TOWARDS SUSTAINABLE FAÇADE CULTURE
THE DEVELOPMENT OF A MODULAR FAÇADE SYSTEM FOR PLUG-AND-PLAY INSTALLMENT USING ECO-FRIENDLY MATERIALS

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ABSTRACT

This study investigates the development of a modular facade system designed to align with sustainable construction paradigms, focusing on a standardized façade structure, renewable materials, and climate design for wellbeing. Using the Dutch climate and societal context as a reference, the research outlines key performance criteria for three programmatic types: dwellings, office space and commercial space. The interscale approach allowed for a multifaceted elaboration, allocating the cassette as core concept.
The findings indicate that closed cassettes provide superior insulation and acoustic performance, while open systems prioritize ventilation and daylight but require careful balancing to maintain energy efficiency. Alternative solutions, such as 3D-printed demountable plugs and internal drainage systems, enhance modularity, reuse potential and the implementation of bio-based materials. Green facades and photovoltaic panels further augment ecological and energy performance. The proposed system achieves significant modularity and adaptability but requires further exploration of complex geometries, advanced biobased materials, and optimized accessories. This work establishes a versatile template for sustainable facade design, suitable for varied architectural contexts.

KEYWORDS: *Modularity, Standardization, Renewable Materials, Climate Design For Wellbeing, Façade System*

I. INTRODUCTION

Humans are increasingly living out of balance with its natural environment. The current construction culture in the Netherlands (but more general in Europe) is one of the areas where this imbalance is most prevalent. The notion of the nature culture divide poses an interesting explanatory framework, everything that is culture (i.e. human created processes) is juxtaposed by everything that is nature (i.e. natural created processes). For finding solutions to the imbalance, using methods and paradigms that align more with natural processes is crucial. This paper aims to develop a façade system using those methods where and paradigms, to create a more symbiotic modus operandi. This system will be designed for dwellings, offices and commercial space. Because they are one of the most common building programs (for both renovation and new construction), a solution can have the most impact (Centraal Bureau voor de Statistiek, 2023).

More specifically, one of the areas where this becomes physically most manifest is with façade construction. Using linear economy principles, air- and water tight construction methods, and creating uniform indoor climates with large energy demands, the current façade culture might be concealing us from this natural world. Moreover, a research on housing in the Netherlands showed that the façade (as defined by Brand, 1997) is the second largest CO2 emitter within a whole building, measured with the MPG (DGBC, 2021). Additionally, façade products are (on average) within the top five largest contributors to environmental impact of a whole building. Simultaneously, the share (by weight) of biobased materials in the built environment is still very low, standing at 2% for wood and 0,1% for other biobased materials (NIBE Research, 2019). Yet, sustainable solutions to these pressing problems is sometimes lacking and innovation relative to other sectors lags behind (Boton et al., 2020). In addition to the earth, are the current practices also damaging the wellbeing of people living within these building, causing diseases like the sick building syndrome. Especially with renovated buildings, energy consumption and related emissions by services takes up a large part of the total (DGBC, 2021).

More specific on the problem statement, can the imbalance be distilled into three points with corresponding solution paradigms. These solution paradigms offer tools and methods to provide answers in sustainable design. Simultaneously, architectural tectonics provides a framework to order the research into three main domains: structure, materials and climate. The concept of modularity unifies these three topics.

1. Intensive use of materials and energy → Circular economy principles (structure)
2. Emittance of damaging and toxic chemicals → Renewable materials (materials)
3. Lack of proper design for longevity → Climate design for wellbeing (use/experience)

This research aims to provide an answer to the following question:

How can a modular façade system be developed with sustainable architectural tectonics theory, designed for Dutch housing, office space and retail?

The to be collected information is structured according to the architectural tectonics framework, as well is the structure of the research.

Chapter II:

What are the requirements for:

2.1 the facade's structure and how can it be standardized for the circular economy?
2.2 the facade's materials and how can it consist of as much renewable materials as possible?
2.3 the facade's building physics and how can it be customized for wellbeing?

Chapter III:

How can the insights of 1-3 be combined in a design for an integral facade system?

In chapter II information for the system by literature studies will be gathered to elaborate each individual pillar of architectural tectonics. The pillars are not necessarily listed in order of investigation. In chapter III will the gathered knowledge be implemented in the development of a façade system. Here, an iterative research by design method is used. This includes sketching, the use of CAD and prototyping. Chapter IV entails the conclusion of the paper, as well as a reflection of the developed façade system. For the sake of scope and complexity of this study, the development of the system will only concern buildings with linear, non-inclined shaped facades.

