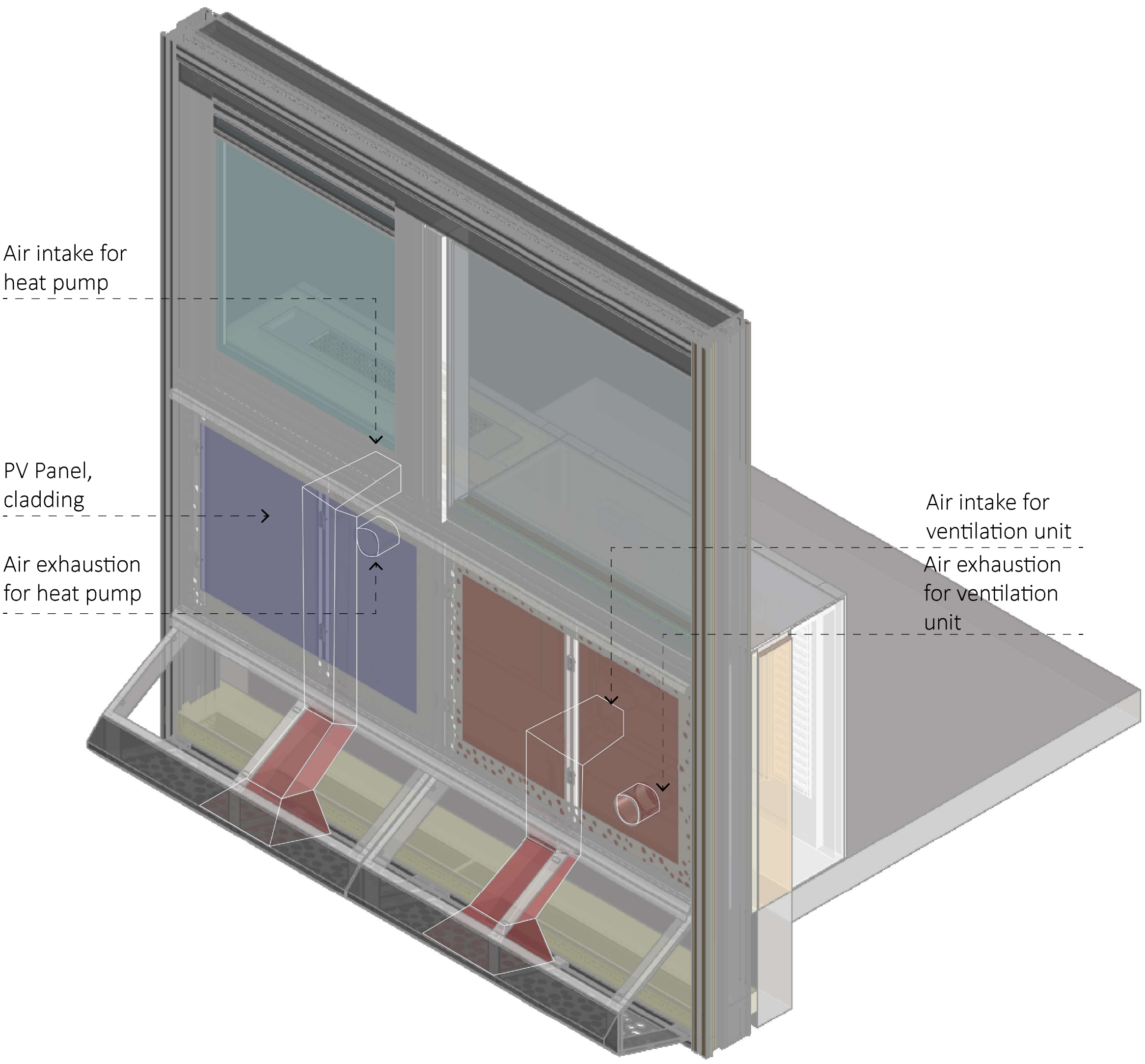


Figure 60. Location of the air inlets and exhaustion ducts within the integrated façade panel. The left side represents the ducts for the heat pump unit and the ducts on the right for the ventilation unit.

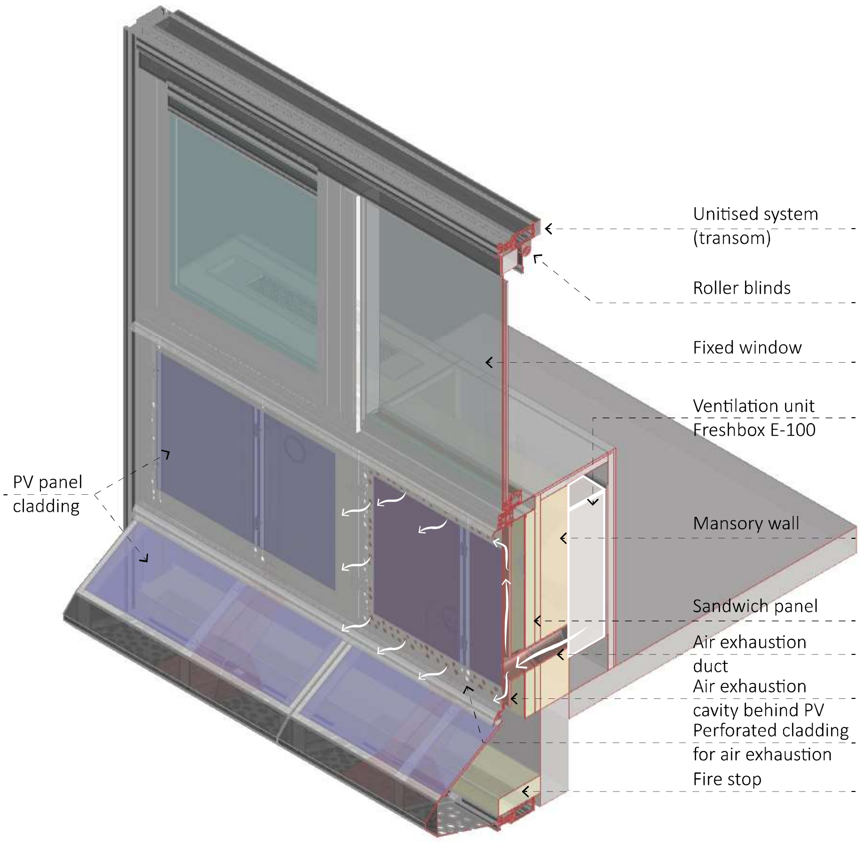


Figure 61. Front view of the integrated façade panel. Air exhaustion duct location for the ventilation unit is behind the PV panel. The air is exhausted from the unit to a cavity behind the PV, then to the outside through the perforated perimeter of the cladding. This way, the air is reducing the temperature of the PV, improving its efficieny. Same concept applies to heat pump units.

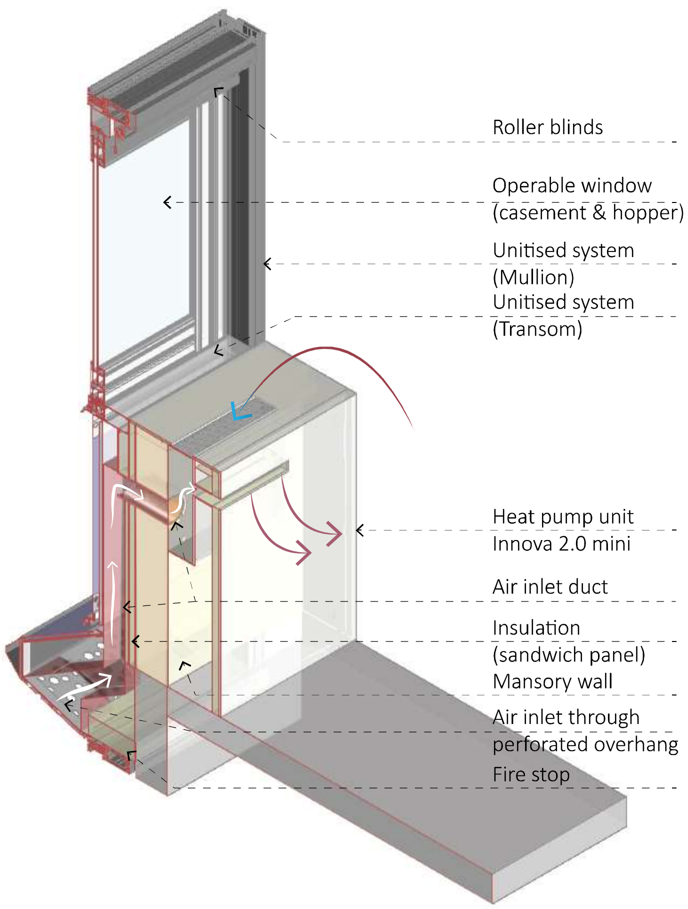


Figure 62. Back view of the integrated façade panel. Heat pump location of the air inlet duct. The air is taken from the bottom through the perforated overhang. Same concept applies to ventilation units.

4.2.6 Panel design

The unitised system consists of three modules subdivided into two and three. The combinations of three panels generate a façade between the concrete columns.

Panel A: Three-unit panel exemplified in Figure 63. A side vertical electrical duct which is a fire-resistant compartment. Next to it are two fixed windows fully glazed. The first one is subdivided into one small and one bigger side to continue with the rhythm and proportion of the façade.

Panel B: Two-unit panel with ½ operable glazing and an opaque part at the bottom for the technologies (ventilation and heat pump), or in case only one technology is required, it can be a storage cavity next to it, or if no technology is needed, then the technology box is not integrated inside. It is exemplified in Figure 64.

Panel C: Two-unit panel for the living room exemplified in Figure 65. It consists of ½ operable glazing with an opaque part at the bottom for the heat pump technology and a fully fixed glazed window on the other half, and the ventilation technology ventotherm twist runs on top of these two units.

Figure 66 shows the unitised panel with a brick wall in between, whereas Figure 67 shows the unitised panel without a brick and with all the technologies integrated inside the panel. Each panel's thickness varies, as the one without a brick is 13cm thicker than the other. However, the unitised panel's width is only 35cm without considering the overhang and 73cm with the overhang. The dimensions without the overhang are 15cm below the design requirements, which makes it a suitable panel for the design. Figure 68 shows the checklist of the panel design accomplishments. All of them were achieved.

Figure 63. Panel A. Three unit panel with electrical duct.

Figure 64. Panel B. Two unit panel with technologies.

Figure 65. Panel C. Two unit panel for living room.

Figure 66. Perspective view panel B with wall

Figure 67. Perspective view panel C without wall

ARCHITECTURE

Modular design
Prefabricated unitised system
2:1 proportion
< 40cm depth
Easy transportation panel dimensions (2,40x2,70m)
Easy use
Components with two uses
Tolerances 3 mm
Technologies depth 25 cm
Designed airflow dynamics
Filter system integrated
Easy access
Flexibility with panel variation in finishes
Avoid of repetition with a dynamic facade design
Dry connections between the parts
Independent access to the parts

ENERGY SUPPLY

Technologies transfer principle: Air-electric
Technologies energy class: A, A+
Heat pump (HP) CoP: 3,2
HP Cooling capacity: 2,640 W per unit
HP Heating capacity: 2,640 W per unit
HP Power consumption: 640 W (monoblock heatpump)

Vent. heat exchanger efficiency: 98% (bedroom), 80% (living room)
Fresh airflow rate [m3/h]: 100 (bedroom), 145 (living room)

PV panels efficiency: 90%
PV tilt angle: 30° (MX), 15° (ND)- 90° both
Orientation: Southeast

COMFORT

VT: 80%
SHGC: 60%
R: 65%
Tvis: 10%
Emissivity: 8%
WWR: 40% (living room) - 50% (bedrooms)

SPL: 25 dB(A) bedroom, 30 dB(A) living room

Glazing u-value: 1,1 (double glazing)
Glazing G-value: 50%
Wall reflectance 0,5
Wall Rc value: 2,15
Sunshade conductivity: 25%
Outside sunshade system (overhang)
Interior manual roller blinds
Technologies operating temperatures: .-10 ≤ x ≥ 35

Filters: F7
CO_2 sensors integrated in the technologies
Fresh air flow rate [m3/h]: 72 (bedroom), 144 (ND)
Air exchange rate per app.[m3/h]: 60 (MX), 125 (ND)

USER INTERACTION

Manual roller blinds with bed chain
Fixed outside horizontal shades (non-operable)
Operable windows with handles accesible at eye level form the inside
Technologies setting can be modified from the app through WiFi or in the touch screen panel inside the technology box

FIRE SAFETY

Materials class B, resistant for 60min of fire
Technology boxes that function as fire compatments
Firestops: horizontally between the panel and the building structure, and vertically in between floors.

Figure 68. Design requirements achieved with the integrated facae panel design

4.2.7 Assembly process

The unitised panels are entirely manufactured in the factory. When on-site, they are lifted by a crane and connected to the concrete structure with a C-rail and adjustable bracket to allow vertical and horizontal moves. The assembly process is exemplified in Figure 69. The panels' height is adjusted using bracket bolts, and the space between the structure and the panel is filled with insulation; fire stops between the slabs and fire protection profiles. Panel A has to be installed first since it has attached to the vertical duct of the whole building. The middle panel will absorb any width adjustments between the concrete columns. The detailing of the panel manufacture and installation will be shown later in the subchapter 4.5

4.2.8 Façade exploded view

Figure 70 shows the façade panel module build-up at a building level. The projections show the assembly sequence of the individual parts of each panel component; horizontal overhang, panel, heat pump box and ventilation box.

Figure 69. Construction assembly sequence

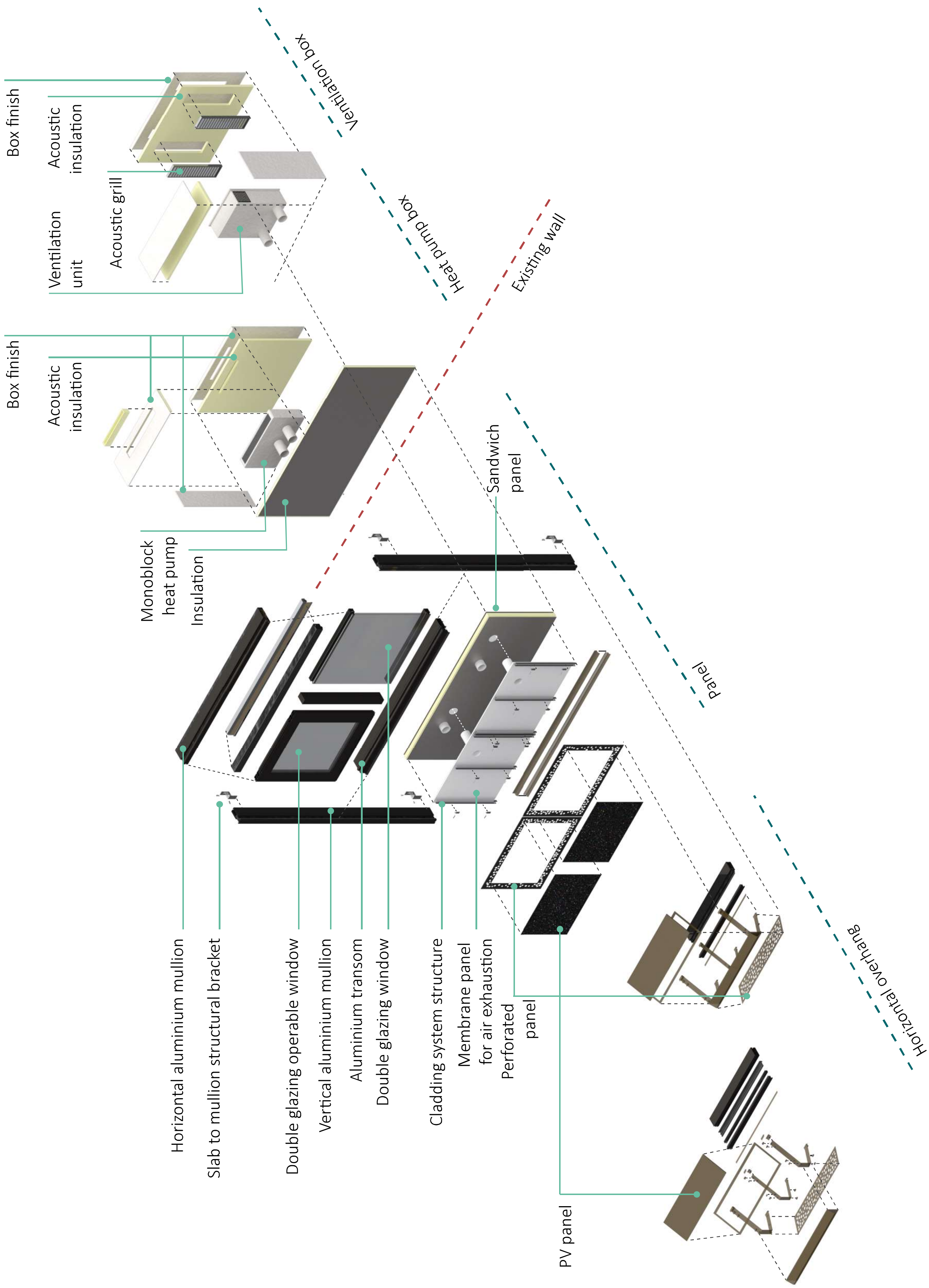
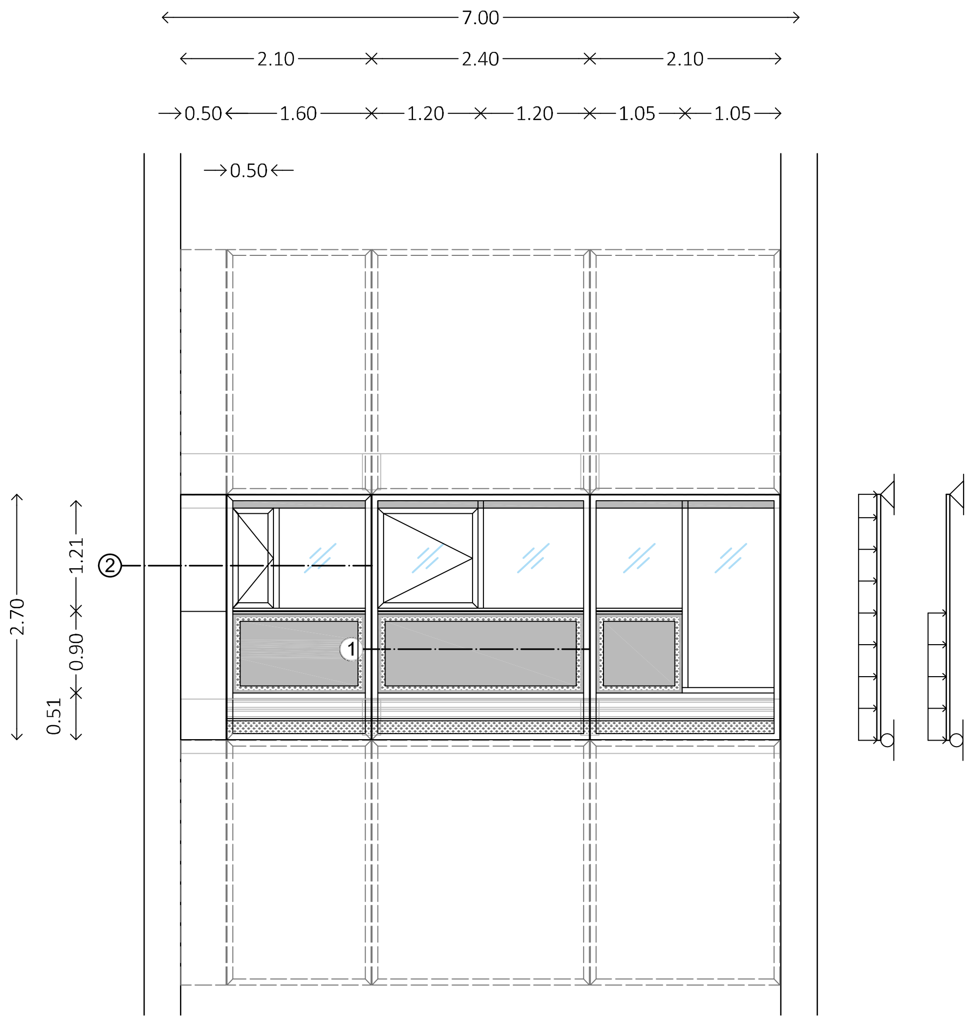


Figure 70. Exploded view of the façade

4.3 Technical plans

4.3.1 Structure

The span between the columns is seven meters. This means there are secondary beams in the opposite direction of the façade around every two meters. Thus, the panel sizes of the system are two of 2.10m on the sides and one of 2.4m in the middle. As stated before, the middle panel is the one that will absorb the differences since, structurally, it can allow for the adjacent panels to move up to 5mm inside its unitised mullion structure. As shown in the façade front view, the free body diagram of the façade panel structure is of a simple beam with UDL in the case of an existing masonry wall and a simple beam with PDUL at one end, the end of the technologies in the absence of a brick wall. The preliminary structural calculation can be found in Appendix G.