II. Architectural tectonic requirements

2.1 Structure

For the structure, the criteria (see below) subsequent of the circular economy are relevant because they determine for a large part the spatial design. For example, standardized façade elements with universal connections that functions nearly independent from the buildings support structure, will (intuitively) have different spatial consequences on the design. In this part, these premises will be elaborated to then stipulate the spatial preconditions of the façade system.

Table 1: criteria for the facade structure (Research Plan, 2024)

Structure
- Reduce, reuse, repair, remanufacture, refurbish, recycle. - Components approach - Open building/ shearing layers stewart brand - Demountable, universal connections - As independent as possible: when cassette a is removed, b can stay - Casette system - Hoisting equipment - Low tech - Prefabrication - Standardization

Façade as a 2D plane

The notion of the façade as a 2D plane is a relevant one for it's spatial determination. Of course, a façade also has a third dimension; the thickness (x), but its implications are less than its width (y) and height (z) (A2.1.1). To guarantee the most flexibility (i.e. customization), the façade needs to answer the most individual demands. This means that a façade needs to be able to change for one household or tenant, whilst remaining the rest for a building. This, of course, does not exclude the option of refitting a façade for a whole building all at once. Therefore, the program of the building largely determines the spatial dimensions of the façade elements for width and height. In addition, it determines to what point the panels will be prefabricated: plug and play panels that cover a full apartment, office space or shop (A2.1.1). Exceptions here concern practicalities, for example: when a program is too large for it's façade to be lifted by crane, it can still be divided into smaller panels to be mounted. Protocol will then be to divide the panel into the grid size of the structure; from column to column. A2.1.2 shows insight into the different building elements though the different scales. These elements are given a name to organize the system respective to the interscale approach. From panels (program scale), to cassettes (individual scale), down to components (sub-individual) and single parts. If all elements on all scales allow some form of differentiation, the most versatile system is established. It can then respond to irregularities on the level of a building, a single program or even on the level of a single person.. A façade construction type called element façade uses much of these properties already and is mainly applied to glass and steel/aluminum curtain walls (figure 1). Therefore it is not only a proven concept (structurally, economically), it provides insights into the spatial design of such system. They usually follow a grid plan (y) dimension of 7,2 meters. It is a multiple of 1,8 meters and is one of the standard dimensions used in grids for larger, multi-tenant office buildings (Rijksdienst voor het cultureel erfgoed et al., 2024). Simultaneously is the 1,8 meter 'module' sized according to individual human dimensions, fitting the spatial experience in the direct human reach (figure 2). This grid also complies with criteria from dwellings and shops. It can be the rough size of a small apartment unit of ±40m², or two can make a larger apartment unit for a family of 4 with ±80m². A brief study in A2.1.3 shows the possibilities and consequences of designing with this grid size. The height (z) will be according to the floor heights. The versatility of the façade system also concerns the application on the scale of a complete building. It is the visual factor of a building to the public and urban domain, and for a large part determines its aesthetics. Different building shapes and orientations require different façade solutions. A massing study in 2.1.4 shows a couple of different general shape strategies for buildings. These possibilities are rough guidelines for the system to take into account when designing in chapter III. Premise is to allow the floorplan to have this flexibility, by favoring an open support structure as much as possible in line with open building practice (i.e. columns and beams). With existing buildings these dimensions are readily determined and a façade system should then be tailored to this.

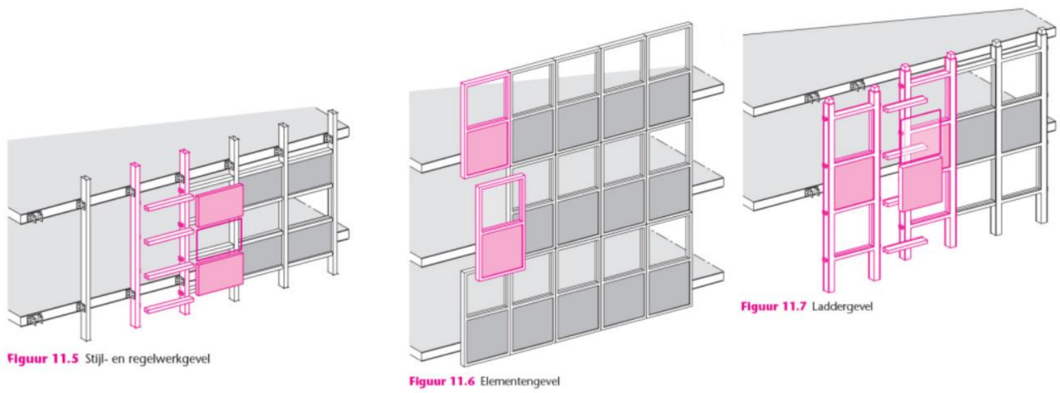


Figure 1: Types of curtain walls: element facade have the highest rate of prefabrication (Knaack & Verkuijlen, z.d.).

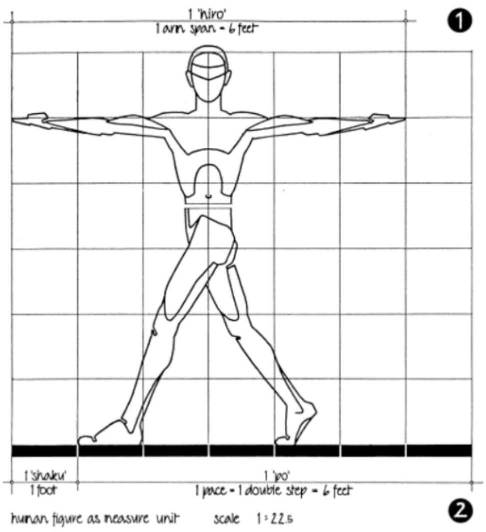


Figure 2: traditional Japanese architecture has been designed according to the human scale for centuries. 1 'po' is 6 feet ≈1,80m (Engel, 1985).

Brands shearing layers in hierarchy

1. Site	(infinite) ↓
2. Structure	(200-300 years) ↓
3. Skin	(50-100 years) ↓
4. Services	(15-30 years) ↓
5. Space plan	(5- x years) ↓
6. Stuff	(1 day - x years) ↓

Figure 3: a buildings shearing layers according to Brand, a hierarchic set extrapolated (Brand,1997) (own image).

Preconditions of standardized connections

Interlayer connections

A building is essentially a highly complex composition of interrelated layers with each their own functions and lifespans. This is the perspective on the built environment proposed by the

notion of open building. If sustainability is the goal, it would be logical to make these elements relate to each other as independent as possible. This way each layer can live the most of its corresponding lifespan, which is one of the circular economy goals. A layer's own functions should not be limited by the properties of the other layers. The layers most adjacent are most critical, for the façade this is the buildings support structure and the space plan (partition walls, connection to outside space, et cetera).
If the shearing layers as proposed by Brand (1997) are solely viewed upon their lifespan, a hierarchical set can be extrapolated (figure 3). In case of the façade, in general only the buildings support structure has a longer lifespan (site excluded, since it has (almost) no spatial consequences in connections to the façade). It creates therefore a kind of spatial template upon which the other layers can be 'filled in'.
A place where the façade and structure always meet and connect (both new construction and renovation), is at the edge of a (structural) floor or on the sides of beams. Here the main mounting will take place. The advantage of this approach is that the façade can take exceptional conditions in the support structure into account: double height floors, double grid spans, enclosures of building perimeter, et cetera (A2.1.1). Since all forces exercised on the façade are transferred into the structure, the connections require significant strength. All connection types are also visually listed in A2.1.5.

Intralayer connections
To accomplish the flexibility in the façade system, all connections need to be identified and designed as demountable. All connection types correspond to the interscale approach described in the previous paragraph: panel connections, cassette connections, component connections, and individual part connections. Since wood is the only structural material used in the façade system (see chapter III) and it is easily processed, all intraconnections are 100% wood based. Each connection type is elaborated below from large to small scale.

- Panel connections (figure): since all cassettes are connected individually to the support structure, only a thermal, water/air proof connection is needed between the panels. This happens horizontally by half overlapping with a wood frame 'ribbon', filled with cellulose insulating mats, along the floor edge. This ribbon is attached to the floor, and subsequently is the cassette attached to the ribbon.
- Cassette connections: these connections require more structural properties to make multiple cassettes act as one panel, especially when hoisted. In addition, it is important that the between-cassette seams are air and watertight. Therefore is chosen to apply the X-fix connector: a plywood friction it connector for structural use (Salzberger, 2024). It can be demounted by drilling it out, leaving little waste.
- Component connections: the connections here are the same as the panel cassette connections, again for structural capabilities and water proofing.
- Individual part connections: these connections depend highly upon their individual characteristics, functions and loadbearing types involved. Inspiration was taken from traditional Japanese construction methods with wood, described in *Measures and Construction of the Japanese House* (1985). 4 main types are formulated for 4 different functions:
- overlapping dowel connection: between frame members for flush cassette perimeter.
- adjacent dowel connection: between frame members directed inwards of cassette.
- tangent dovetail connection: connection of anti-buckling plates to cross beam.
- perpendicular dovetail connection: connection of panel caps to panel frame.
These connections are mostly friction fit, but are also locked in by cancelling each others only remaining DoF (degree of freedom).