Drawing 14. Façade panels dimensions in front view and structural static diagram sections (SCALE 1:75)

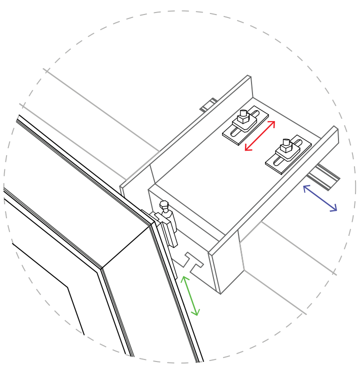


Figure 71. Structural bracket detail connection between mullion and concrete slab (from the top)

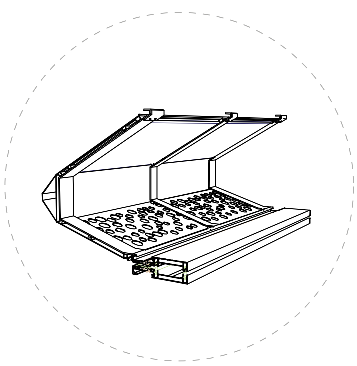
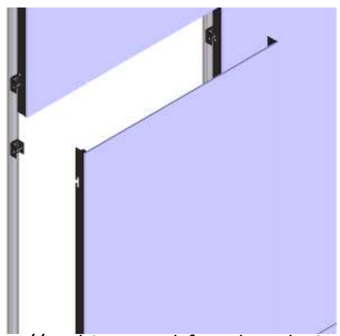


Figure 72. Overhang substructure



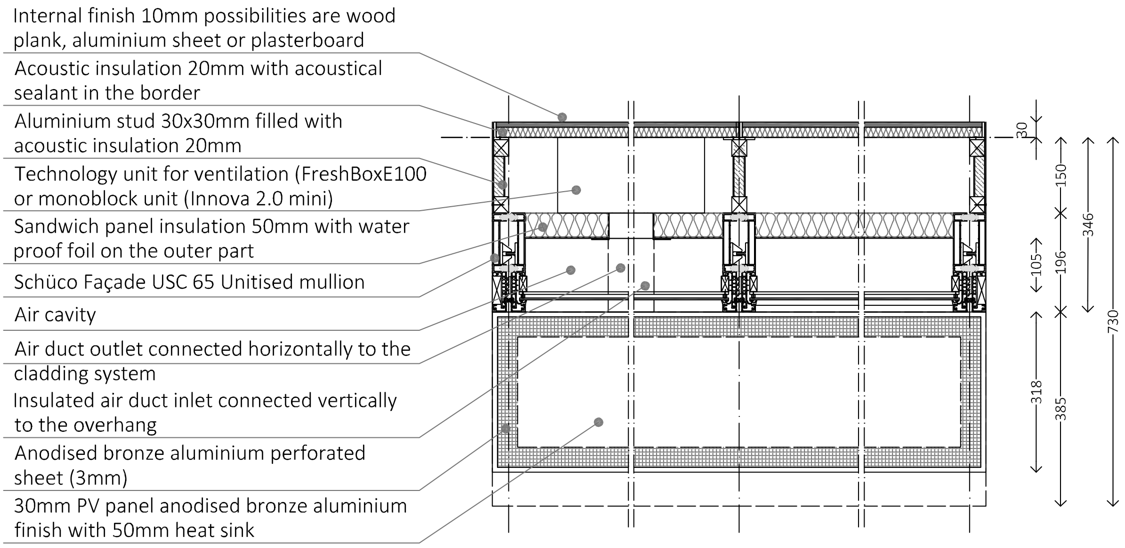
https://architectural-façade-solutions.com/product/solar-façade-panels/

Figure 73. PV panels mounting exemplification on substructure

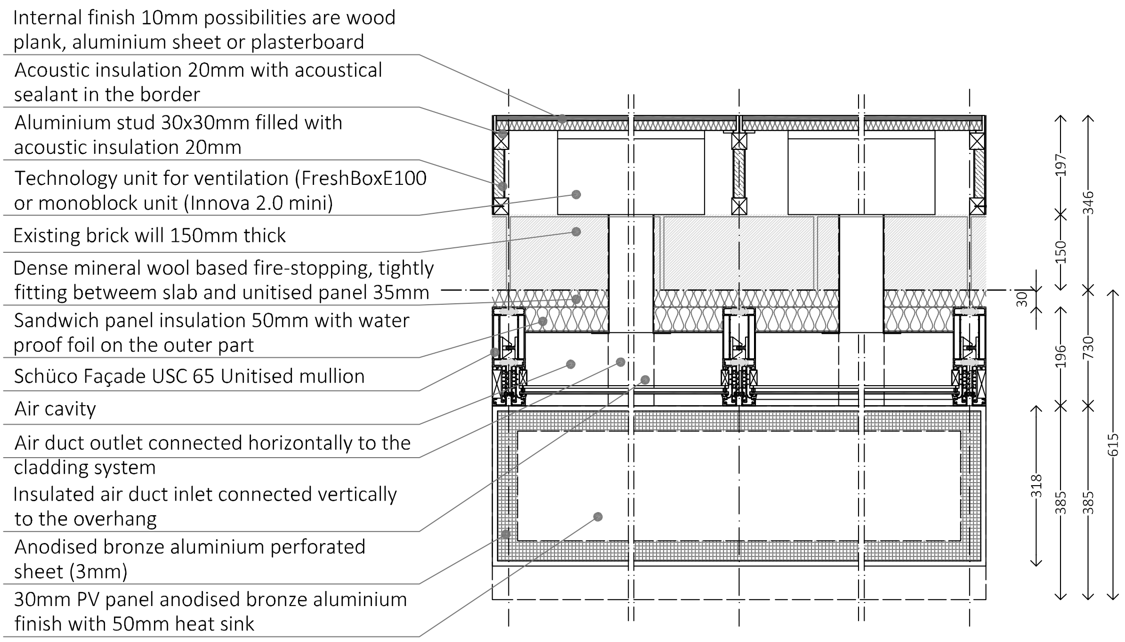
4.3.2 Horizontal details

Detail 1.0 exemplifies panel C without a brick wall. One technology is added on the left side with void cavity storage space on the right.

Detail 1.1 exemplifies the implementation of two technologies on each side of the panel. This is panel B which includes a brick wall between the technology boxes and the unitised panel.



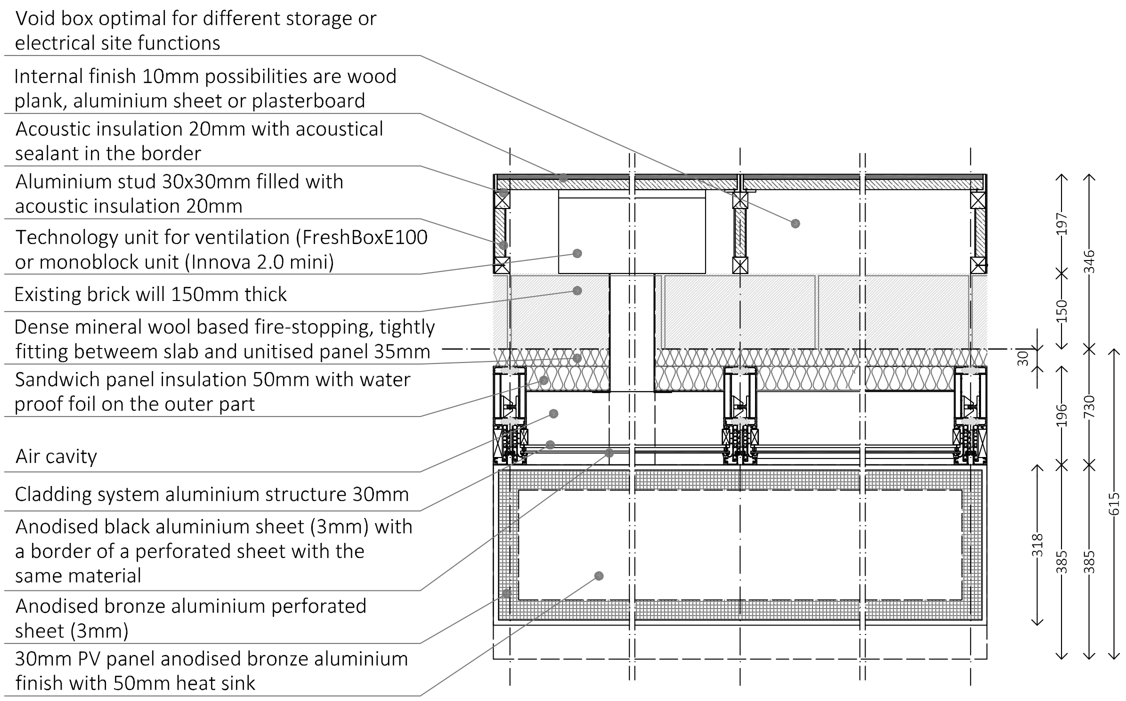
Drawing 15. Panel C horizontal detail without a brick wall in between the façade panel and the technology box (SCALE 1:15)



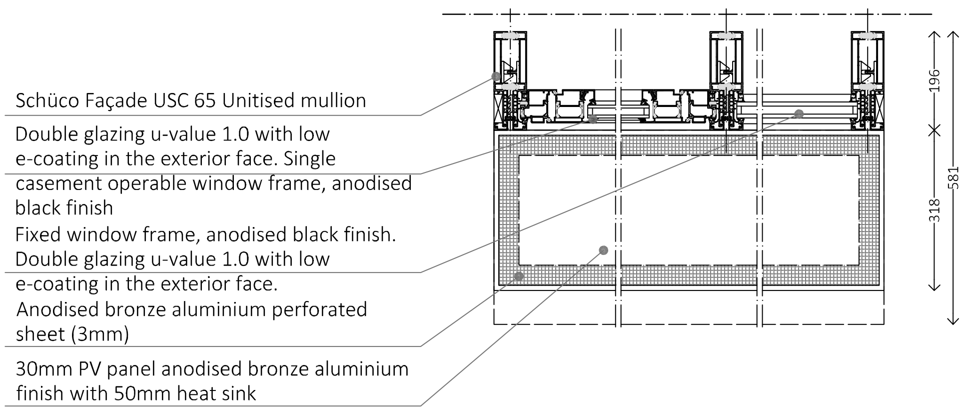
Drawing 16. Panel B horizontal detail with a brick wall in between showing two technical units on each panel side (SCALE 1:15)

Detail 1.2 exemplifies another possibility of panel B with a brick wall. One technology is added on the left side with void storage space on the right. The decision to keep the right box despite not having technology inside comes from an architectural need from the inside to see a plain wall running from side to side.

Detail 2 exemplifies the window detailing between an operable window on the left side and a fixed window on the right. This situation happens in panels B and C and applies to both.



Drawing 17. Panel B horizontal detail with a brick wall in between showing one technical unit and a storage space on the other side (SCALE 1:15)

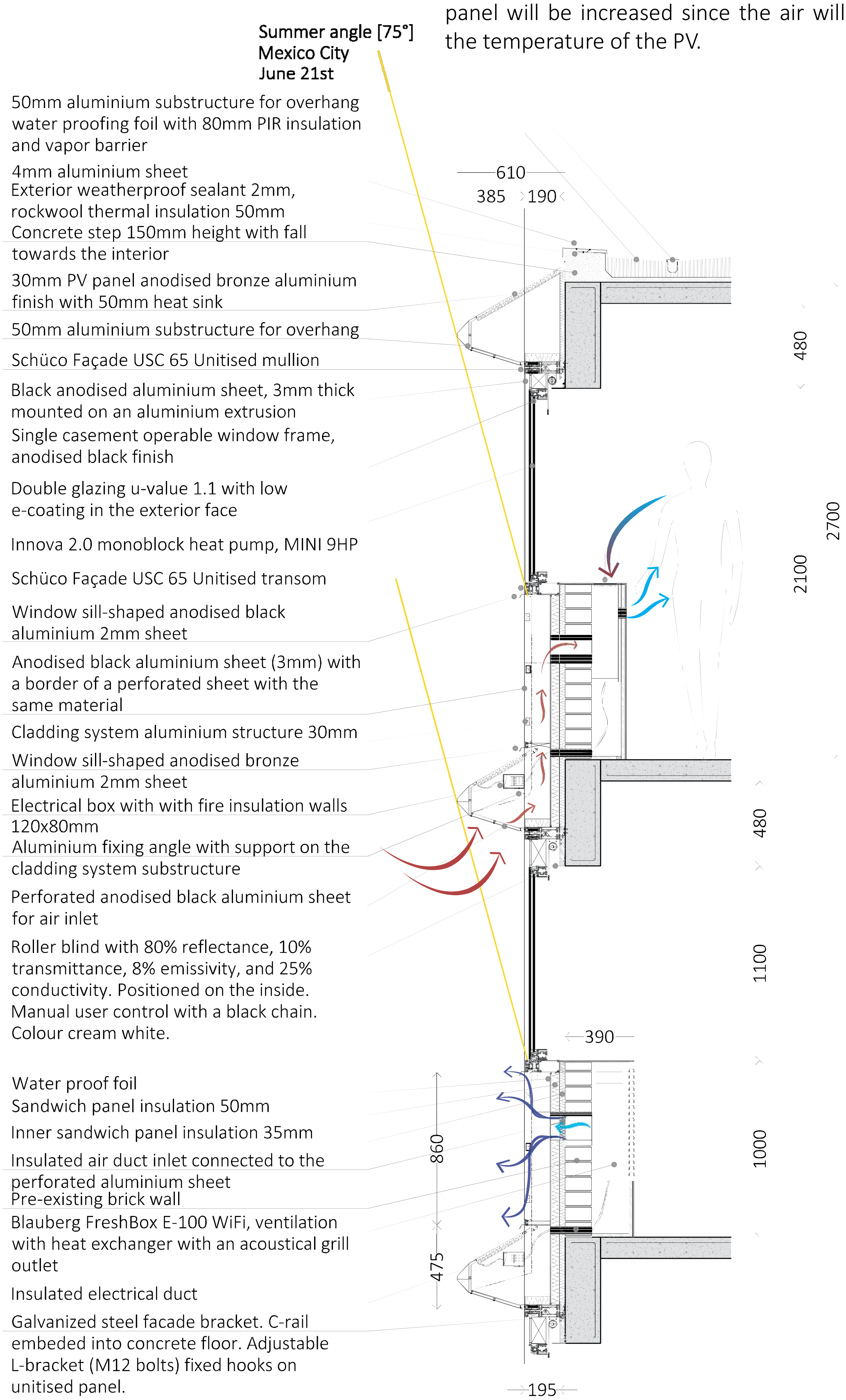


Drawing 18. Horizontal detail with an operable window on the left side and a fixed window on the right (SCALE 1:15)

4.3.3 Detailed crossed sections

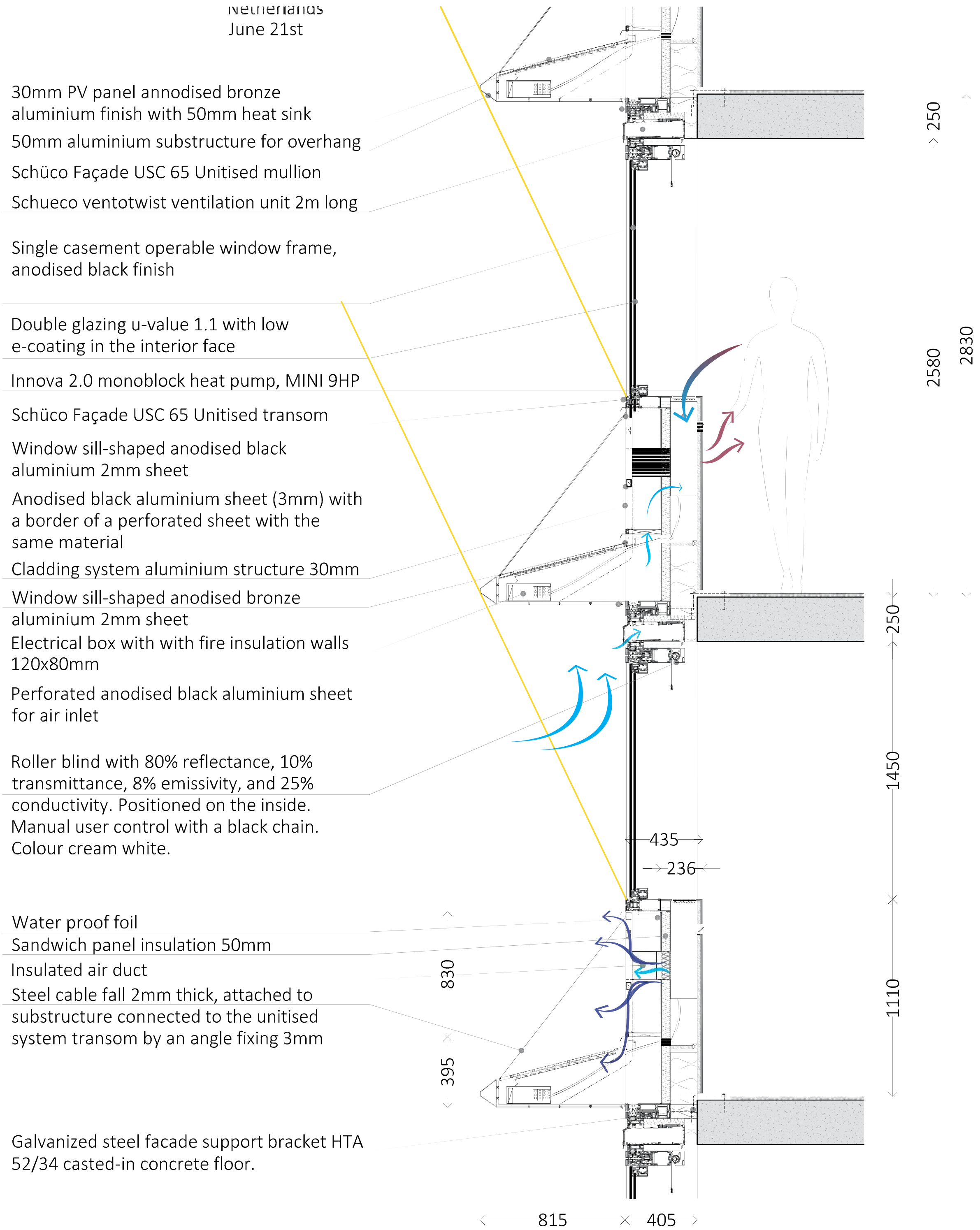
Cross section 01 exemplifies the unitised system with two parts, the outside panel and the inside technology box with a masonry wall in between. The overhang represents the dimensions required to block the sun's angle during summertime in Mexico City.

The air floor in the upper level represent the air inlet of the system whereas the level at the bottom the exhaustion. As it can be seen, the air access are different. This with two purposes, firstly to not mix the incoming with the outgoing air, and secondly to cool the back of the PV panels with the air exhaustion. By doing this, the efficiency of the PV panel will be increased since the air will decrease the temperature of the PV.



Drawing 19. Detailed cross section exemplifying the façade panel design in Mexico City (SCALE 1:35)

Cross section 02 exemplifies the unitised system with one part where the outside panel includes the technology box and no masonry wall in between. The overhang represents the dimensions required to block the sun's angle during summertime in the Netherlands. A more significant overhang was needed since the sun's inclination is lower in the Netherlands than in Mexico City. For this, a substructure of tensile steel cables was added to support the overhang. As the previous section, the bottom floor represents the air exhaustion and the top floor the air inlet.

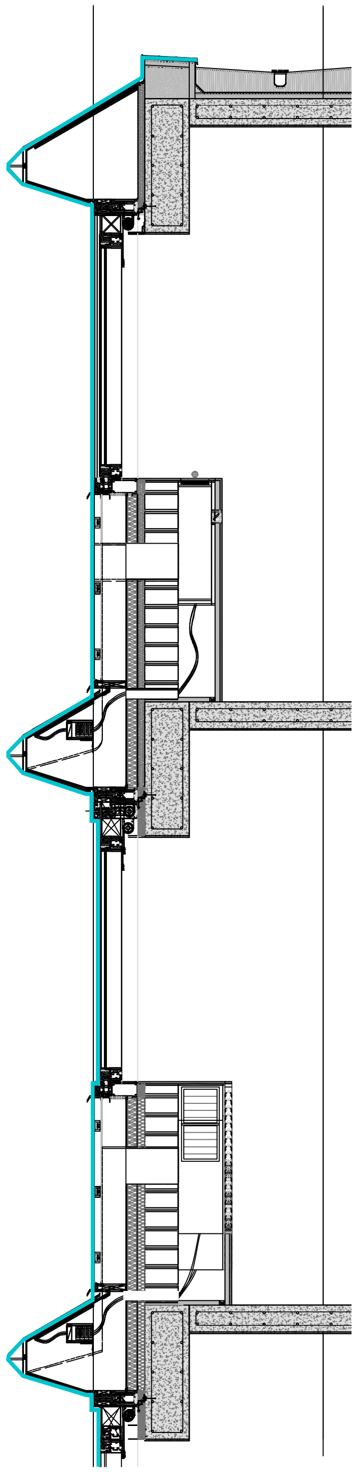


Drawing 20. Detailed cross section exemplifying the façade panel design in The Netherlands (SCALE 1:35)

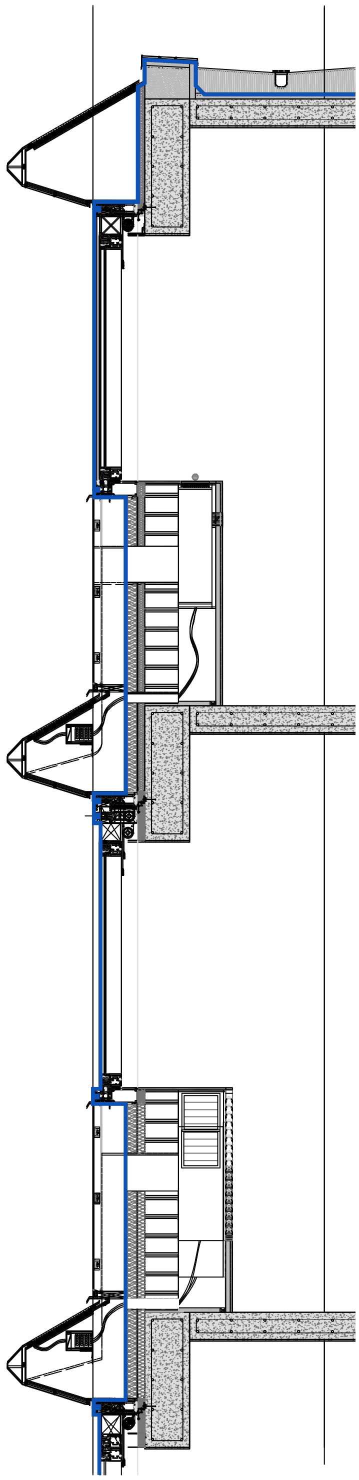
4.3.4 Façade lines of defence

Two lines of defence give the weather tightness of the façade; water protection and water tightness. The second line of defence shown in drawing 8, the water protection, functions as an "umbrella", keeping the most significant part of the water outside. The water that passes through this second defence will encounter the first line of defence, see drawing 9, which is the water-tightness layer. Finally, to enhance the thermal performance of the façade panel, a continuous insulation line is designed along it, see drawing 10. This insulation line runs vertically and horizontally in the panels. It includes the insulation inside the panels, the double-glazed windows and the thermal breaks inside the frames.

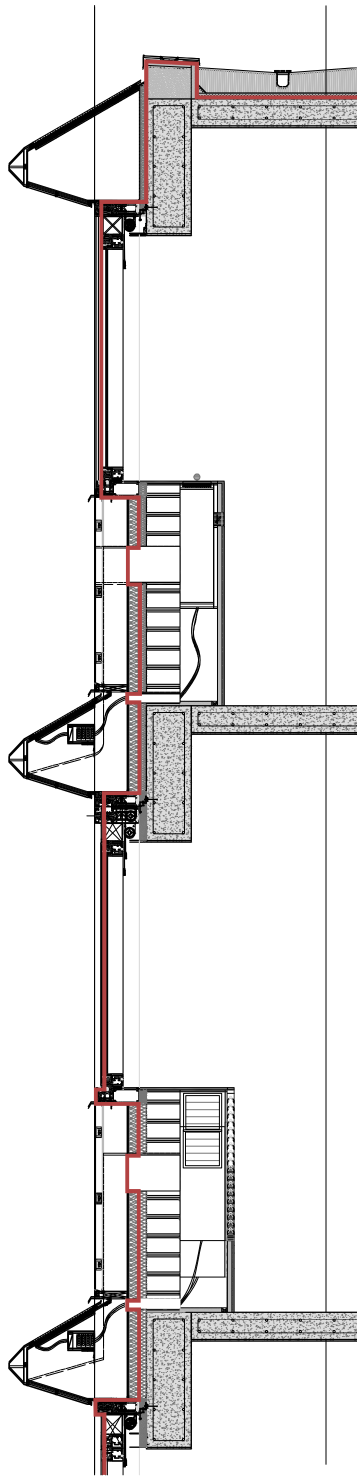
SCALE 1:35



Drawing 21. Water protection, first line of defense.