2.2 Materials

In this chapter the material possibilities of the faҫade system will be explored. The criteria for materiality are listed below. The spatial preconditions determined in previous chapter, in combination with the climate criteria in 3.3, offer a template where materials can be chosen for. This template (figure 4) provides the minimum for a typical faҫade formation, with materials complying with the criteria. In some cases, more options are suited for a certain part. For example, multiple faҫade finishes create more visual and aesthetic diversity.

Table 2: criteria for the facade materials (Research Plan, 2024)

Materials
- Physical properties - Mechanical properties - Fire proof - Rule: use biobased materials, only a finite (but 100% recyclable) material substitute if necessary - Manufacturing properties (embodied carbon) - Local availability materials - LCA - No or limited amount of toxics chemicals or VOCs

Most materials were found on online databases and websites, and their validity was checked by additional FSC, PEFC, EPD or other sustainability certifications. Another important factor was the vicinity of the product production (within Europe), to prevent high transport emissions. The final selected materials are listed in A.2.2.2 and comply almost completely with all criteria.

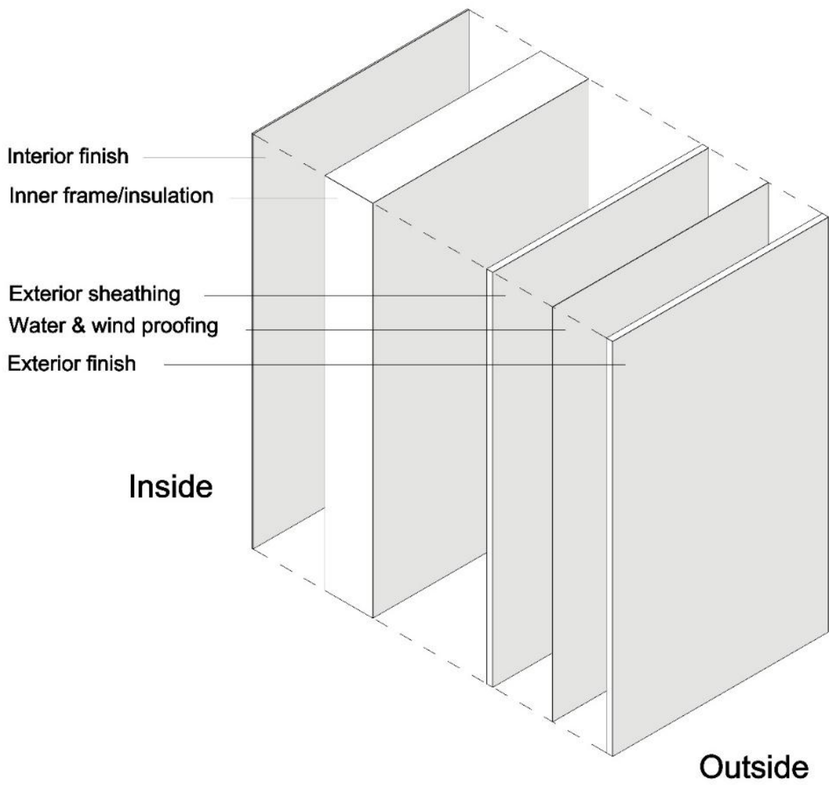


Figure 4: The material template with all minimum requirements for the faҫade (own image).

They are discussed for their choice below, per material (or layer). This chapter does not cover façade accessories (balconies, galleries).

Inside finish

The inside finish has to comply with multiple functions, and is therefor difficult to comply completely. Firstly, high fire resistance is required to a; prevent potential inside fires to spread outside and b; protect the steel connectors. Another aspect is a low vapor diffusion coefficient, allowing inside vapor to travel outside and vice versa. In contrast to normal gypsum boards, do clay boards have a very low coefficient of because of the metycellulose and wood fiber content. Lastly, the boards are very strong, and dimensionally stable. This allows clean inside finishes, that can be further finished (e.g. clay stucco with pigment).