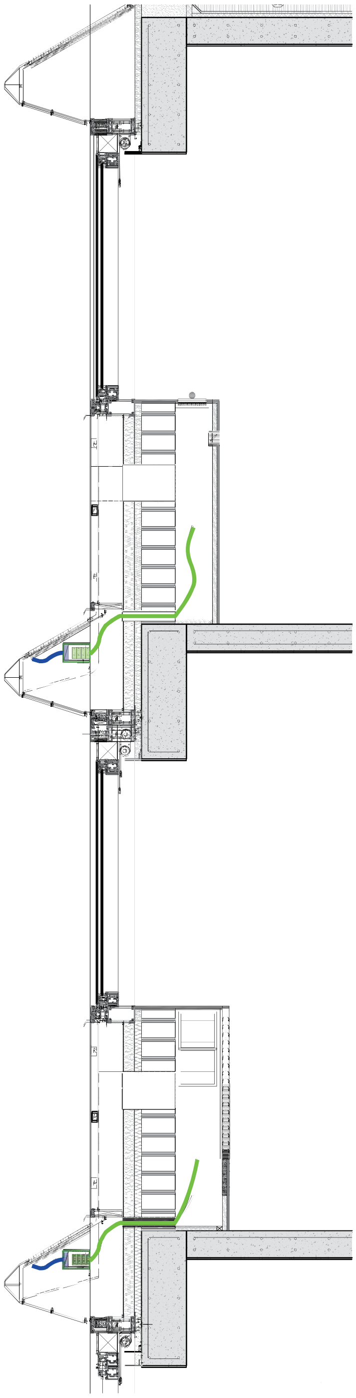
Drawing 22. Water tightness, second line of defense.



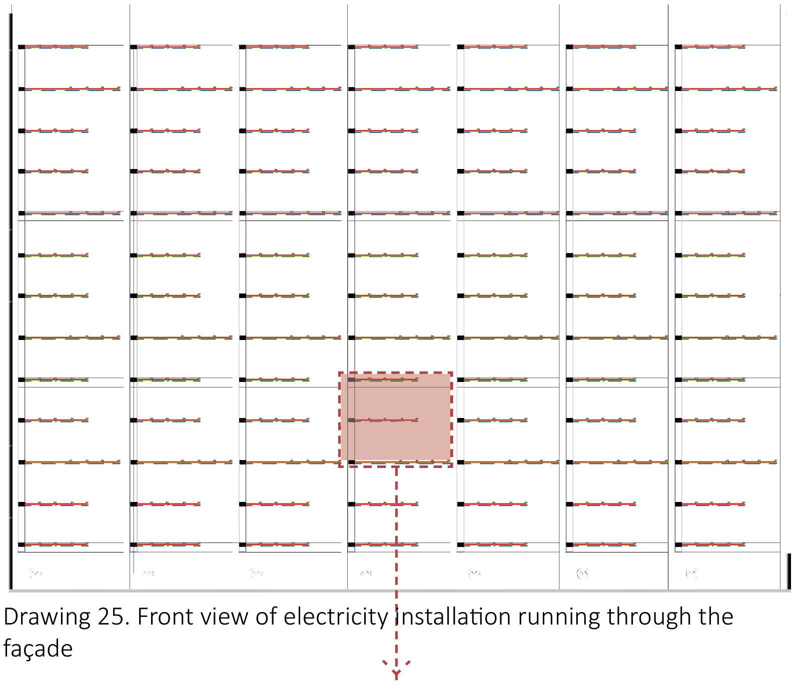
Drawing 23. Insulation, third line of defense.

4.3.5 Electrical installation

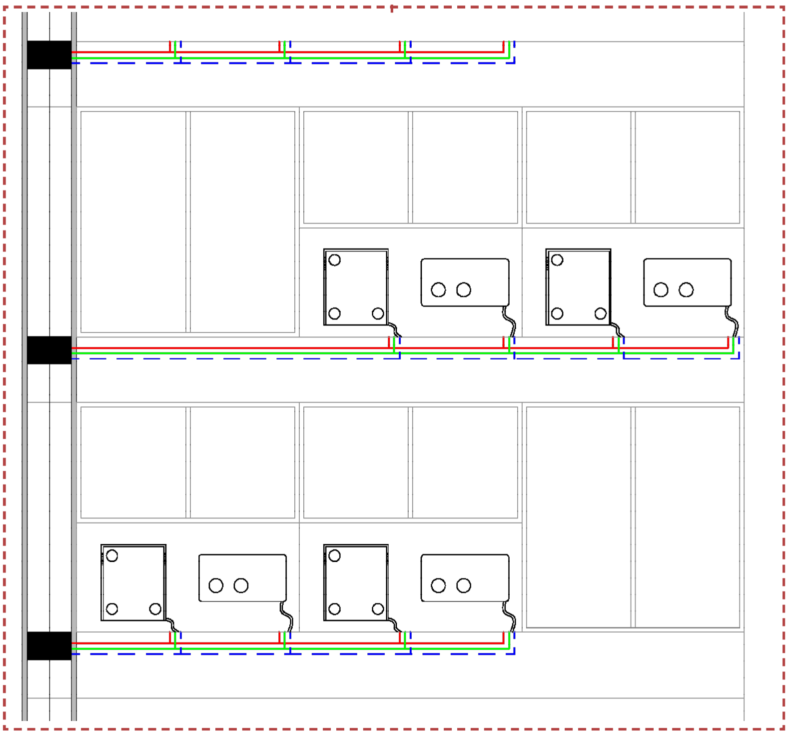
The integrated serviced façade panel requires electrical connections for its functioning. The electrical connection running through the façade is separated in a fire safety compartment that runs vertically through the façade (see Drawing 13) and, from there, is divided per floor horizontally through the overhang. Drawing 11 shows the box's location in the overhang and how it reaches the wall. This part of the overhang must be manufactured in the factory to be placed at the right place. Even though this means an extra step while transporting the panels to the site. The transportation will be developed further later in this chapter. The front view in Drawing 12 shows how the vertical line connects to the horizontal overhang and then to the technologies from the back through a flexible metal conduit (FMC). The vertical pipe has black boxes representing the register for future maintenance and installations, accessible from the apartment's interior (see maintenance subchapter). Each technology unit requires a three-phase installation with three conductors; neutral, one-phase and earthing, as shown in Drawing 13.



Drawing 24. Electricity connection in the cross section façade (SCALE 1:35)



Drawing 25. Front view of electricity installation running through the façade



Drawing 26. Front view electricity connection from duct to technologies (SCALE 1:75)

4.4 Maintenance and life span

The DR are met because all the technologies integrated are easily accesible at floor level, and their access are independent from one another. This avoid the risk of warranty lost between the different contractors and enhances an easy maintenance dispite the number of building services integrated.

The roller screens are hidden behind the concrete beam and are accesible from the bottom up as shown in Figure 74. The electrical duct positioned on the panel side can be accesible via an operable door from the inside, see Figure 75. The replacement of the glazing can be done at floor level since the design was thought from the beginning to allow for the window frame to be disassemble from the inside (Figure 76). The technology boxes look like a credenza from the outside for aesthetical purposes but in reality they store the technologies inside (Figure 77).

The lifespan of the components vary in time. Figure 78 show the lifespan of each integrated serviced, the maintenance periods, renovations and changes. The ventilation system requires the most maintenance due to the filters that need to be changed twice a year. The HVAC technologies can last between 10 to 15 years. However, to achieve 15 years it is important to provide periodic maintenance. That is why its location is at-hand for the user through the credenza. Visualisations from the manufacturers on how to clean the filters and the grills of each technology can be found in Fig. 79, 80 and 81.

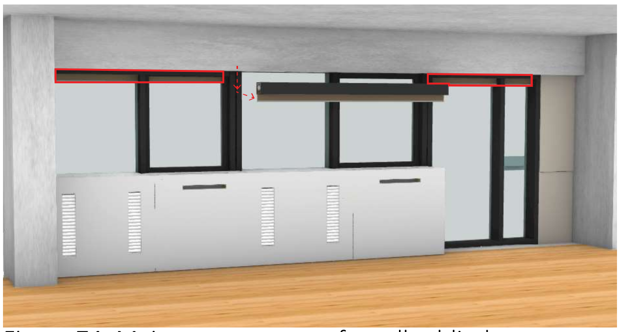


Figure 74. Maintenance access for roller blinds

Figure 75. Maintenance access for electrical duct

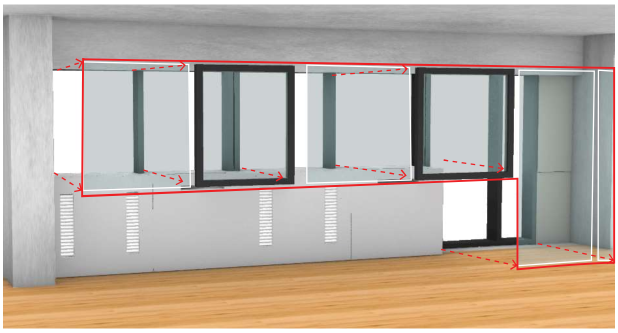


Figure 76. Maintenance access for glazing replacement

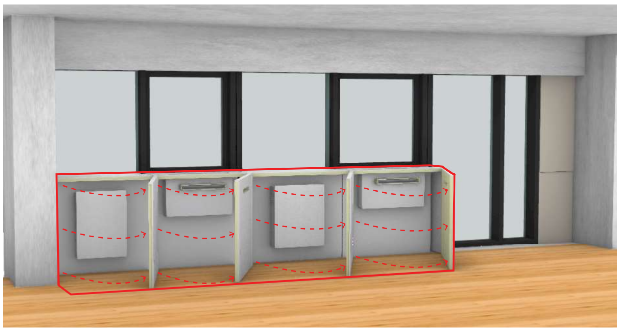


Figure 77. Maintenance access for technology boxes

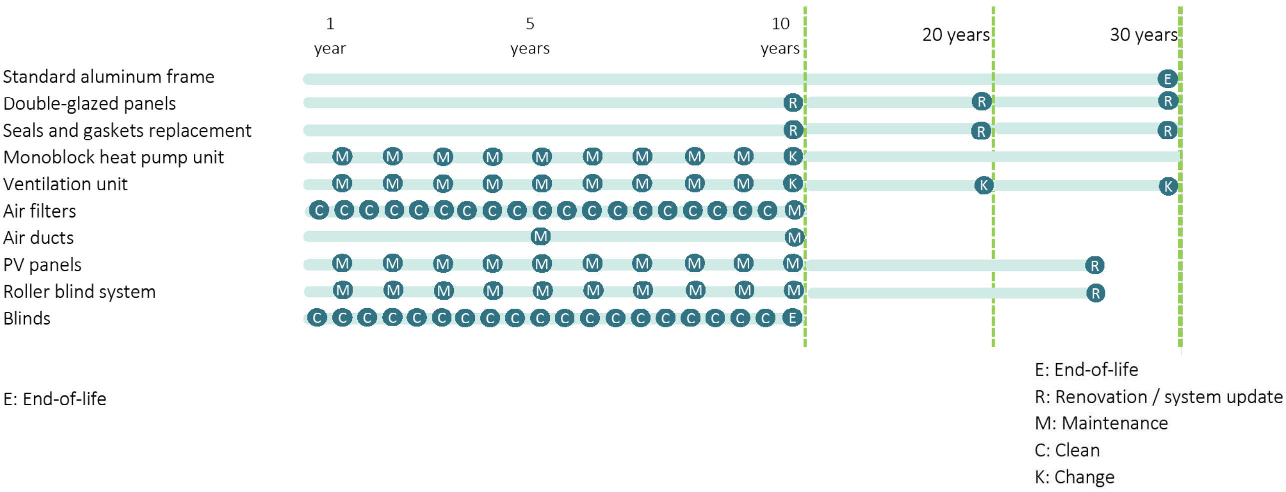
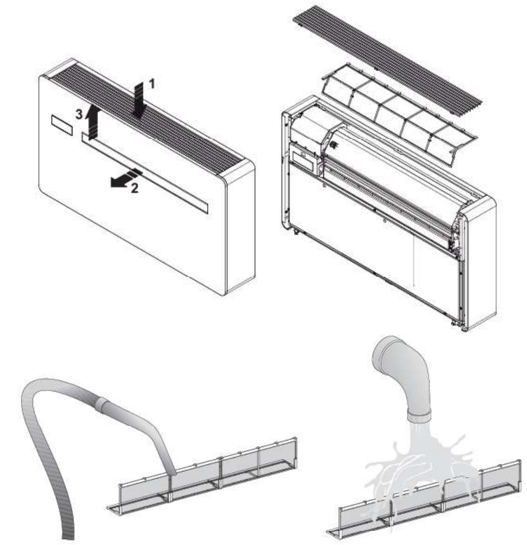
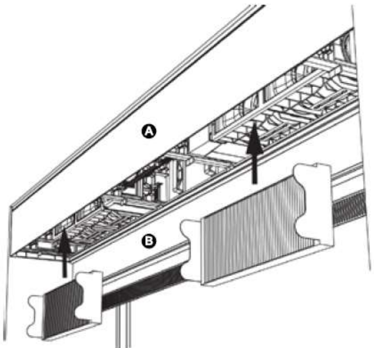


Figure 78. Life span, maintenance, renovation and clean time table of the integrated façade panel.



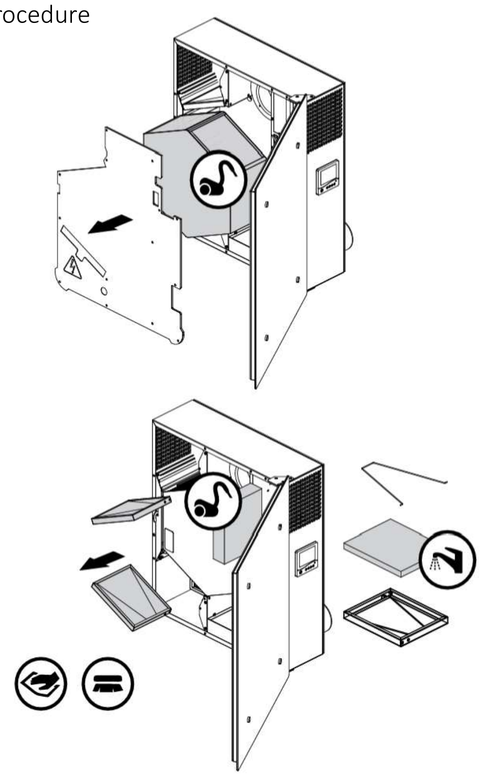
https://www.innovaenergie.com/en/docs/manuals/

Figure 79. Monoblock heat pump filters and grill cleanning procedure



chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/ https://blaubergventilatoren.de/uploads/download/ b73_5en_07preview2.pdf

Figure 80. Ventotherm Twist filters cleaning procedure



https://blaubergventilatoren.de/en/product/ freshbox-100#downloads

Figure 81. Freshbox E-100 filters cleanning procedure

Figure 82. Electrical duct and façade maintenance procedure with a ropeclimber and a substructured at the top of the building

4.5 Façade installation

1. Factory

Manufacture of the whole unitised façade panels in the factory to enhance high quality production and decrease the inconsistancies on-site. In the case of the technology box, it will also be manufactured in the factory. (Figure 83)

2. Transportation

By standard semi-trailers from the factory to the construction site. The panels will need to be protected in wooden boxes and to make the transportation more efficient each panel box will be mirrored like a puzzle. (Figure 83)

3. Lifting

A mechanical crane will be installed in the ground floor to avoid the deterioration of the inner floors during the refurbishment process. (Figure 83)

4. Installation

In the case of an existing wall in the building structure, the unitised panel will be attached to the structure from the outside with the before mentioned crane whereas the technology box will be installed from the inside of the apartments with qualified installers. (Figure 83)

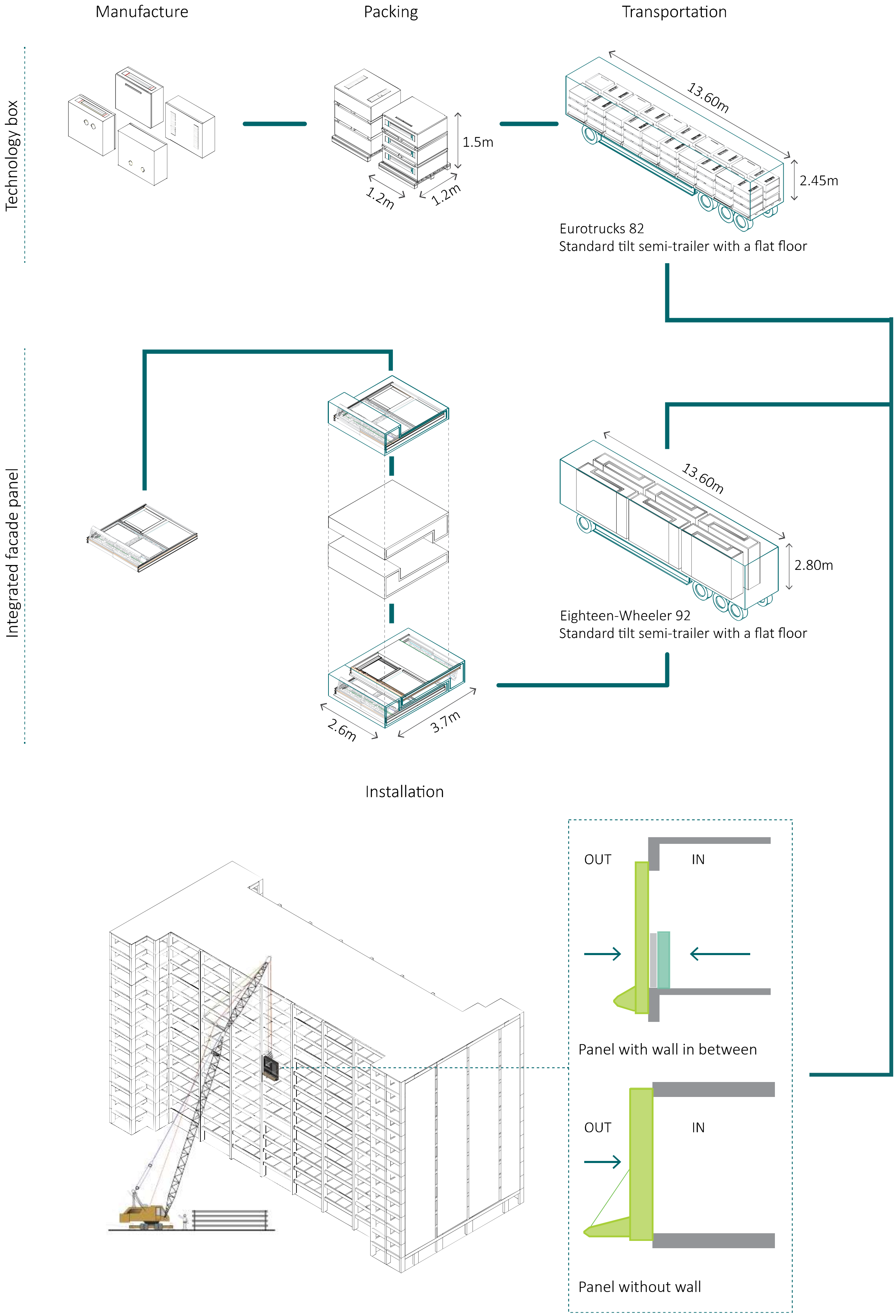


Figure 83. Façade installation

4.6 Aesthetics

In the maintenance subchapter, it is stated that the technologies are kept in a credenza box. A credenza is a type of storage furniture that is characterized by its low height or lack of legs and features cabinet-style doors. This design gives the credenza a long and low storage profile, making it suitable for use as a cabinet-style storage piece for the technologies in various areas such as the dining room and living room. Additionally, the credenzas can serve as an extra surface for serving or displaying items, when the ventilation technologies are inside or when its empty. For the heat pump technology is not possible since it requires a grill on top of it.

The credenza box is designed to have the flexibility of different finishes and air outlets in the credenza covers (Figure 84). Figure 85 shows the flexibility in terms of materials for the façade cladding. Thanks to the cavity inside the panel several options of finishes can be added, as long as they can be mounted in the substructured installed in the panel. Thus, the options are PV panels which can vary in figures, color and finishes such as ACM, ceramics, natural slates, anodised aluminium sheets and green walls. The aluminium unitised profiles can be found in different colours too.

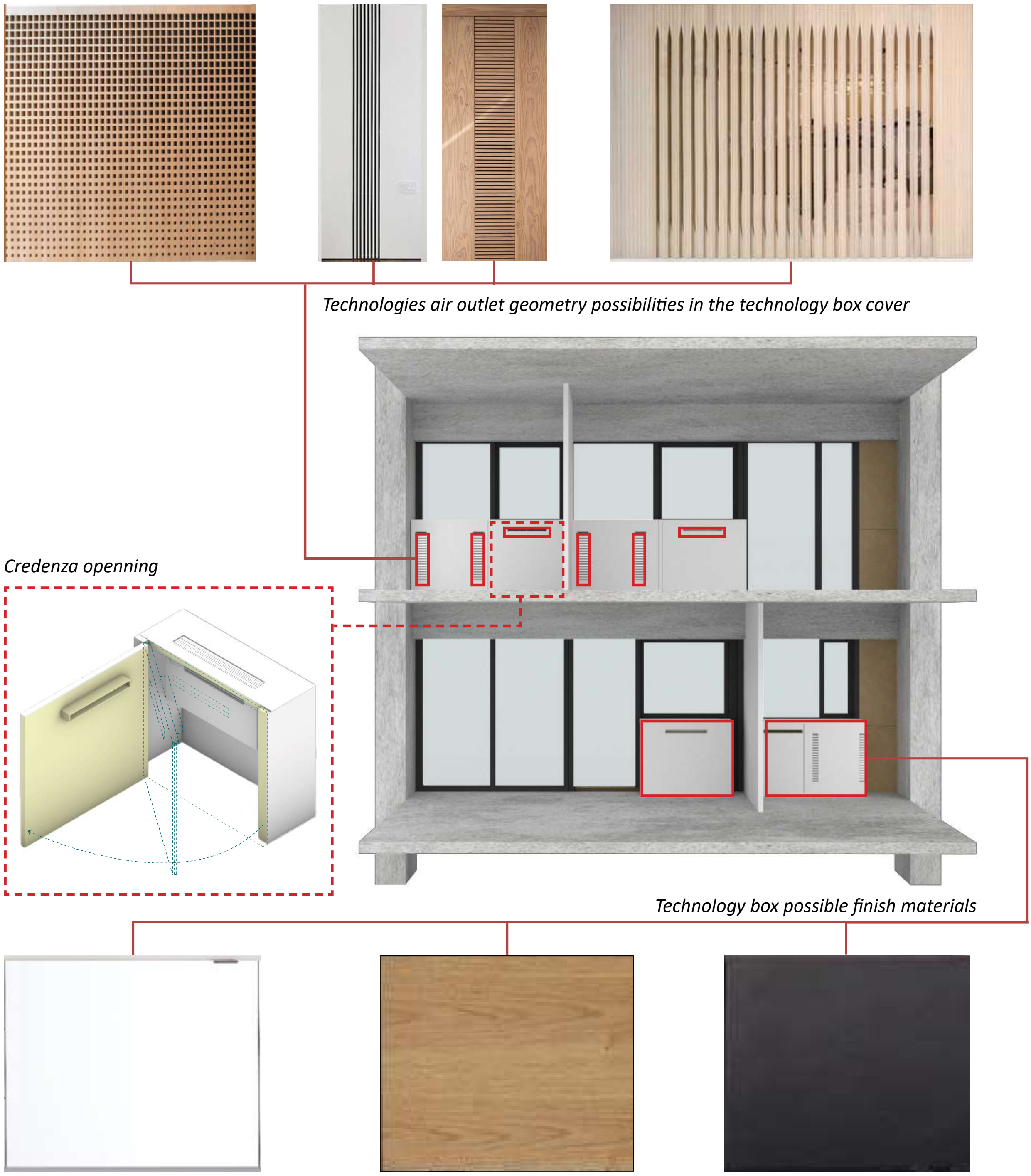
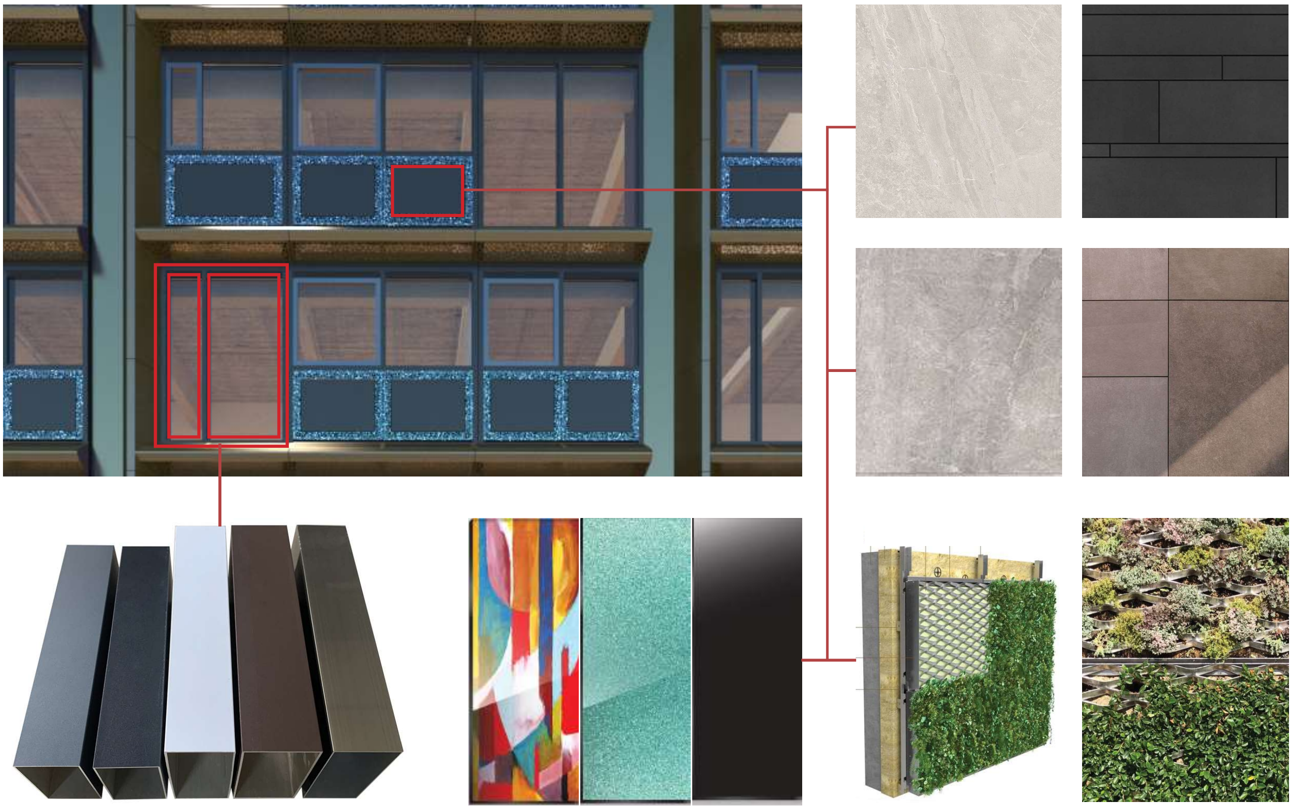


Figure 84. Finish possibilities for the technology box air inlet and cover



Aluminium colour posibilities.

PV Panels: Figure design, colour, black.

Façade cladding: ACM, ceramics, natural slate, anodised aluminium and green wall.

https://www.pohl-façades.com/en/systems/back-ventilated-green-façade_912

Figure 85. Façade finishes possibilities for the aluminium profiles, the PV panels and the cladding.

4.7 User control

The technologies chosen allow for user control through its own app. To ease user control a new app that integrates both units, the heat pump (A/C) and the ventilation units, is proposed (figure 86). In a future case scenario, where the blinds are upgraded to automatic roller blinds, they could also be integrated in this app along with the light system of the apartment (Figure 87). For now, the app could be linked to a virtual assistant such as Google or Alexa to control the units by voice. The physical/manual control of the technologies is inside the technology box / credenza. Where the touch screen from the manufacturer is integrated in the outer surface of the technology. This, to avoid monitors in the walls of the apartment.

Figure 86. Home screen A/C & ventilation

Figure 87. Home screen future upgrade

Both technologies include the option to be turn on/off and to be refresh to default settings The parameters that the user can control in the app are based on the original app of each technology unit. The icon on the bottom left of the interface will indicate the alert of when the system requires a change of filters or the unit maintenance.

Figure 88 shows the parameters that the user can control in the heating and cooling scenarios for the air conditioner. They can control temperature, night cooling mode, fan speed, week programme and operation mode.

Figure 89 shows the parameters for the ventilation. The first view for the user is to choose from the ventilation unit location (room or living room). Afterwards, they can choose to modify the parameters of fan speed, week programme, heat exchanger, CO2 sensors, operation mode, as well as add a timer for the unit operation and have a clear review of the filter's maintenance.

Figure 88. A/C user control parameters for the heating and cooling scenarios.

Figure 89. Ventilation user control parameters for the ventilation units in the living room and the bedrooms.

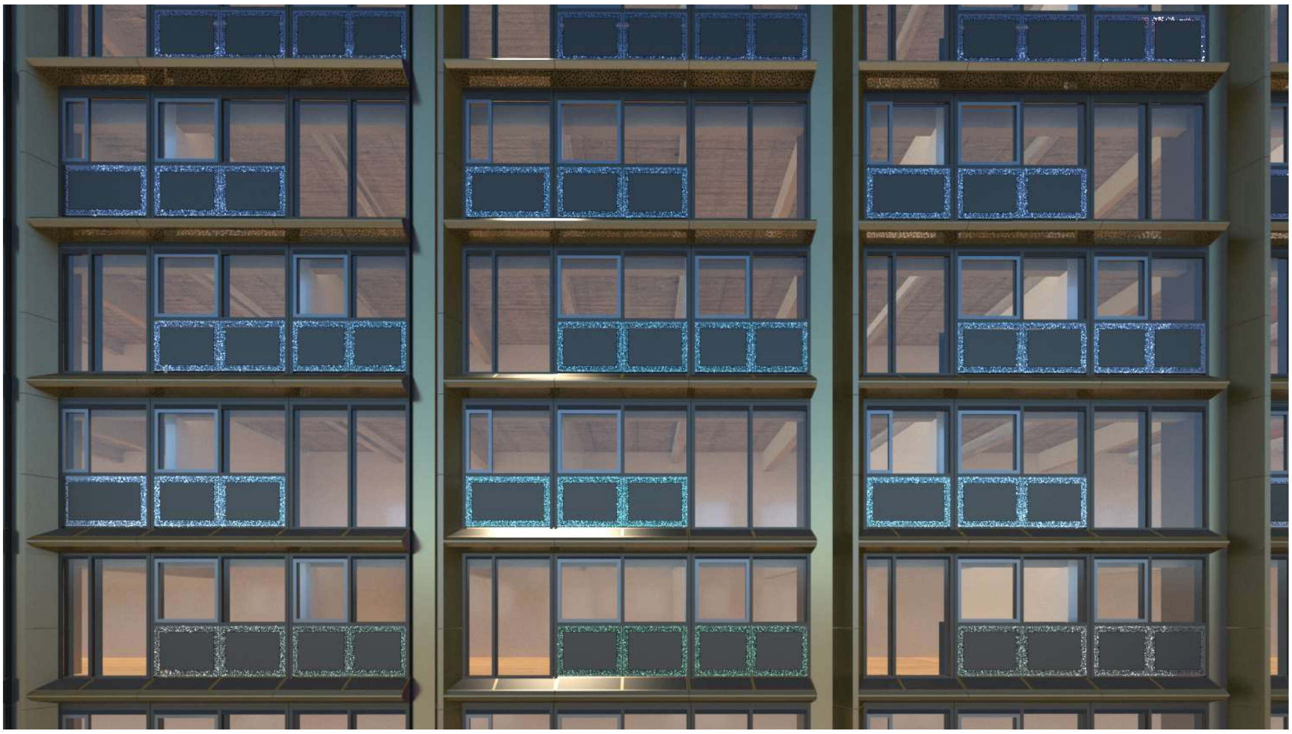


Figure 90. Façade panels visualisations of the horizontal disposition

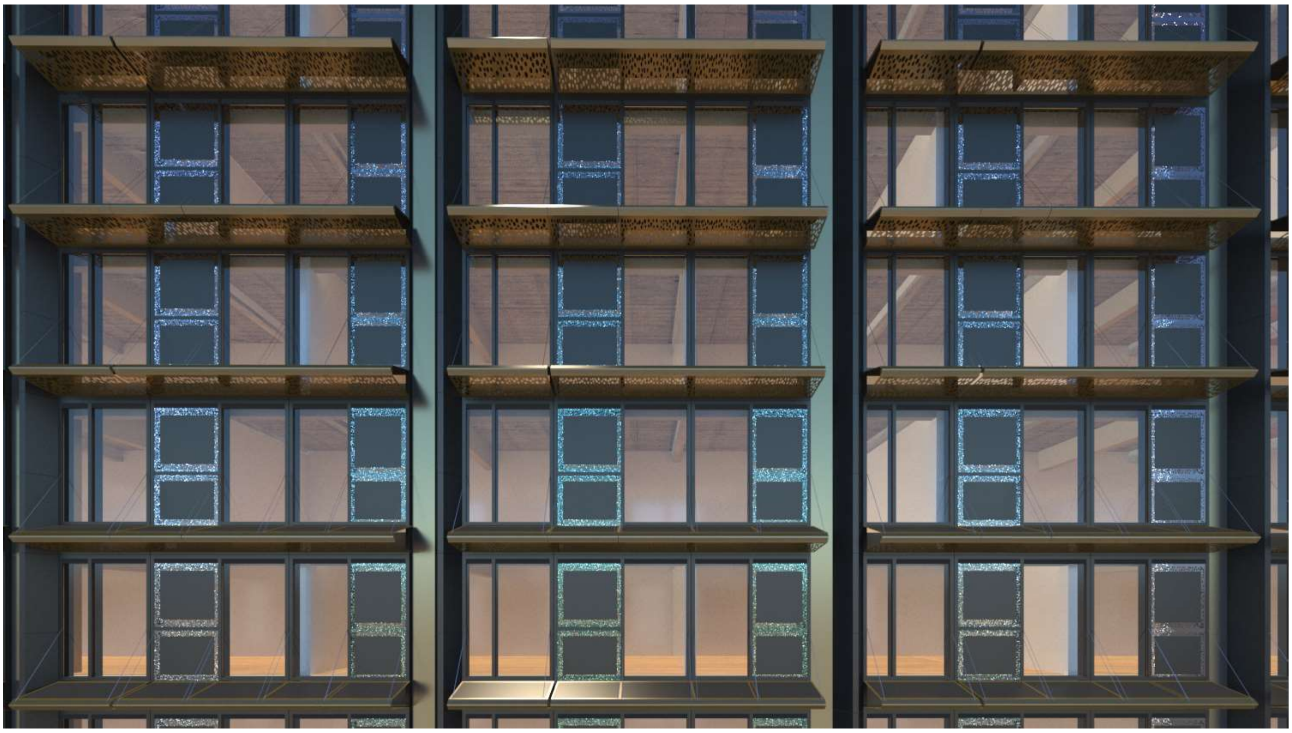


Figure 91. Façade panels visualisations of the vertical disposition

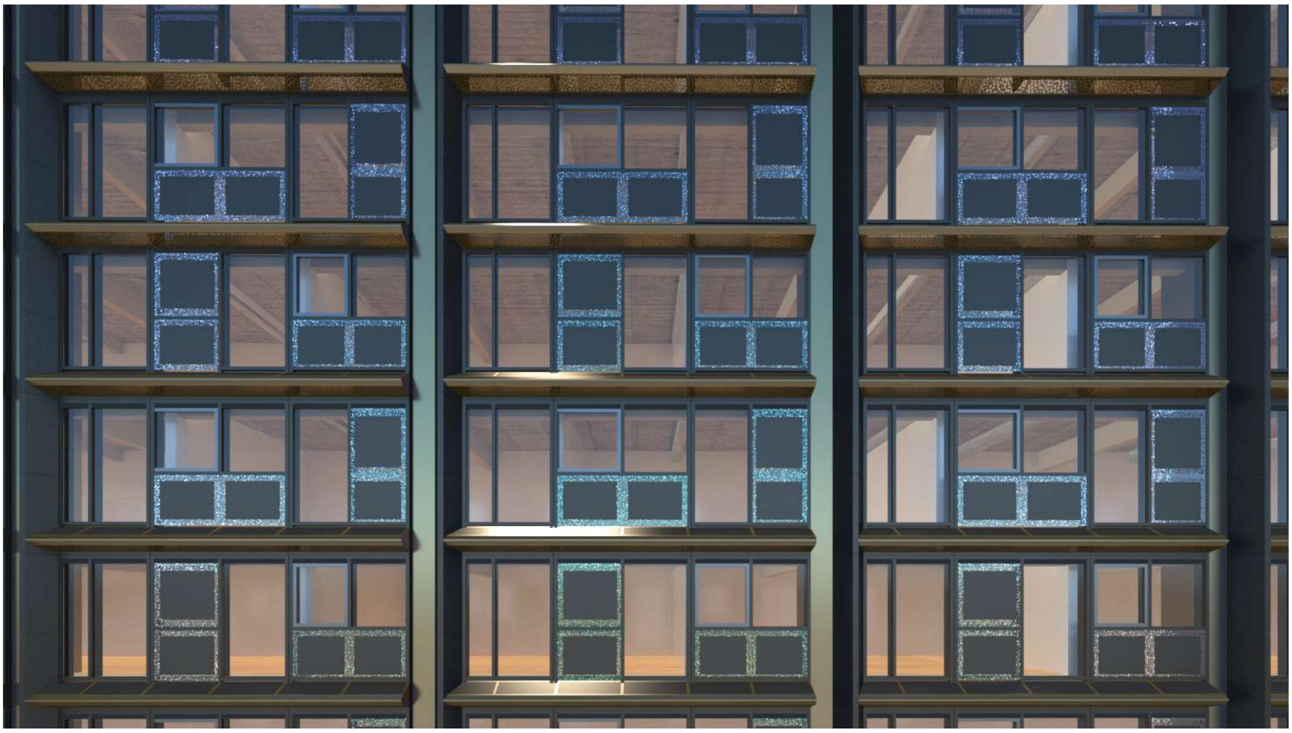


Figure 92. Façade panels visualisations of the combination between horizontal and vertical disposition

4.8 Simulations

Simulations were performed to assess the acoustic noise levels of the designed panel, to analyse the thermal performance of the design in terms of the heat exchanger, and interior and exterior sunshades, as well as to compare the energy input required vs the energy produced. Excel was used to generate the comparison graphs for each simulation; acoustics, thermal and energy input and energy production.

4.8.1 Acoustic simulations

For the acoustic performance simulations the software used were Rhino 7 with Grasshopper and the plug-in Pachyderm 2.0 (Figure 95).

To calibrate the model, the base case scenario (Figure 93) had to measure 33 dB(A) for A-weighted Sound Pressure Level at a 3m distance from the measurement point (the technology unit). This was based on the technical information gather from the ventilation technology (see subchapter 3.4 - Building Services Technologies). The improvements to reduce the noise levels in the bedroom consisted of adding a credenza box around the ventilation unit (Figure 94). Two different finish materials for the credenza were tested to determine the feasibility of the aesthetical options proposed (Table 25). The materials used for the 3D model analysis are shown in Table 26, where the absorption level per frequency are exemplified per material. The insulation and the perforated metal sheet have the highest absorption coefficients (Tabellarium Akoestiekengeluid, n.d.) (Absorption Coefficients Of Common Building Materials, n.d.)

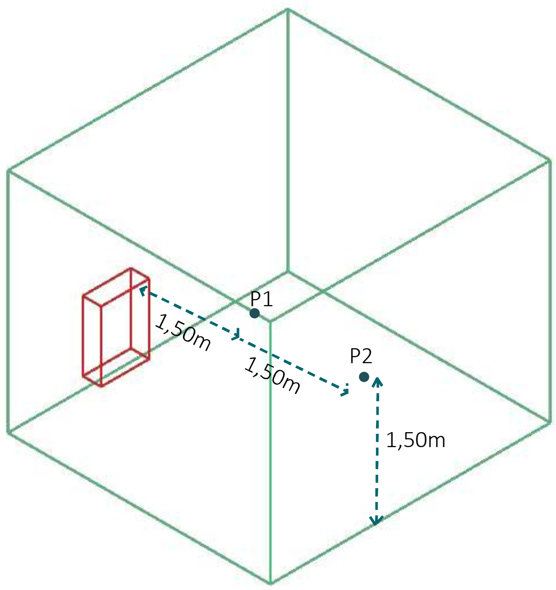


Figure 93. Base case scenario for acoustic simulation.

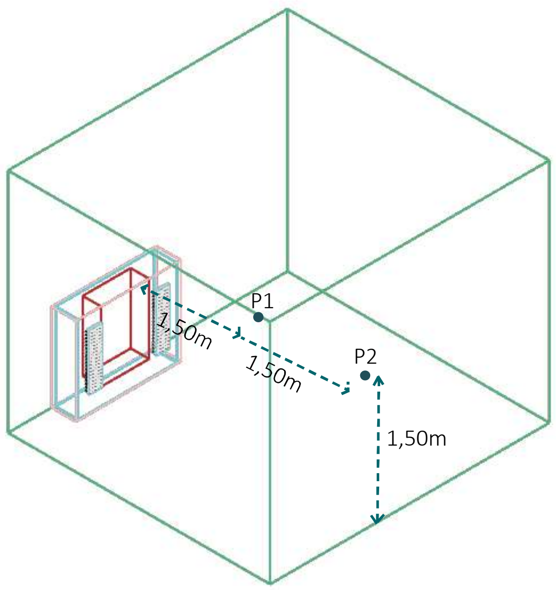


Figure 94. Improvements scenarios with technology box.

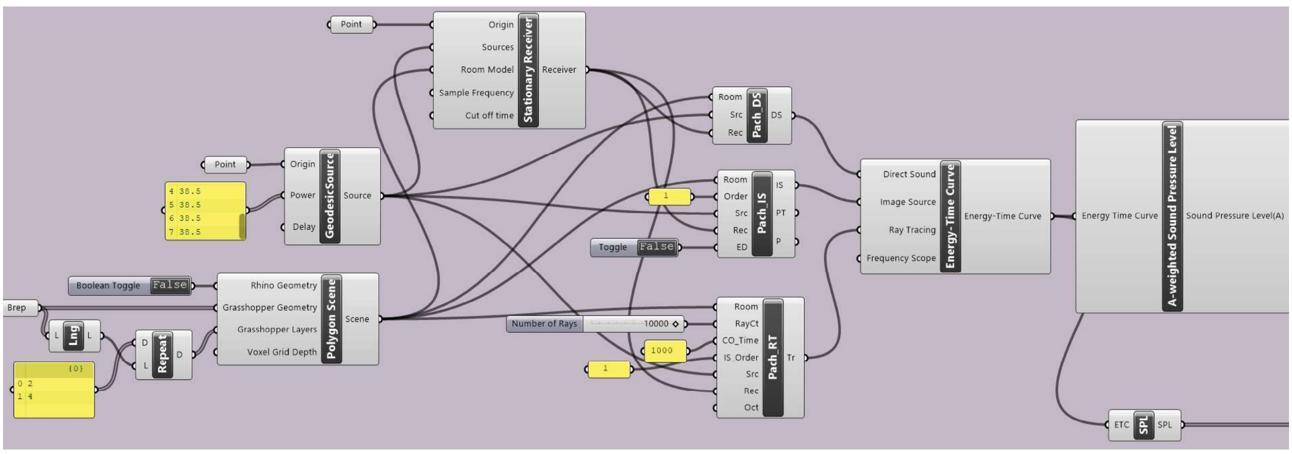


Figure 95. Script to determine the A-weighted Sound Pressure Level of the improvements (addition of the credenza with different materials).

The measures were done at 1.5m and 3.0m distance from the measurement point at a height of 1.5m. As expected, the 3m measurement points results presented a lower A-weighted SPL than results at 1.5m distance (Figure 96). The proposed cases, 1 and 2, show an improvement of around -17dB(A) compared to the base case. The D.R. determines 30dB(A) SPL for the bedrooms. Therefore, the sound levels with the addition of the credenza meet the requirements at 1.5m with 18,24 dB(A) for the first case and 18,16 dB(A) for the second case, see Figure 97. This is due to the insulation of the credenza walls. The simulation shows that the finish of the credenza do not represent a significant influence in the A-weighted SPL. This is because the noise coming from the air is absorbed through the walls while the air is projected into the interior.

Cases:	1st	2nd
Credenza finish	3/8'' Plywood	Perforated metal sheet
Grill insulation	Melamine based foam 25mm	Melamine based foam 25mm

Table 25. Materials simulated for the first and second credenza scenarios.

Sound absorption

		Frequency [Hz]							
Location	Material	62.5	125	250	500	1000	2000	4000	8000
Walls/floor/ceiling	Smooth concrete painted	1	1	1	1	2	2	2	2
Technology unit	Coated aluminium	4	7	14	19	28	7	4	2
Credenza finish	Perforated metal sheet	25	25	64	99	97	88	92	92
	3/8'' Plywood	1	1	1	1	1	1	1	1
Grill insulation	Melamine based foam 25mm	9	9	22	54	76	88	93	93

Table 26. Sound absorption coefficients of the materials used in the simulation per frequency. The location of each material in the model is also shown.

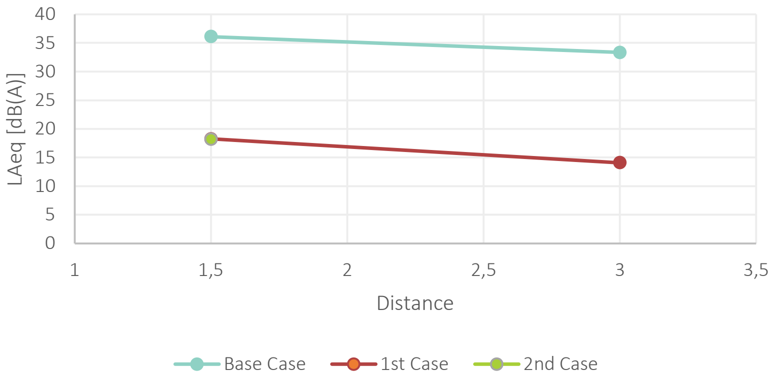


Figure 96. A-weighted Sound Pressure Level decrease per distance per case.

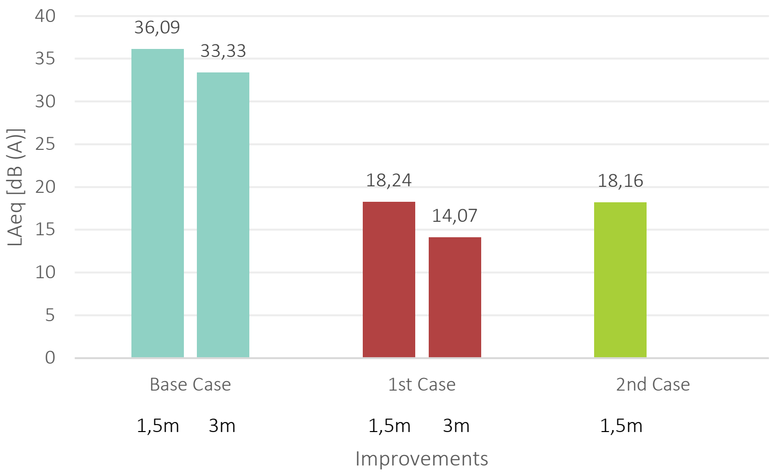


Figure 97. A-weighted Sound Pressure Level performance per distance per case.

4.8.2 Thermal and energy simulations

Design builder (D.B.) with Energy Plus as an engine were used for the thermal analysis. The weather data used to simulate were epw files from Mexico City and Amsterdam. The analysis was made based on the biggest bedroom (Room 01) of the case study which consists of 12,67 sqm. The HVAC system was designed manually on the software with the templates of Design Builder for AHU (simulating the bedroom ventilation: FreshBox E100) and the heat pump (Innova 2.0) named Packed terminal heat pump (PTHP) in D.B. with operative temperatures in accordance with the D.R. (MX; winter 20-25°C, summer 23-23°C and ND; winter 16-22°C, summer 23-26°C respectively).

In the case of Mexico City, the heat pump has the air inlet activated since the temperature differences between the inside and outside are less than 20 degrees during winter and therefore less heat losses were simulated compared to the Netherlands, and a heat exchanger with 90% efficiency, in accordance with the technology technical information (Figure 98). The wall construction U-value is 0,16, the interior roller screen is actived with a schedule for glare control with medium reflectivity slat.

For the case of the Netherlands, the heat pump was assumed to not have an air connection to the outside and the AHU was assumed to have an ideal scenario of a 100% efficient heat exchanger, to avoid energy losses. (Figure 99). The wall construction U-value is 0,56 The interior roller screen is actived with a schedule for heating night with medium reflectivity slat.

For both case studies, the parameters for AHU include a heat exchanger with no air recirculation, extract and inlet air, and fresh air supply of 10 l/s. Whereas the heat pump, in accordance with the technical information of the unit, has a CoP of 3,15 a cooling capacity between -700 and -2350W, and a heating capacity higher than 750W, it is an air to air HP with an electrical connection. The glazing U-value is of 1,1

The simulations were done yearly to analyse the sunshades and the heat exchanger performance, and monthly to analyse and corroborate the expected system loads during the year. All the simulations were done for both case studies, Mexico City and the Netherlands.

The detailed graphs that resulted from the simulations can be found in the Appendix H.

Sunshades analysis

The sunshade analysis was done with four scenarios; with an inside and outside shading system, with an overhang only (0,62m for Mexico and 0,82m for the Netherlands), with interior blinds only, and without sunshading devices. This analysis was done with the aim to analyse the effectiveness of the design shading devices and to proof their efficiency. Figure 100 exemplifies the performance of each scenario. The importance of adding passive measures, namely the overhang with the right projection, is demonstrated with the simulation. Figure 100 shows a considerably decrease of the the cooling loads. In both case studies, the use of inside and outside shading systems represent around two (Mexico) to three times (Netherlands) less cooling energy demand. The impact of the interior roller blinds is mostly at a visual level since, since as the graph shows, the decrease of cooling demand with only implementing interior roller blinds is almost negligible with less than 1 kWh/m2/yr.

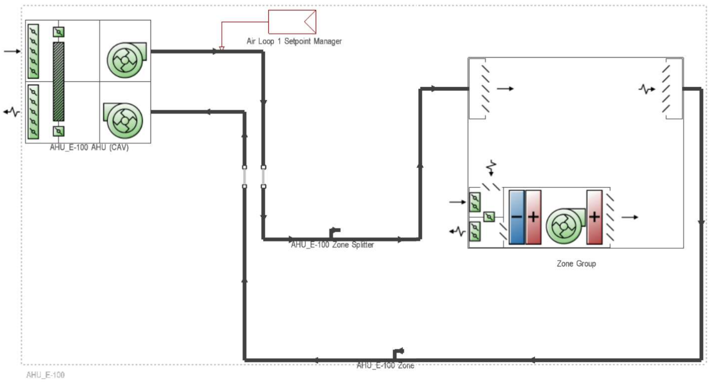


Figure 98. Designed HVAC system in Design Builder for Mexico City with the activated air intake for the HP.

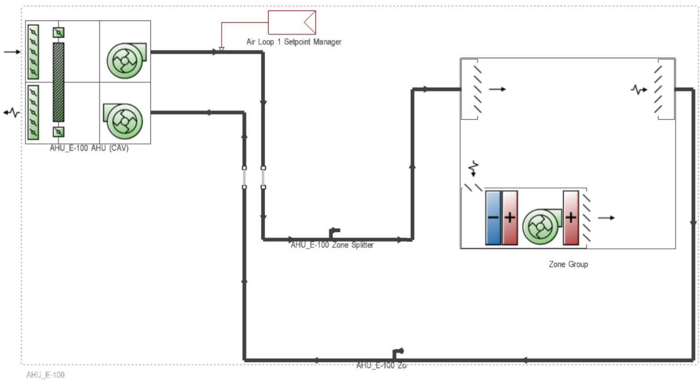


Figure 99. Designed HVAC system in Design Builder for the Netherlands without activating the air intake for the HP.

Heat exchanger analysis

The analysis of the heat exchanger performance was done based on the system loads for heating and cooling per country, one per month and another per year.

Figure 101 shows the case of Mexico City over a year. It can be seen that with the heat recovery on during summer time, the cooling loads are higher than when its off. Whereas during winter time, with the heat recovery on the heating loads decrease. Overall, the yearly system load with the heat recovery on represent 0,1 kWh/m2/yr less than with the heat recovery off. It could be possible to turn the heat recovery off manually through the app during summer time, to further decrease the cooling system loads. Figure 102 shows the expected curve of the system loads in Mexico City, a cooling demand climate with cold temperatures during December and January only.

Figure 103 shows the case of the Netherlands over a year. The same effect as in Mexico City during summer time repeats with the heat recovery on, during summer time, the cooling loads are higher than when its off. Whereas during winter time, with the heat recovery on the heating loads decrease. Overall, the yearly system load with the heat recovery on represent 2,9 kWh/m2/yr less than with the heat recovery off. The same situation as in Mexico could be repeated. Thus, the possibility to turn the heat recovery off manually through the app during summer time, to further decrease the cooling system loads by up to 2kWh/m2/yr. Figure 104 shows the expected curve of the system loads in the Netherlands, a heating and cooling demand climate with cold temperatures from September until mid-April and warm temperatures from mid-April to September. Therefore, the cooling loads during winter season are 0 whereas the opposite occurs during summer season with the heating loads.

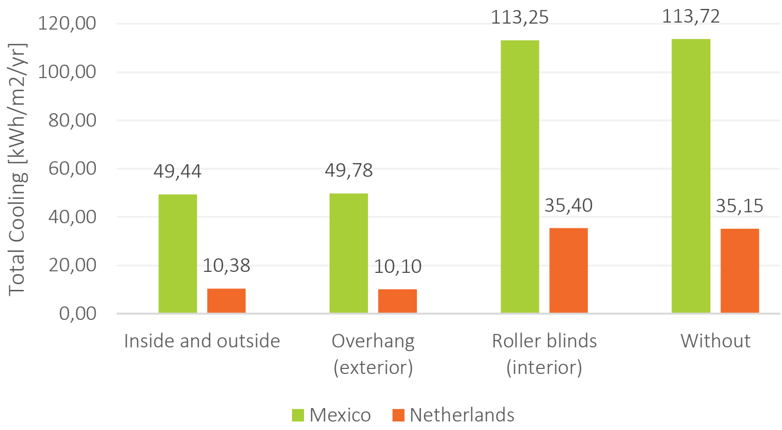


Figure 100. Sunshade performance effect in the total cooling per square meter per year per case study country.

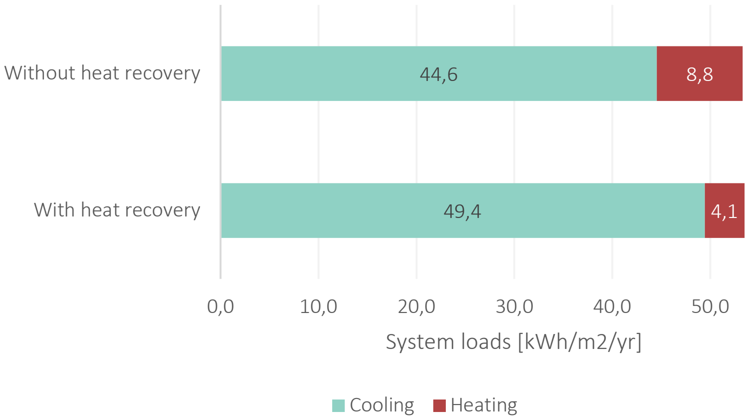


Figure 101. Yearly system loads performance with and without heat recovery and their effect for heating and cooling in Mexico City.

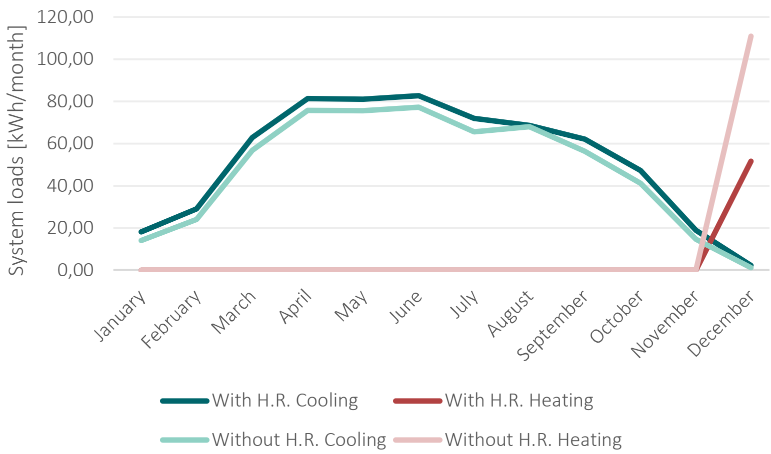


Figure 102. Monthly system loads performance with and without heat recovery and their effect for heating and cooling in Mexico City.

4.8.3 Energy input vs energy production

The tool M5000 was used to calculate the energy production of the PV panels. This tool was developed for the Zero Energy Design course at TU Delft. The energy input was extracted from the DB simulations (fuel breakdown) for heating and cooling. The comparison is done per kWh/year. The energy production during the months with cooling demand were added to compare to the cooling energy input of the system. The same was done for the heating demand. To compare the energy production vs the energy input the same bedroom (Room 01) was considered. This given that each panel group needs to satisfy the room behind them at a local level.

The façade of the case study is Southeast, and therefore, the analysis will be done with regards to that façade. However, calculations for a South and West façade were also done to give the reader an idea of the energy production potential in those orientations. The PV panels efficiency was set at 50% given that the tilt angle of the PV panels placed in the overhang are directly oriented to increase the energy production (14°C for the Netherlands and 30°C for Mexico City). The breakdown of the PV panels production per month and per tilt angle can be found in the Appendix I.

For Mexico City, the energy input for cooling represents 15% of the energy production in the Southeast façade. During heating season, the heating energy input represents 50% of the energy produced. Thus, the system is energy positive during the whole year.

For the Netherlands, the energy input for cooling represents 3% of the energy production in the Southeast façade. During heating season, the heating energy input represents 33% of the energy produced. The PV panels area in this case study decreases given that the structure of the unitised system needed to be connected to the slab without a

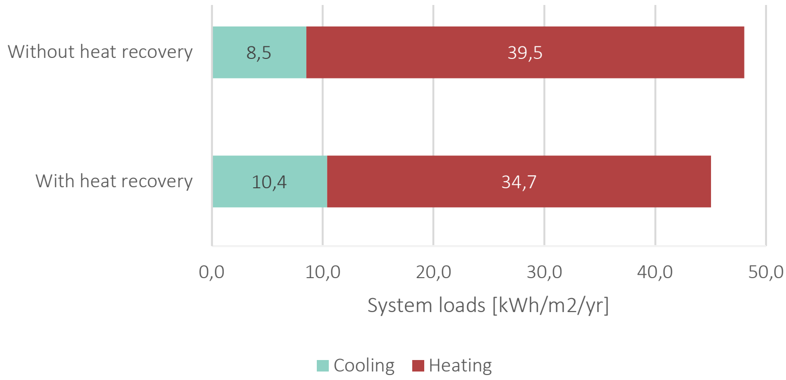


Figure 103. Yearly system loads performance with and without heat recovery and their effect for heating and cooling in the Netherlands.

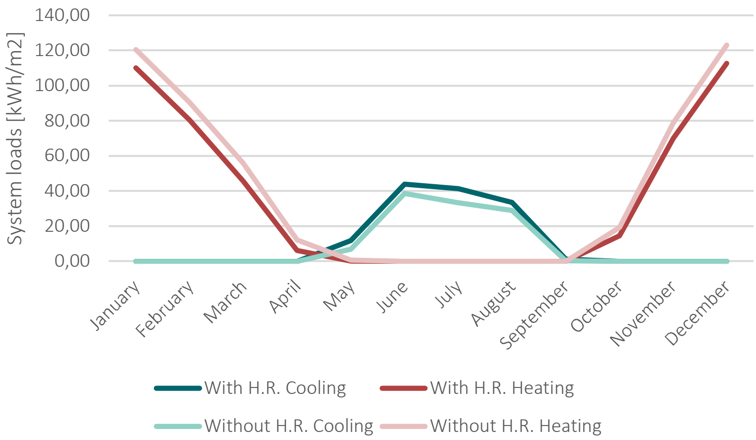


Figure 104. Monthly system loads performance with and without heat recovery and their effect for heating and cooling in Mexico City.

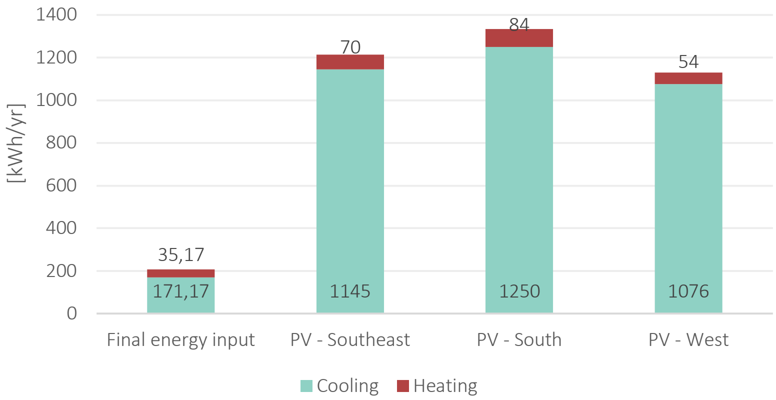


Figure 105. Energy input vs energy production: Case Mexico City.

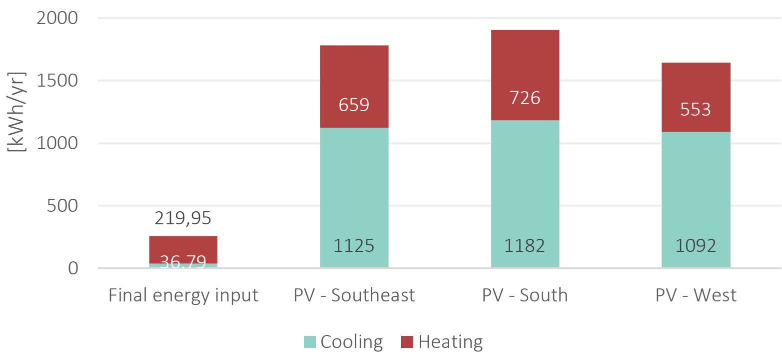


Figure 106. Energy input vs energy production: Case the Netherlands.

perimetral beam. Therefore, the opaque part that was destined for PV panels is reduced. However, the system is still energy positive during the whole year for the case study of the Netherlands too. This broadens the aesthetical possibilities of the integrated façade panel since it is possible to have less PV panel area and instead include the cladding of the architect's choice without jeopardizing the stand-alone characteristic of the design.

Since the production of energy is considerably higher than the energy input required for the technologies different possibilities were thought to store the energy. One was the use of batteries, however this option will only be suitable to store the energy for 3 to 5 days. A second possibility was to store the energy at a building level per appartment, however this option requires a considerably area equiperable to that of the appartment area. Thus, is not viable. Another option is to store the heat or cold produced undergound but this is not viable with the concept of this thesis since it would require pipes going through the façade or from the façade to the building core. A final option could be to use this energy for lighting or equipment devices in the household. The access to this energy could be though the façade with sockets. The same way the technology units are connected to the electric system.

4.9 Design conclusion

This chapter solves the main research question: "How can a façade design integrate building services for heating, cooling and ventilation and enhance user comfort in residential concrete buildings?". Based on the results of the previous chapters that answer the sub-research questions and taking the design requirements (DR) as an assessment design tool, a proposal for the integrated serviced façade panel was made. The design was addressed at three levels; building, façade panel and integrated technologies in two stages; the pre-design and the design.

The pre-design stage involved developing iterations at the building, façade panel, services and detailing. The iterations continuously evolved based on the integrated façades studied in Chapter 2. For instance, the different technology locations and compartment iterations are born from the design concepts studied. A month of pre-design concluded in five iteration families, from which four were interconnected. Finally, the façade panel design iterations that met most of the DR were chosen to be further developed. Design D2-2 is determined to further develop in the second subchapter, the architectural panel design. It is based on iterations A2-2, which located the unitised façade panel in front of the slab at the middle of the beam; C2 located the technologies in a compartment box at the bottom of the façade panel, and C3 consisted of adding a service duct in the façade panel. However, the duct concept was transformed into an electrical rather than a technology duct. Moreover, design D2-2 is born as a two-part solution with all the panel parts, including air inlets, sunshades, insulation and operable windows in the outer part of the building and a second part installed independently from the inside part.

The first level addressed for the architectural design was the building level; the decision to use a concrete residential building defined the layout of the structure and panel sizes for the façade due to the use of concrete beams and slabs in a modular grid. In terms of panel sizes, to meet the DR, a subdivision of the panel's length was required for easy transportation. Whereas the structure of the building allows for the implementation of the DR façade system, unitised, the connection façade-building structure is done through structural brackets in front of the slab that enables the movements required by the DR horizontally and vertically. Moreover, the unitised façade system structure allows for movement tolerances for the panels between the concrete columns by absorbing the moves in the middle panel. This simultaneously allows for an architecturally aesthetic adjustable panel that is not readable at a building scale by the user.

The second level, the façade panel, was a challenge since it had to meet all requirements from the DR. Two iterations were developed from the same concept. One consisted of preserving a masonry wall in the façade and the other without it. The panel with a masonry wall in between requires the installation to be in two parts. One from the outside (the unitised façade panel) and another from the inside (the technology compartment box). This had the advantage of being fireproof, easy maintenance, easy to access and comprehension for the user, flexibility for upgradeability of the technologies or replacement without altering the layout of the façade panel. The other concept was the same but without considering a wall in between. Although thicker than the previous mention, this made a concept of a fully integrated façade panel possible. However, the thickness was still within the DR (<50cm). Both ideas meet the passive thermal performance of the panel and are climate dependent. This means that the façade panels developed for the Netherlands have punctual differences compared to the ones designed for Mexico City.

For instance, the overhang for the Netherlands is more significant and requires a substructure to block the sun angle during summertime as well. The location of the technologies depends on the climate to enhance a natural airflow that improves the user comfort avoiding drafts or not depending on the country. By doing this, the façade panel design has allowed uniqueness, flexibility, and applicability to different climates and locations. The less amount of parts demanded by the DR has been accomplished thanks to the design limitation of each element being used for at least two purposes. For example, the horizontal overhang was functioning as a flat shading system and an electrical duct and ventilation inlet for the technologies.

There are three types of panels, subdivided into two parts each. All of the panels count with the horizontal overhang at the bottom. The first panel (A) consists of the electrical duct on the side that will be installed next to the concrete columns, the second panel (B) can add the technologies and operable or fixed windows with a wall in between, and the third panel (C) is the option without a wall in between the façade and the interior.

In the third level, the integrated technologies are exterior sunshades, internal roller blinds, heating and cooling devices, ventilation with heat exchangers and electricity production. All the HVAC technologies are decentralised, driven by electricity and use air as a medium to heat or cool inside. The technologies were also chosen based on the DR and the passive measurements. Two combinations depend on the room of the apartment. The Ventotherm Twist ventilation unit and the 2.0 mini monoblock unit were used for the living room. The Freshbox E-100 plus the 2.0 mini monoblock unit was used for the bedrooms. The modularity and flexibility of the panel design are linked to the integrated technologies since it allows them to be positioned in different sets within the façade design, vertically, horizontally or mixed between both. However, there is an ideal location for the technologies depending on the climate in which they are installed. For the case of Mexico City, horizontal under the window seal is preferred. In the Netherlands, the ventilation is at the top, and the heating is at the bottom. However, according to the DR, the users might prefer the horizontal disposition of the technologies due to the WWR enabling views to the outside at all times. At the same time, the use of roller blinds enhances the dwellers' privacy. Regarding the DR for user control, the technologies chosen have access through an app to allow users to control them with virtual assistant technology.

At a detailed level, there are three lines of defence: water protection, tightness, and thermal insulation. In the opaque part of the panel between the water protection and the water tightness defence, there is a cavity that could have possibilities to explore further for passive design measures. Both panels B and C count with fire compartments for the technologies.

At an installation level, the electrical ducts were designed at a building and panel level at the same time. The main line runs vertically through the façade and then is subdivided horizontally for each floor. This system allows us to constantly connect and integrate the PV panels with the electrical feed. It is essential to mention that the DR of factory manufacture will ensure that the electrical ducts are placed in the correct position within the panel to connect with the technologies.

At a façade construction level, the panels outside the building are installed with a crane from the ground floor. No other assembly processes are taken on-site to avoid quality issues; everything comes assembled from the factory.

The technologies in the façade are strategically positioned to allow direct access from the apartment floor for maintenance. Users can easily change filters by lifting the technology box door, and window glazing can be replaced from inside without the need for a crane. This is facilitated by the window sizes above the technology boxes and the alignment of the unitised façade panel with the building structure. Interior roller blinds can be accessed from inside the apartment using a small ladder. The most challenging maintenance task is the overhangs, which will have substructures installed at the top of the building to provide safe access for cleaning and maintenance.

Additionally, the design offers a range of aesthetic finish options. The cladding for the opaque part allows for almost any material that meets class B requirements, and even allows for the inclusion of a green wall. The technology box and grill share the same finishes. The grill offers various mesh options, including circles, random circles, squares, and lines, as long as the air volume intake remains consistent.

The simulation allowed to prove the efficiency and give an empirical proof of the design ideas for the overhang sunshades, the heat exchangers use in the technologies and the the credenza box.

The credenza box was simulated to determine the acoustic improvements from the ventilation unit: Freshbox E-100 in the main bedroom. The simulation was run in Rhinoceros with the plug-in Pachyderm for grasshopper. The measurement points for the A-weighted Sound Pressure Level were done at two distances, 1,5 and 3,0 meters from the façade. The 3m point was used to calibrate the model with the technical information of the technology in terms of sound levels (33 d(B)A). The results show that by adding the credenza box, the sound pressure level at 1,5m distance is reduced from 36 to 18 d(B)A. This meets the demands of the DR (30d(B)A). It was found that the materiality of the finish of the credenza box do not have a significant impact on the sound absorption of the noise levels. The impact is primarily given by the insulation of the credenza and the grill.

The thermal and energy simulations were done in Design Builder with energy plus. The room simulated was the main bedroom of the case study, same as the acoutic simulation, with an area of 12,67 sqm. The simulation results are given per year and monthly. The software parameters had the same values for both case studies in terms of glazing u-value (1,1), air supply (10 l/s), WWR, heating (750W) and cooling (-700 and-2350W) capacities of the system, CoP (3,15) and the designed ait to air HVAC system (AHU which simulated the bedroom ventilation: FreshBox E100, and the heat pump: Innova 2.0 named Packed terminal heat pump (PTHP)) without air recirculation. The weather data used to simulate were epw files from Mexico City and Amsterdam. Values that differed from each case study were the wall u-value (0,16-MX, 0,56-ND), the epw file, the length of the overhang (0,82-ND, 0,62-MX), the schedule of the roller blinds (glare for Mexico and heating during night for the Netherlands), the heat exchanger was assumed 90% for Mexico which meet the technology data provided by the developer and for the Netherlands it was assumed 100% given that the temperature difference was making the designed HVAC act unstably. Thus, this last should be considered a limitation on the simulation for the Netherlands in terms of accuracy.

A comparison of the four different sunshades scenarios were simulated; with the overhang, with roller blinds, with both, without any type of shading system. The scenario with only roller blinds are mostly efficient for visual comfort and privacy. Whereas the use of the overhang presented two (Mexico) to three times (Netherlands) less cooling sensible loads of the system.

Overall, the sensible loads graphs behaved as expected with higher loads for cooling in Mexico except for winter (December), lower loads in the Netherlands with heating during winter months (September-March) and cooling during summer months (April-August) this helped corroborate that the simulation was behaving accordingly to each case study.

According to the simulation results, it is advisible to turn off the heat exchanger in Mexico and the Netherlands during cooling season and turn it on again during winter to further improve the energy efficiency of the system. This can easily be done through the app. However, even if the user decides to keep the heat recovery on the whole year it is more energy eficient than to have it off. The impact of this is higher in the Netherlands given the higher temperature differences during winter time.

The PV panels production analysis vs the energy required for the system shows that the PV produce more energy than what the system requires for its functioning. For both scenarios in the Southeast façade the PV panels produce more than enough energy for each season. For Mexico it is 85% more than the energy demand and for the Netherlands is 50%. The PV panels were considered to be 50% efficient and the part of the façade where they are located serves the room behind it. However, the production of the panels was only analysed for the South, East, Southeast and West façades given that there is where they have their best performance. Thus, the energy required in the North side of a building is still a concept to be further analysed and solved. A general brain storm on how to store the excess of energy was done without finding a solid solution. This happened because the design aim is to avoid pipes and use the lesser amount of area possible and the ideas did not meet the requirements, between the ideas were the use of batteries, energy storage at appartment level, underground heat/cooling storage, and the use for household sockets.

Chapter 5 | Conclusion

5.1 Thesis conclusion

This thesis aimed to design a façade panel that integrates decentralised building services for heating, cooling and ventilation while enhancing user comfort for refurbishments in residential concrete buildings under different climate conditions. This was achieved by developing an adaptable and flexible stand alone integrated serviced façade panel with three panel types that allow the integration of exterior sunshades, internal roller blinds, heating and cooling technologies, ventilation with heat exchangers and filters, and electricity production technologies. The panel is driven by electricity and uses only air to air technologies to ventilate, heat and cool the indoor spaces, making it suitable for a non-invasive, fast and efficient façade refurbishment that does not require water pipes.

The approach to achieve the beforementioned façade panel design consisted of developing a design requirements document that set the assessment criteria and limited the design decisions to fulfil a feasible integrated panel design in terms of architecture, user comfort, energy supply and consumption, user interaction and fire safety. A systematic literature review on the state-of-the-art analysis of integrated building services façades gave an overview of the design barriers and possibilities for the panel design. In addition to the beforementioned systematic literature review, a Google search and a field trip to the BAU fair in Munich were made to determine the latest cutting-edge integrated building services technologies available in the market. This led to recognising potential air-to-air technologies for the façade panel integration. The field trip enabled me to gather the latest updated data from the technologies available, exchange ideas with different product developers, see the latest aesthetical façade solutions, and clearly understand the technologies' capacities and limitations in one place. Moreover, the talks with the professionals from the field to see the reception of the concept, to enrich the DR, to see the aesthetic acceptability of the design and receive new perspectives and ideas. This was of paramount importance for the improvements of the pre-design iterations of this thesis as well as seeing where the market is moving in the future and what are the possible upgrades that the façade panel designed can undergo in the coming years and design accordingly. For instance, the companies that developed the technology units used in this thesis façade panel design, Innova and Schüco, are working or willing to create an all-in-one technology that allows for heating, cooling and ventilation in the same unit. There was confirmation from the professionals that there is potential for developing an integrated services façade. Moreover, they all agreed that there is potential for this ambitious integrated façade panel design. However, the high number of technologies required per apartment is one of the concerns in terms of cost and maintenance.

The main findings of this thesis are that the design of a stand-alone serviced façade panel requires highly qualified professionals that understand and comprehend the integration of the different domains in one design. Nowadays, very few companies dare to take the risk on this topic primarily due to the cost and maintenance risk. This is why the design requirements document developed in this thesis can lead to further research on the building services façade integration to lower the latent concerns from the industry.

However, there are limitations to the design requirements that are case study specific like the operable temperature for heating and cooling season as well as the structural tolerances, the overhang shape and panel dimensions along with the building structure. In terms of user comfort, both case study countries, the Netherlands and Mexico, present them as requirements and thus, are not compulsory, only a recommendation for the architects. The only values that are compulsoryare the ventilation flow and the minimum light entrance in the room through the window.

In terms of the building services façade cases reviewed, all of them were designed for office buildings and require a water pipe connection, creating a knowledge gap in the air-to-air integrated services façade. The technologies found in research papers for heating and cooling did not simultaneously meet the design requirements for size, comfort and energy efficiency, translating into an early niche in the research field that is yet to be developed. Regarding the technologies found in the market, they offer electricity-driven HVAC units with air as a medium suitable for façade integration. However, their CoP efficiencies are not as high as a conventional system (average of 3-4) but are high enough (3) for small apartments such as the 60 sqm used as a case study for this thesis. Moreover, in terms of the technologies' geometry, at least three different geometrical options are available. But all these technologies work separately and have not yet been integrated into one design. Despite the concerns of noise levels, the technologies have a 5 dB(A) difference with the DR; 25 dB(A) for bedrooms and 30 dB(A) for living rooms. That is why the credenza design has an acoustic insulation. This concept was proved with the acoustic simulation which results shown that the A-weighted sound pressure level decreased from 33 d(B)A to 18 d(B)A at 1,5m distance from the façade. It can be concluded that now the design meets the demands of the DR (30d(B)A).

The façade panel design generated within this thesis gives a solution to the knowledge gap of the integration of air-to-air technologies and the address of residential refurbishments in the façade industry while enhancing user comfort. Since the design is conceived on a residential concrete building in two different climate contexts, it demonstrates its adaptability, flexibility and applicability at a large scale. The modularity aspects of the design solve barriers found at the design, production and assembly stages of the existing integrated façades, such as coordination between the contractors, physical integration without entanglement, reduction of connections and the compatibility between the building structure and the façade component. However, an issue has been created with this solution, technologies related. The large number of units required per apartment is equivalent to the number of rooms, which can translate into high investment costs. However, the scope of this thesis was to develop an integrated façade panel design, and it did not consider the prices as part of the design requirements for practical matters. Added to this, the maintenance of the air inlet and exhaustion ducts can be complicated given its positioning inside the façade panel. However, given the time it could not be further analysed and designed. At the same time, the monoblock heat pump heating and cooling capacities allow it to be implemented in bigger rooms than the ones shown in this thesis, to meet the user's comfort but to enhance dwellers privacy reasons the concept was left at locally serve each room. The talks with the industry and the field trip lead the author to believe that in the future, the tendency of the technologies will be to be developed into an all-in-one compact HVAC unit that can function with second units connected to a main one in the façade. Thus, optimising the number of technologies used in an apartment can be a topic for further research.

The thermal simulations in Design Builder shown that the energy input require for the system to work is 15% of the energy produced by the PV panels in Mexico City and 50% in the Netherlands. Therefore, it can be concluded that with empirical information the designed integrated serviced façade panel is stand-alone for both countries.

5.2 Reflection

The reflection for the thesis Plug-in Services Façade will be divided into four parts. The first part will address the graduation process; the second part, the societal impact of the research; the third part will discuss the limitation of the design; and the fourth part the recommendations for further research. Each part consists of a set of questions that aim to give a critical and personal reflection on the work done during the development of this thesis.

5.2.1 Graduation Process

What is the relation between your graduation project topic, your master's track, and your master's programme?

The building envelope functions as the in-between layer from the outside world and the interior, allowing the user to interact with the exterior. Thus, the façade joins the user with architecture with urban life. In this sense, my master thesis aims to design an envelope that integrates building services for heating, cooling and ventilation on demand into a façade panel design that is flexible and adaptable depending on the climate. Moreover, the façade panel aims to be driven with electricity and use air as a medium to meet the user comfort requirements per climate. Therefore, this thesis is developed under two research themes: Façade Design and Building Services Innovation in the Department of Architecture Engineering & Technology of the Master Track Building Technology at the Delft University of Technology. The main tutor is Dr Alessandra Luna Navarro, and the second is Prof. Dr. ir Atze Boerstra; their tutoring focused on façade design engineering, and building services, respectively.

How did the research approach and methodology work out? And did it lead to the results you aimed for?

The research approach of the presented thesis builds on design through research. The methodology was made in six parts; introduction, design requirements (DR), literature review, pre-design, final design, and final evaluation. The second, third, fourth and fifth stages aimed to answer one sub-research question and had the strength to contribute continuously with a feedback system of information exchange between the thesis parts. In this sense, the research approach and methodology followed were non-linear. The DR were a strength since they always worked as a tool to assess the whole thesis development, making the design decisions more technical, logical and with fundament. At the same time, they were a weakness because they could have harmed the final design's accuracy if they had not been done as meticulously as they were. However, the disadvantages of the DR were overcome with the use of desktop research on norms and guidelines and constant upgradability along the process, especially with the field professionals' input and expertise corroboration. This is also why different field professionals analysed the tables during the pre-design stage. In the end, the process led me to the results I aimed for in the understanding that the thesis goal was to design an integrated façade panel that enhance the user's comfort in residential concrete buildings, and it was achieved. If I could change part of my methodology it would be to be more clear and specific in the terms I was using to be clear of what my goal was. For instance, once I defined to only use air to air technologies my process speeded up. This could have not bee possible if I had not done the DR. Moreover, running the simulations helped me wrap up and see first-hand how using the DR it was a straight forward process to set-up the simulation parameters with clarity despite being simulating two different countries at the same time. It was a satisfactory process to confirm how the simulations were proving my concepts and ideas. However, there were limitations with the simulation for the Netherlands given that I had to assume a 100% efficient heat exchanger when this was unrealistic. Not only my thesis results were as I aimed for in the sense that I managed to solve my research question but also, personally speaking, I was able to merge my architectural knowledge with my building technology knowledge to further develop my design ideas.

How did your research influence your design/ recommendations, and how did the design/ recommendations affect your research?

The design requirements document was developed based on a thorough literature review, which provided insights into integrated serviced façades and their key characteristics. The analysis of existing façades helped identify important considerations, such as the optimal positioning of technologies and the avoidance of design barriers, like entanglement of units. Technical data collected from the technologies was compared to manually calculated heating and cooling demands to ensure they could meet user comfort requirements. Throughout the research process, the design requirements document evolved continuously through findings from literature, industry discussions whom incorporated valuable insight, and the design process itself. During the pre-design phase, constant reference to the literature research was made to explore better options for performance when placing technologies in the façade panel. The field trip also played a crucial role in finding a ventilation technology with lower sound pressure levels for the bedroom. Therefore, the design requirements document served as a foundation for selecting suitable technologies to meet comfort demands during the literature review, and it also acted as an assessment tool during the pre-design, final design stages and simulations.

5.2.2 Societal impact

How do you assess the value of the transferability of your project design in practice?

Since the beginning, the aim was to develop a design that could be implemented at a significant scale under different climate conditions. An adaptable standard integrated façade panel design. The case studies are based on Mexico City and the Netherlands, which have different climates and solar radiation conditions. This led to a design that, between other characteristics, can adapt its horizontal sunshades to block the sun's angle during summertime in both climates generating slightly different design views per country. In addition, during the meeting with the professionals from the chosen technologies' product developers, a genuine interest was shown regarding the future of my thesis research, such as the accessibility of my research once I had finished my thesis. Similarly, during the meetings with the industry, several professionals mentioned that the façade industry would be interested in developing such a façade concept product. However, a risk evaluation had to be done, especially for maintenance, cost and market demand but this could not be conducted due to time constraints.

To what extent has the projected innovation been achieved?

I would go as far as to say that no integrated façade panel design in the market integrates air-to-air technologies with a modular design adaptable to different climate conditions. Therefore, the achieved façade panel design is an ambitious ground-breaking stand alone serviced façade panel with no-water-pipes-connections. The project's innovation comes from the design decisions and choices and external input; in this sense, the design requirements tool was key to achieve this.

Does the project contribute to sustainable development?

Yes with limitations. Regarding energy efficiency, the design integrates technologies with A or A+ energy performance. The ventilation technologies chosen have integrated heat exchangers and an average CoP efficiency of 3 or more. They were chosen to achieve an energy-efficient system based on demand-driven control that optimised energy consumption to achieve comfort demands. Moreover, passive measurements were implemented to decrease the technology's heating and cooling loads and thus the energy consumption of the façade panel, such as integrating double glazing with u-values of 1,1, internal and external shading devices, and upgrading the thermal performance of the façade depending on the climate. At the same time, the façade panel integrates energy generation with the use of PV panels that generates from 85% (Mexico) to 50% (Netherlands) more than the required energy demand. The design's modularity characteristic allows for the system's upgrade in the future, the exchange of technologies for new ones and flexibility in the technologies to meet comfort demands during higher temperature differences resulting from climate change. However, the number of units required per apartment can jeopardise the sustainability aspects of the design since the embodied energy and the number of critical materials used in the panel due to the technology units are higher than an average refurbishment façade panel. The lifespan of the technologies is of 15 years but since they have been on the market for less than 20 years, there is no proof of this information. However, the product developers are confident that the units will have a long time lifespan. Moreover, the heat pump technology chosen uses a refrigerant with one of the lowest GWP in the market.

What is your project's socio-cultural and ethical impact on sustainability?

It is easier to oversee health and comfort issues that are invisible to the eyes, for example, the air quality consequences in our life expectancy. With the implementation of ventilation devices with filters (F7) in the façade panel, users will not only extend their life expectancy in polluted cities such as Mexico City, but by using an integrated façade panel daily, they would get to understand, value and appreciate the importance of energy-efficient systems and demand-driven control in their daily lives and the impact this has on the energy bills. The energy production characteristic of the design allows for the generation of clean energy for its functioning. Currently, the system makes an energy-efficient refurbishment for concrete tenement flats. This means that the impact of such a system can be applied to many apartment buildings worldwide with the limitations of making the respective country requirements changes in terms of thermal comfort. This highly technological concept can start the conversation on different possibilities to improve the dweller's comfort and generate a discussion on how we address architecture and building services.

How does the project affect architecture / the built environment?

The project design allows for different cladding finishes in the opaque façade parts. It is even possible to add a green façade system. This could positively impact the urban scale because the significant concrete buildings have taken away nature, and by adding green façades within the integrated services façade panels, the wildlife could take back their space and regenerate the biodiversity of the cities. At an architectural level, designing architecture and building services separately is reconceptualised into an integrative design that allows for more efficient solutions for enhancing user comfort.

What are the limitations of the design?

There are two main limitations to the integrated façade panel design. Firstly, the amount of technology devices required per room is considerably high since it is equivalent to the number of rooms in the apartment. However, for privacy reasons, a unit installed in the living room cannot supply the bedrooms with ventilation, heating and cooling since it would mean having the doors open and more powerful fans or ducts to further away areas. Both possible solutions are out of the design goals. Secondly, the lack of passive design strategies, apart from the thermal performance upgradability of the panel. This happened because I developed a standard façade panel that can be applied in different climates and contexts. Therefore, I needed a system that had technologies that met the requirements of different climates. Whereas, in the case of passive design strategies such as double- cavity façade, it tends to be more site-specific and tailored to each building's and location demands.

5.3 Further research

- The development of a digital twin connected to the façade panel system through the BMS controlled and analysed by AI to further optimise the energy and comfort performance of the integrated façade panel design.

- Development of an ait to air HVAC system that includes all the functions in one unit.

- Since the centralised building services are taken away with a decentralised integrated façade panel system, it is recommended to analyse a solution for the centralised DHW in countries like the Netherlands, where they do not have tankless gas water electric heaters like Mexico.

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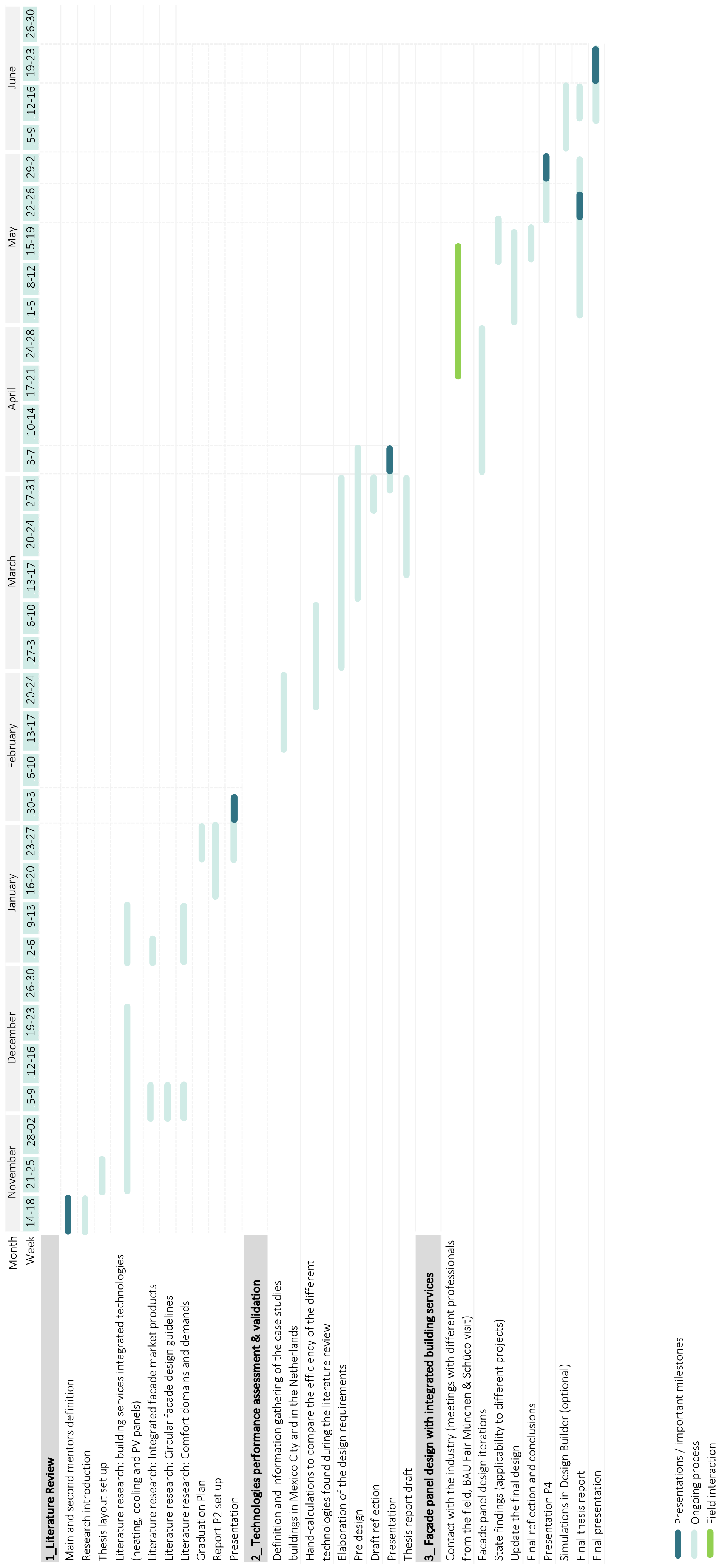
Chapter 7 | Appendix

7.1 Appendix A: Thesis timeline planning



7.2 Appendix B: Comfort requirements per country

	Units	Mexico	Netherlands
Thermal Comfort			
Operative temperature	[°C]	20 (min. winter) 26 (max. summer)	18 (min. winter)* 24 (summer)3
Operative temperature range	[°C]	20-25 (winter) 23-26 (summer)	16 - 22 (winter)3 23- 26 (summer)3
Relative humidity* *40% for heating season and 60% for cooling season	[%]	25 (humidification) 60 (dehumidification)	≤ 65*
Ventilation			
Max. CO_2 concentration	[ppm]	800	,+450 (above the outside air concentration)3
Total ventilation	[dm3/(s per m2)]	0,42	0,9
Air velocity	[m/s]	0,1	< 0,2
Sound			
Living room	[dB. (A)]	≤ 35	≤ 30 3
Bedroom		≤ 30	≤ 25 3
Envelope			
Floor	[m2K/W]		≥ 2,6
Walls		≥ 1,10	≥ 1,4
Roof		≥ 1,10	≥ 2,1
Light			
Illuminance	[lux]	≥ 100 (bedroom)	≥ 10
Window area (% in relation to the floor area)		≥ 17.5%	≥ 0,5m2 + 10%

Sources:

1. Norma técnica complementaria para el Proyecto Arquitectónico en México
2. PROY-NMX-C-577-ONNCCE-2020
3. NOM-020-ENER-2011 https://www.dof.gob.mx/normasOficiales/4459/sener1/sener1.htm

1. Bouwbesluit
2. BKT-PGW-living-2022-01

**Standard 55-2017 -- Thermal Environmental Conditions for Human Occupancy (ANSI/ASHRAE Approved)*

*WHO guidelines

7.3 Appendix C: Calculation qsun

The value of qsun was defined using the software Climate Consultant and the epw file of Mexico City and the Netherlands. The qsun of each case study can be found in the Figures bellow, the orange bar on the far left give the mean qsun anual value. However, for the hand calculations, the values for the hottest month (July) and coldest month (February for the Netherlands and December for Mexico City) were used.

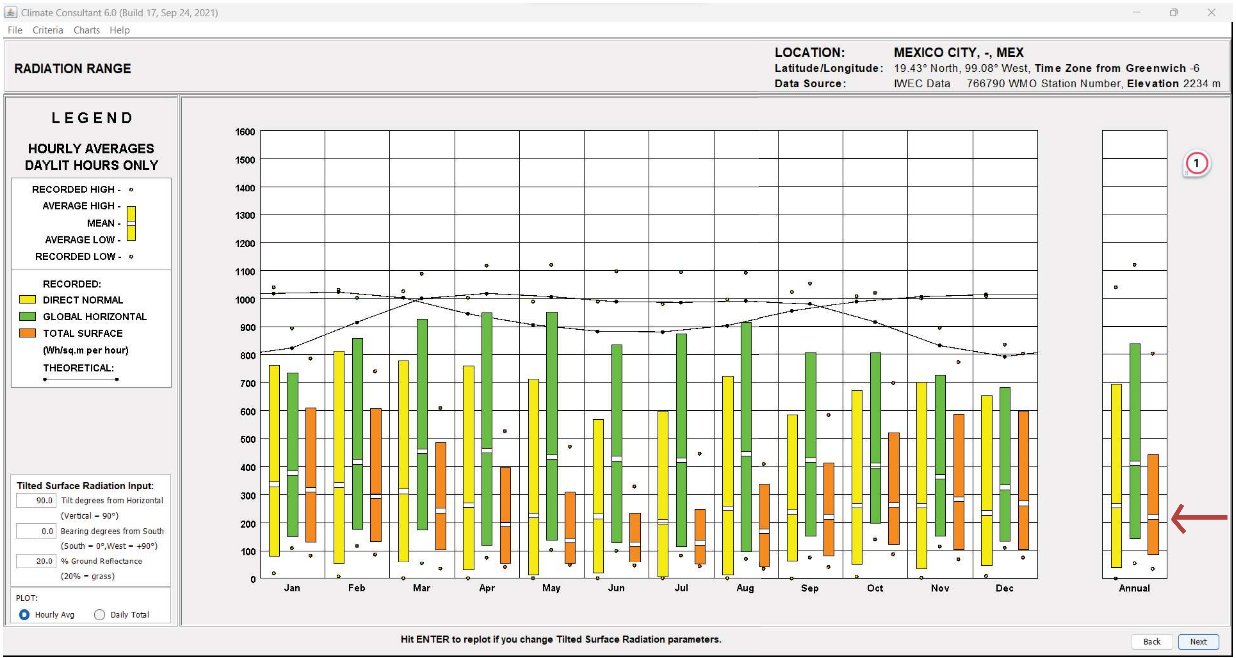


Figure 108. qsun value for the case study of Mexico City

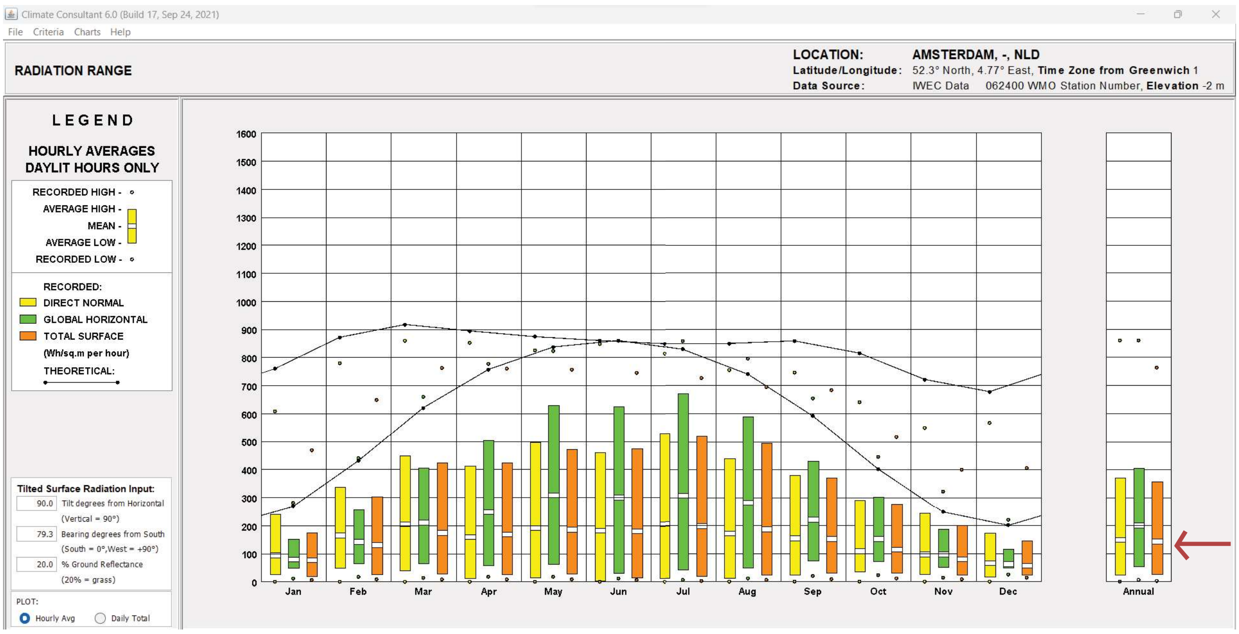
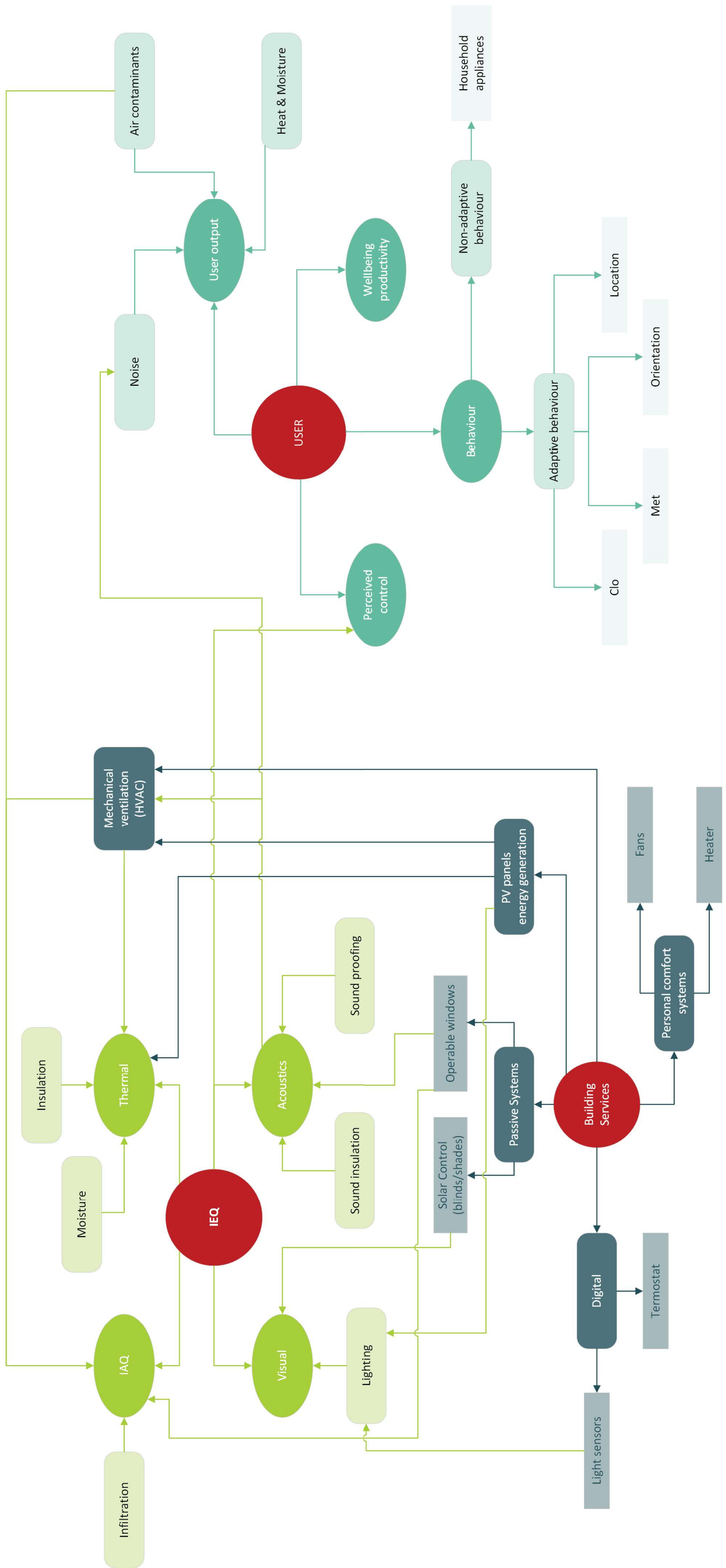


Figure 107. qsun value for the case study of the Netherlands

7.4 Appendix D: Façade and building services world interaction



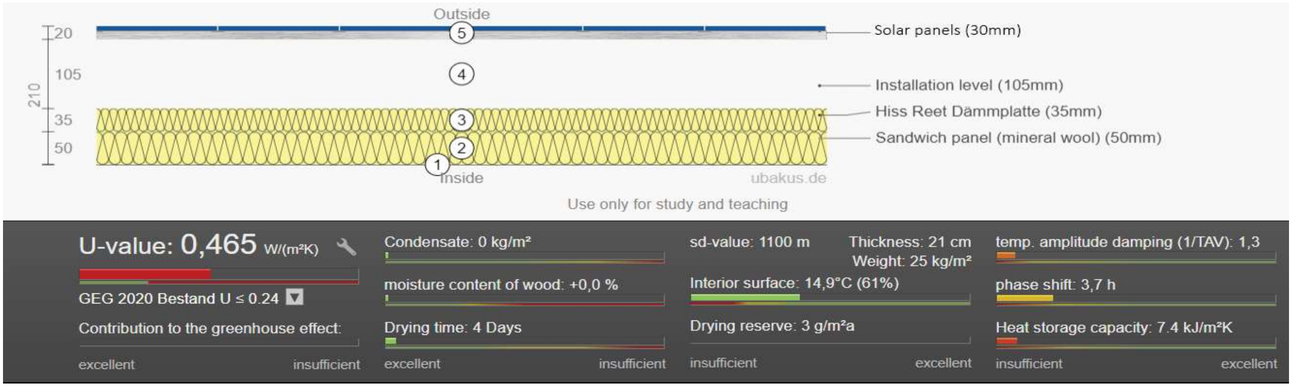
7.5 Appendix E: Contact with the industry details

Eight proffesionals from the built environment were interviewed as part of the pre-design process. The table below show the names, proffesion and the company that they work for. At the same time, a field trip to the BAU Fair Munich, a World leading trade fair for architecture, materials and systems, where I gathered the latest information from professionals with expertise on architectural building materials, façade systems, renovation, aluminum, steel, solar technologies, building systems and energy, light/ smart building, and glass.

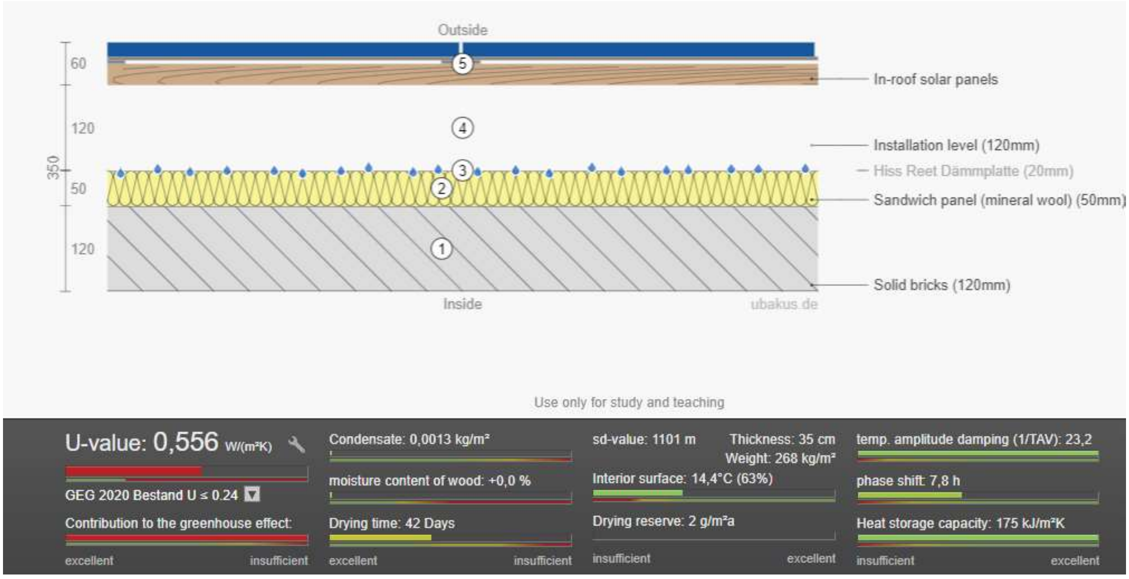
Name	Profession	Company	Location base
Olga Ioannou	Assistant Professor, Circular Education & Social Relevance of Circularity	BK - TU Delft	Netherlands, Delft.
BAU Fair München 2023	Architectural building materials Facade systems Renovation Aluminum Steel Solar technologies Building systems and energy Light/smart building Glass	Fair exhibitors	Germany, Munich.
Klaus Wolff	Schuco Welcome Forum Manager	Schüco International KG	Germany, Bielefeld.
Henning Koeln	Product developer	Schüco International KG	Germany, Bielefeld.
Mauro Parravicini	Architect, Master's coordinator lecturers AE+T	Mauro Parravicini Architects, BK TU Delft	Netherlands, The Hague.
Gertjan Verbaan	Building Physics Consultant	DGMR	Netherlands, The Hague.
Maria Meizoso Aguilar	Façade Consultant	Octatube	Netherlands, Delft.
Gertjan Peters	Façade Consultant	ABT	Netherlands, Delft.
Karen Frieventh	Architect	Ciudad Maderas	Mexico, Queretaro.

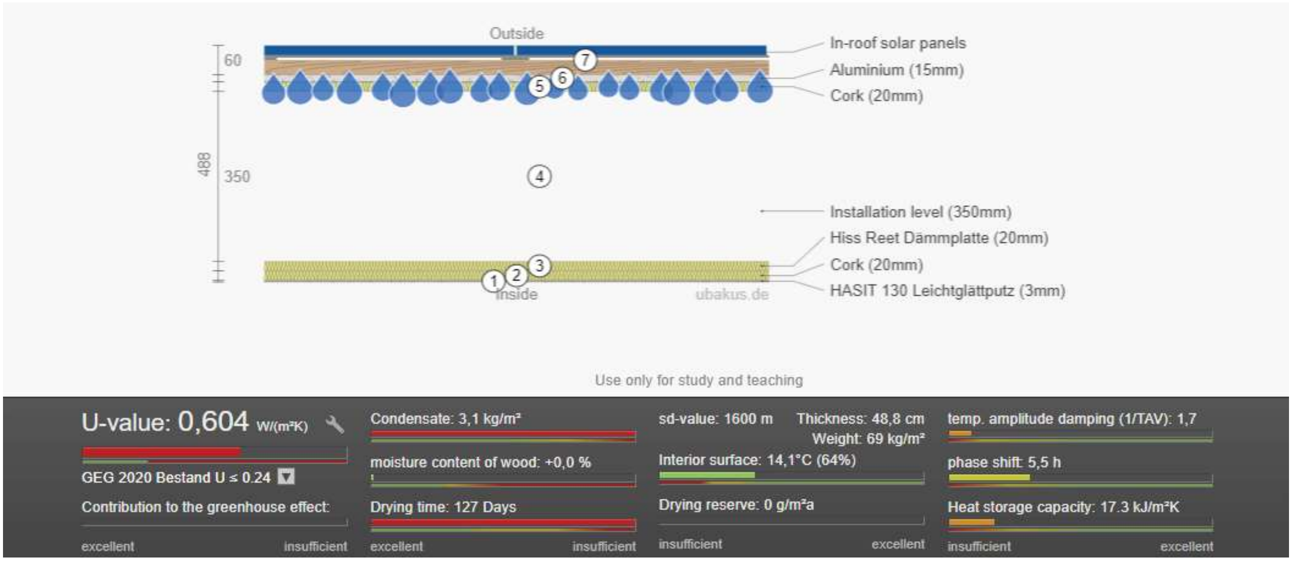
7.6 Appendix F: Materials analysis

Insulation values above 1,1. The iterations were done on the online software ubakus. Different insulation materials were tested such as cork and sandwich panel, different installation cavities were tested but their depth did not had a direct impact on hte insulation. The figures are shown from the latest to the first iterations. In the first iterations risk of condensation was present due to positioning of the insulation layers, namely sandwich panel.



https://www.ubakus.de





https://www.ubakus.de

7.7 Appendix G: Unitised-system preliminary structural calculations

The software utilized was the integrated tool provided on the Schueco website. The decision to use this brand was based on the fact that the integrated design panel employed the Schueco unitized system. Additionally, for practical reasons, the ventilation system in the living room was also sourced from Schueco, using the same unitized system for consistency.

UNIT PROPERTIES

Mullion
PV frame 25/125 - 331940

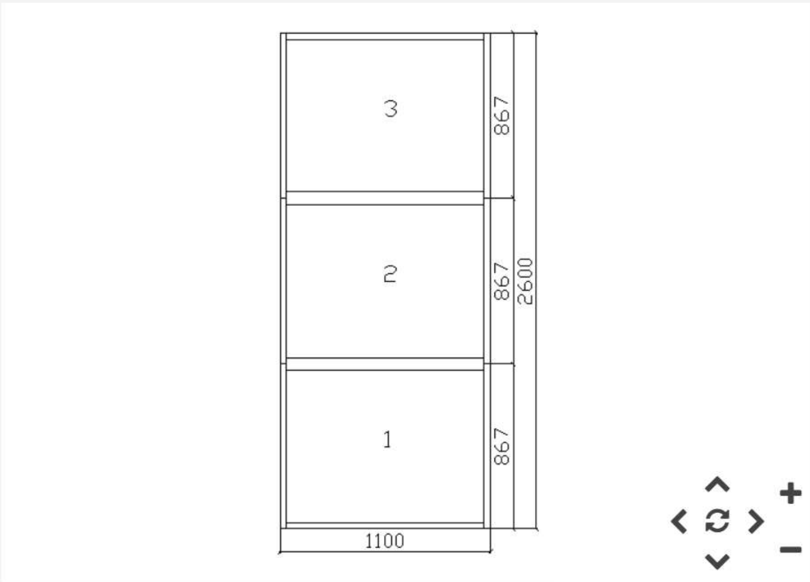
Transom
PV frame 25/125 - 331940 (Face width 65mm)

Glazing
Glass 28 mm (6-16-6), Ug=1.1 W/m²K, Stainless steel, from standard

Number of lines
3

Number of columns
1

VIEW FROM OUTSIDE



RESULT

TECHNICAL BASIC DATA

U VALUE | STATICS

ITEM BOUNDARY CONDITIONS

Side of the building	Side of eaves
Distance [r]	1 m
Installation height (z)	20 m
Height of transom load	1000 mm
Distance between blocks	150 mm
Angle (α)	90 °
from load resulting from snow drift	not consider

DESIGN LOADS

Wind	
aerody. coefficient	1.000
Velocity pressure	kN/m²
Snow	Zone
Ice	0.000 kN/m
Horizontal load	none

MAXIMUM PERMISSIBLE DEFORMATIONS

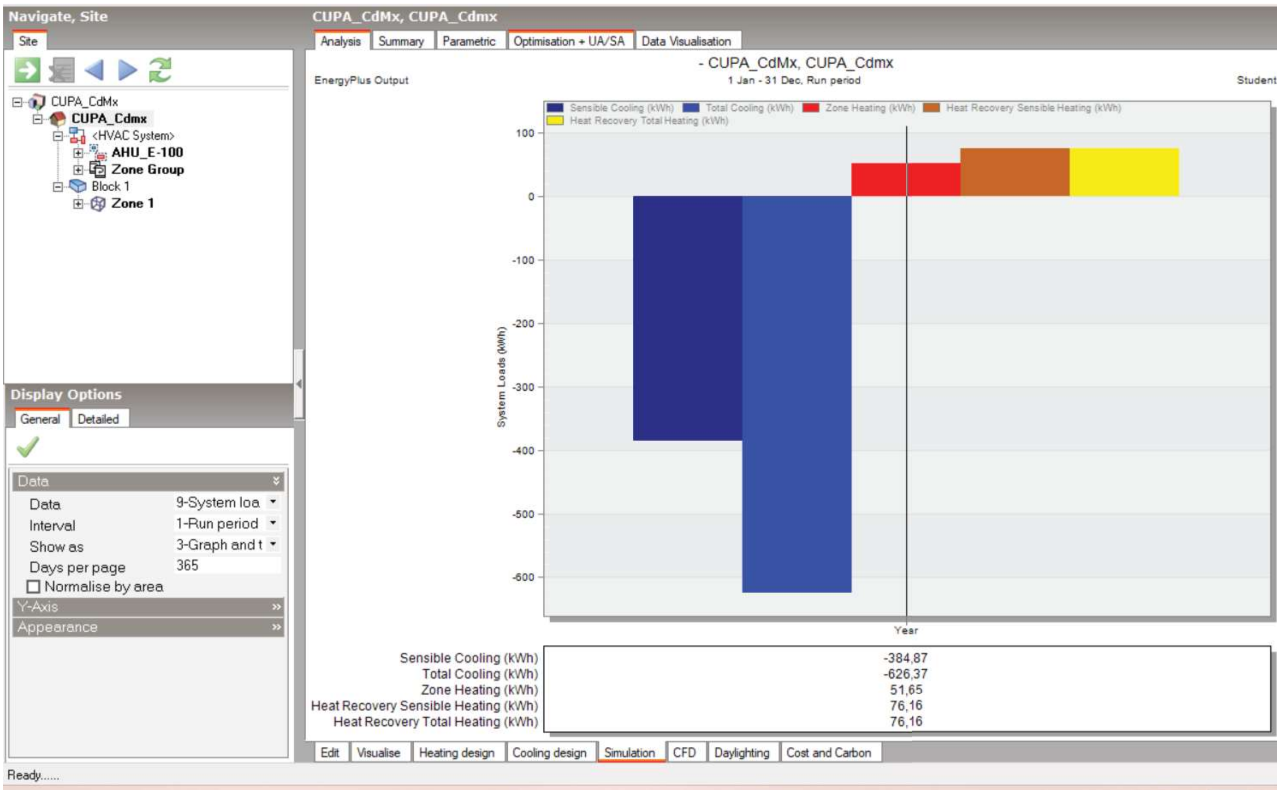
in the% s direction	
Bar/profile (e.g. wind load, snow load)	Standard specification
Bar/profile (e.g. horizontal dynamic load)	Standard specification
Largest pane (eg wind load)	Standard specification
in the% s direction	
Bar/profile (e.g. dead load)	Standard specification

https://www.schueco.com/u-cal-tool/index

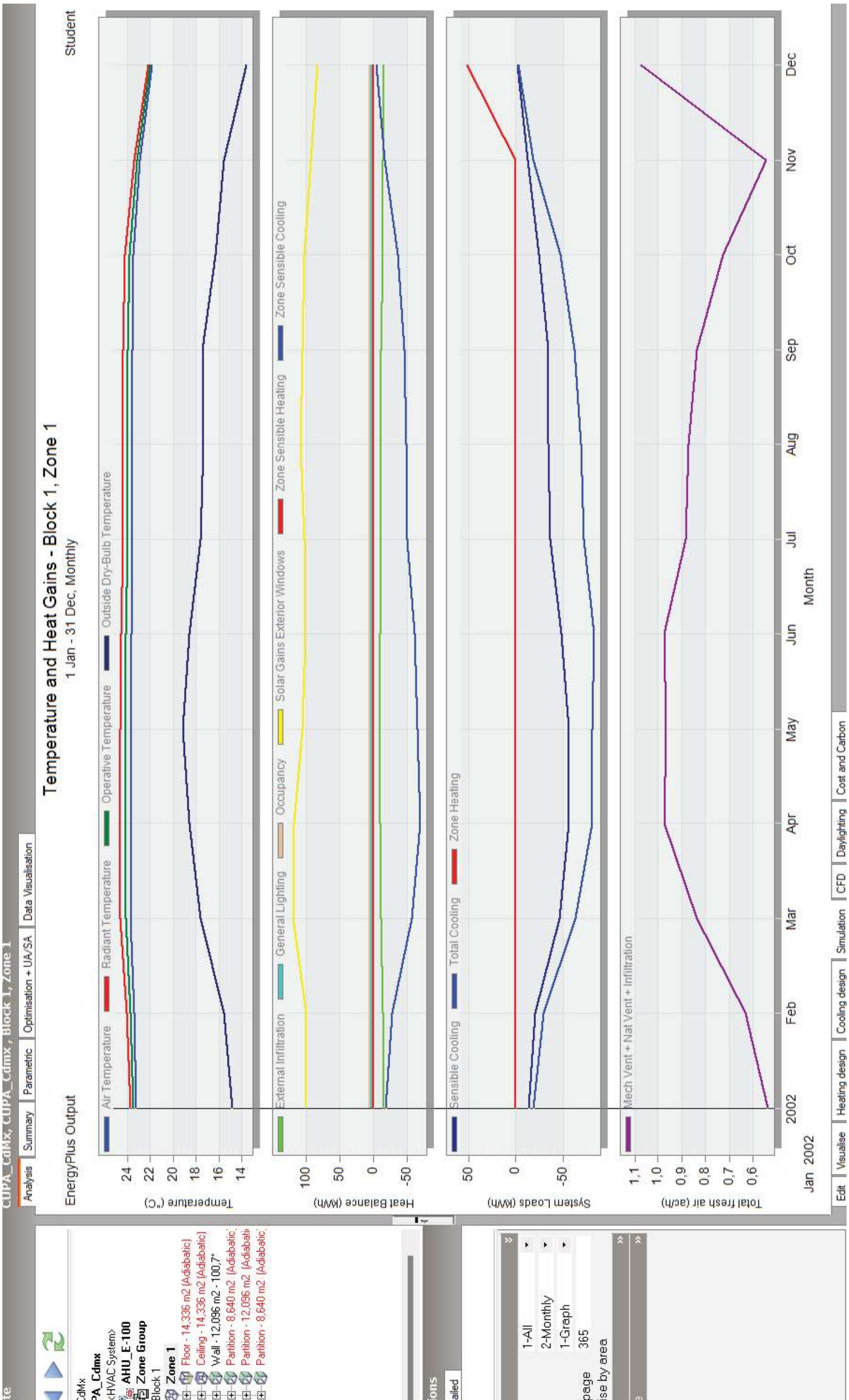
7.8 Appendix H: Thermal simulations

Case study: Mexico City, Mexico.

Annual fuel breakdown for Mexico City

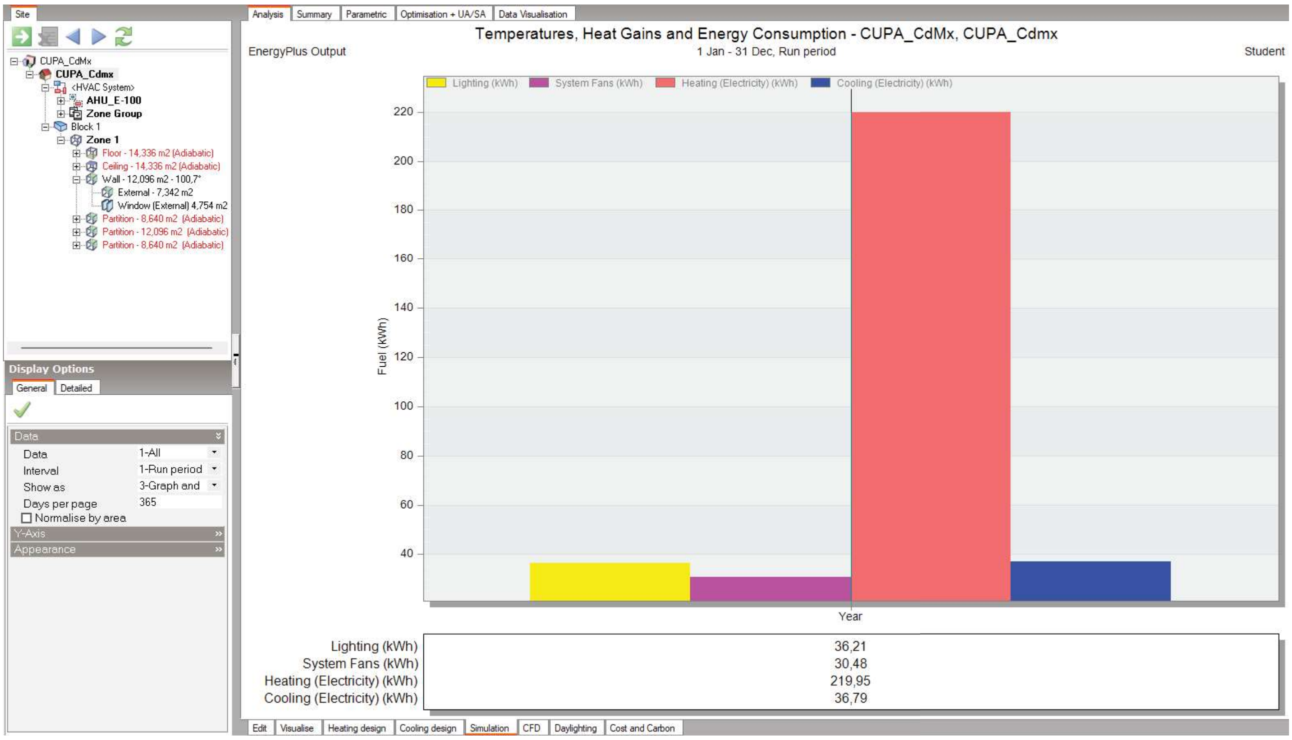


Annual system loads for Mexico City

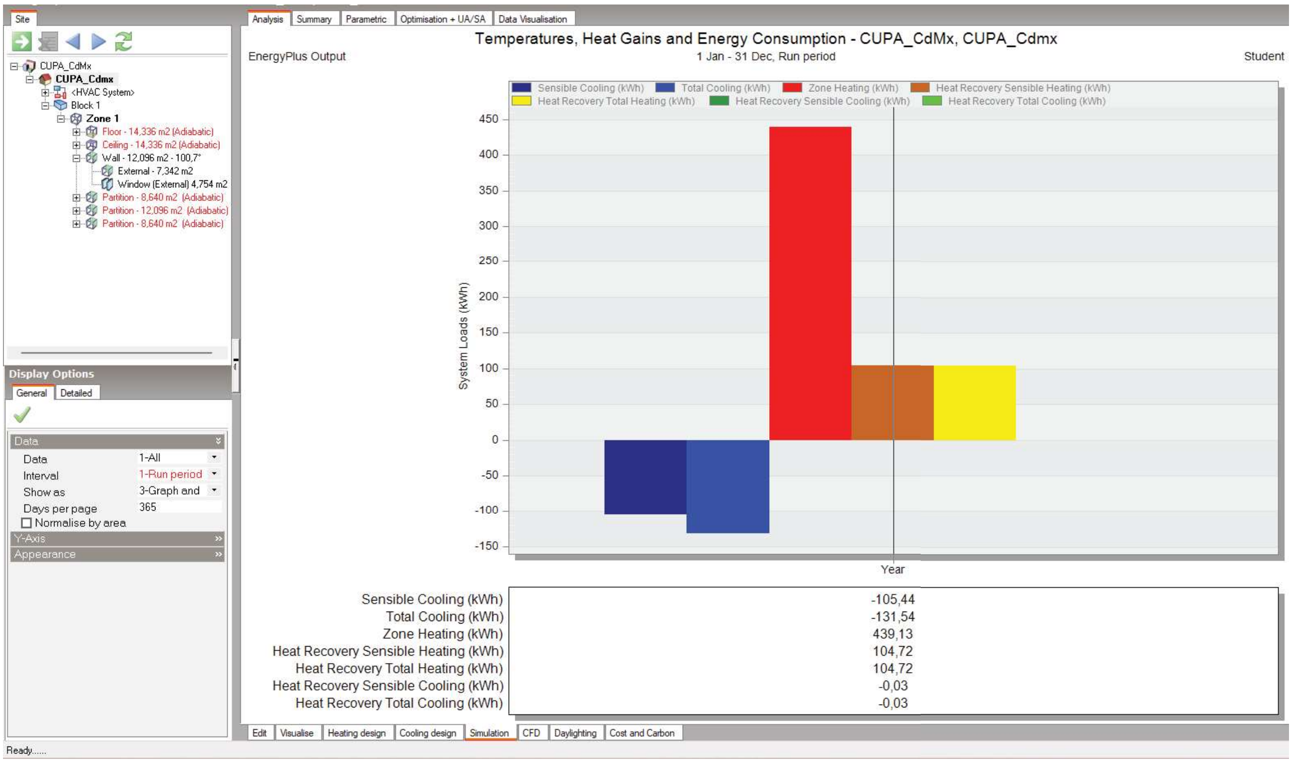


Overview results of the simulation for Mexico City

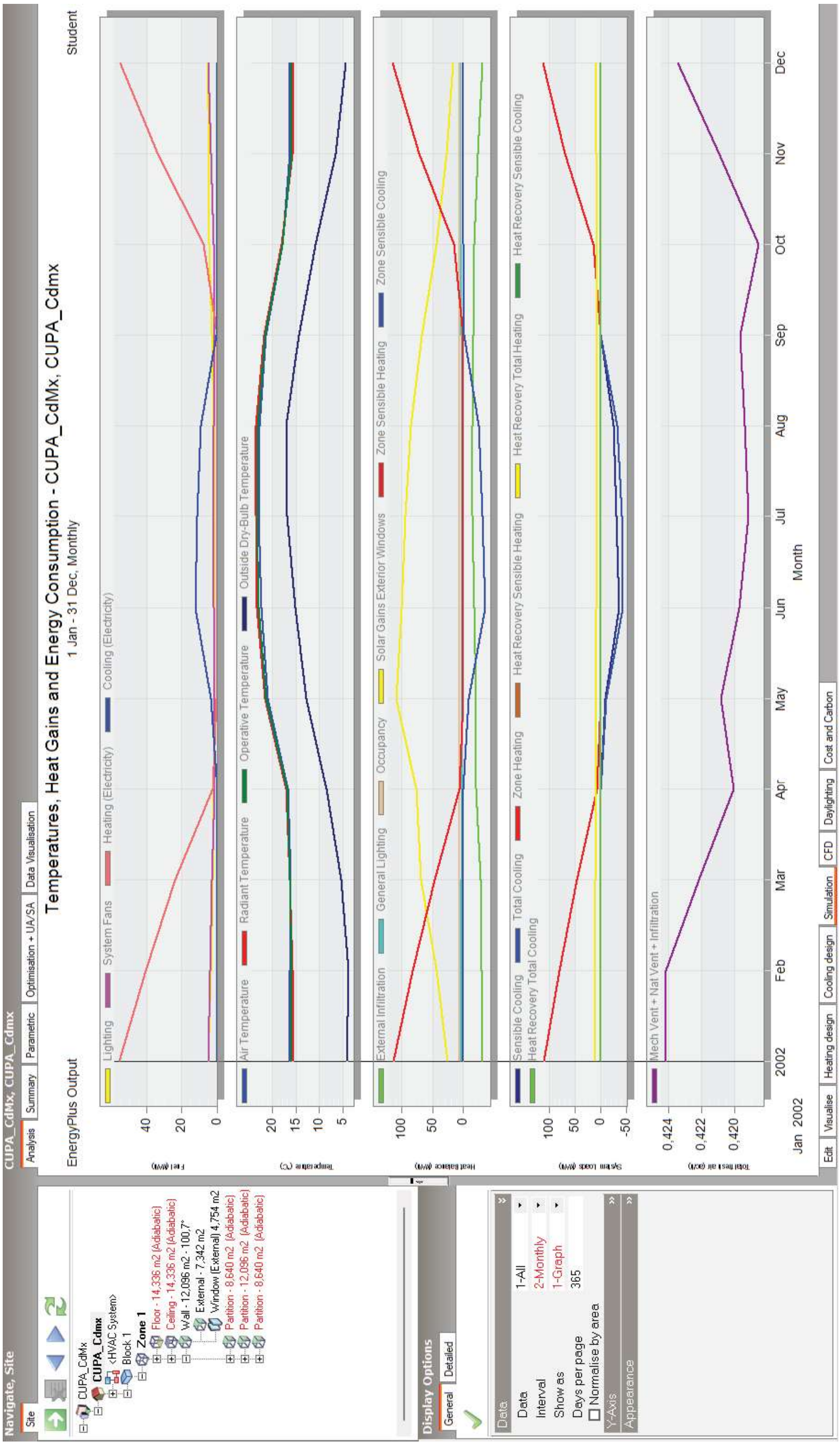
Case study: Netherlands, Amsterdam.



Annual fuel breakdown for Mexico City



Annual system loads for Mexico City



Overview results of the simulation for Mexico City

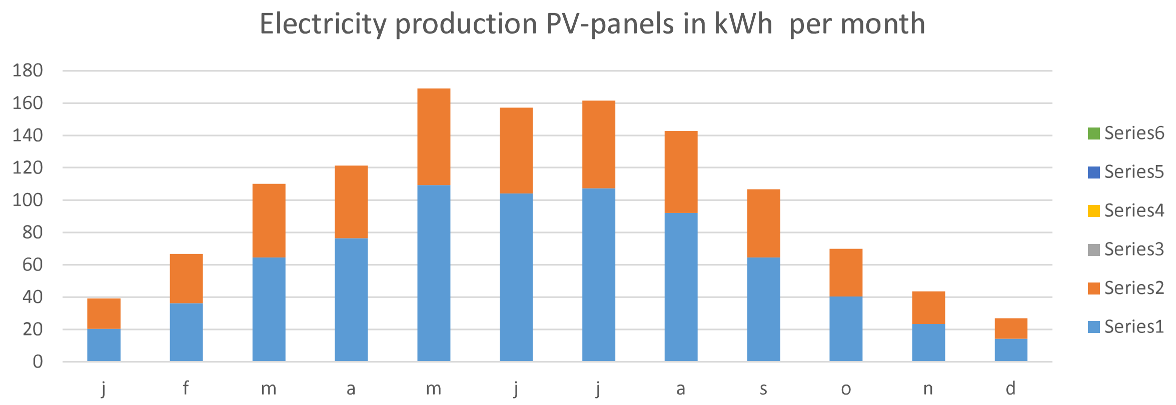
7.9 Appendix I: PV panels electricity production

Case study: Mexico City

Calculating electricity production by Photo Voltaic systems

Electricity production by Photo Voltaic (PV) panels

PV-systems	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	SE	30	1,6	50%
PV-system 2	SE	90	1,2	50%
PV-system 3	NE	0	0	11%
PV-system 4	S	90	0	11%
PV-system 5	S	90	0	11%
PV-system 6	S	90	0	11%

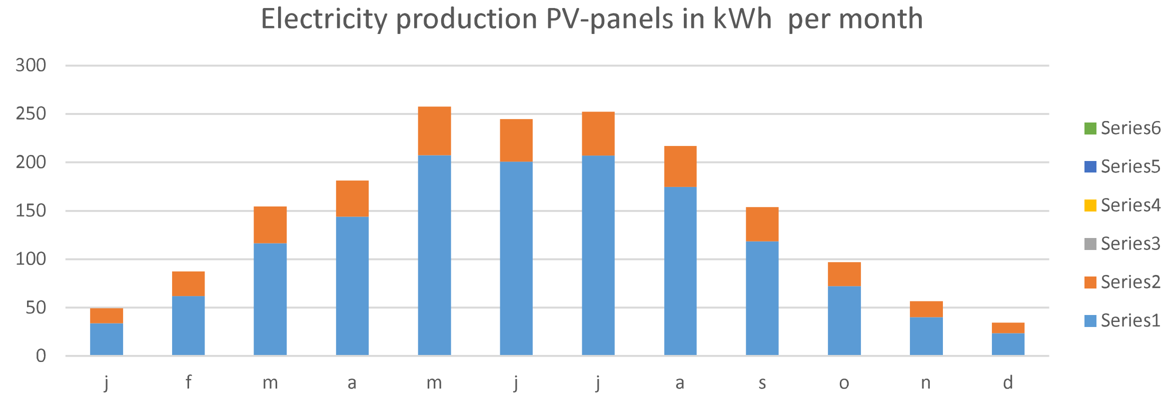


Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	20	19	0	0	0	0	39
f	36	30	0	0	0	0	67
m	65	46	0	0	0	0	110
a	77	45	0	0	0	0	121
m	109	60	0	0	0	0	169
j	104	53	0	0	0	0	157
j	107	54	0	0	0	0	162
a	92	51	0	0	0	0	143
s	65	42	0	0	0	0	107
o	40	29	0	0	0	0	70
n	23	20	0	0	0	0	43
d	14	13	0	0	0	0	27
year	753	462	0	0	0	0	1.215

Case study: Netherlands

Calculating electricity production by Photo Voltaic systems

PV-systems	Orientation	Tilt angle	Area [m2]	PV-efficiency
PV-system 1	SE	14	2,84	50%
PV-system 2	SE	90	1	50%
PV-system 3	NE	0	0	0%
PV-system 4	S	0	0	0%
PV-system 5	S	0	0	0%
PV-system 6	S	0	0	0%



Calculated produced electricity per month in kWh							
month	PV-system 1	PV-system 2	PV-system 3	PV-system 4	PV-system 5	PV-sytem 6	total systems
j	34	16	0	0	0	0	49
f	62	25	0	0	0	0	87
m	116	38	0	0	0	0	154
a	144	37	0	0	0	0	181
m	207	50	0	0	0	0	257
j	200	44	0	0	0	0	245
j	207	45	0	0	0	0	252
a	175	42	0	0	0	0	217
s	119	35	0	0	0	0	154
o	72	25	0	0	0	0	97
n	40	17	0	0	0	0	57
d	24	11	0	0	0	0	34