The frame & insulation

The frame concerns the façade's structure, while also holding space for insulation. One product came forward with potential relatively quickly: pressed straw panels made of wood, biobased plywood and straw. These panels can have high R-values (with 30-40cm thickness), are almost completely biobased and are constructed of relatively abundant and nearby materials: (spruce) wood and straw. Moreover, they are vapor open and are fire resistant above minimum regulations. They are relatively lightweight and are suited for prefabrication. The plywood is needed for capping the bottom and top of the frame. Currently, the plywood is only produced in either China or South America, resulting in higher transport emissions. The frame only needs to account for bearing it's own weight and small wind loads. Other insulation options include the cellulose mats or wool mats, and are applied on more exceptional location in the façade.

Sheathing

This layer is needed for the outside of the façade to have a smooth and uniform surface, allowing outside finishes to attach more freely. It also serves as a seal between panels (in addition to improved insulative, sound and air tightness properties). Wood fiber board is readily used with straw panels, and is the main choice here. It is fairly vapor open, fire retardant in the straw panel construction and fully biobased consisting of wood fiber and lignin. This sheathing is not structural, but is dimensionally stable. It is attached to the straw panel by screws.

Water & wind proofing

This product is anthracite in color, leaving the aesthetic image fully to the facade finishes. The foil does contain polypropylene and TEEE that releases volatile organic compounds, but because of the outside placement, in combination with a vapor open façade, results in a lesser risk. The foil is waterproof but vapor open. Another point is that the material is not biobased and made from fossil raffinates, but fully recyclable. The foil is UV-resistant, protecting the materials it covers.

Outside finishes

For a diverse aesthetic appeal, multiple façade finishes were chosen. Marc Koehler differentiates three main visual façade types: monolithic, rhythmic and patched/collage. These three types were adopted, and linked to similar biobased materials. For the monolithic appeal, the Nabasco tiles and chestnut shingles were chosen that - on the building scale - appeals more as one object. Wooden cladding is suited for rhythmic patterns and can play in depth. This can concern treated wood or charred for a darker tone. Lastly, a combination of these can make a more playful, contrasting image. They could vary per panel or even cassette. The finishes are nailed/screwed onto horizontal and vertical battens, which are in turn screwed to the wood fiber boards. Other optional finishes include a planted façade and PV-integrated finishes, but are not elaborated in this research.

Connectors

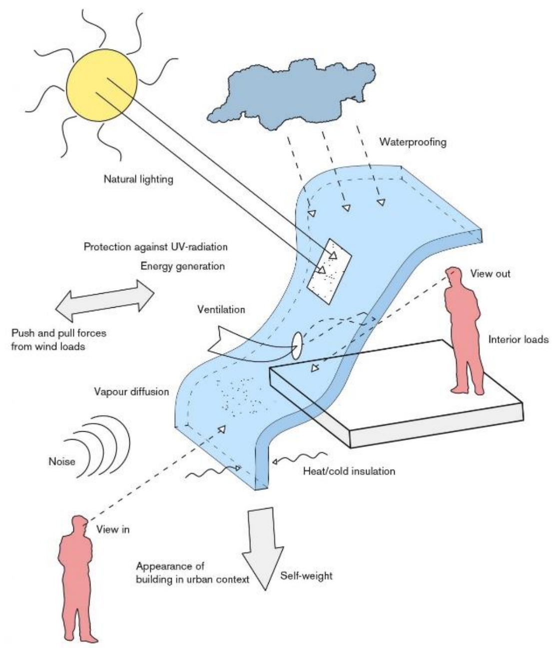
Connectors are divided into two types: for the strawpanel frame and for the further in- and exterior finishes. The strawpanel connectors are largely biobased and consist of dowels, together with the X-fix connectors. The X-fix connectors will probably – like other plywood produchts – contain about 2% of urea formaldehyde glue. Other connectors are regular screws, nails and nuts and bolts of stainlesss steel.

2.3 Climate and experience

The faҫade plays an important role in the building's climate regulations. It protects us against heat, cold, wind, rain and everything other outside phenomena. It is the reason facades are tailored to their respective climate. The Netherlands has a moderate maritime climate (type

Table 3: criteria for the facade climate and experience (Research Plan, 2024)

Climate and experience
- Thermal insulation - Sound insulation - Water and wind tight - (direct or indirect) Daylight entry/ % glass and shading - Rainwater drainage - Heating/cooling - Vapor regulation (vapor open) - Integration of vegetation - integration of animal habitats (insects, nesting boxes) - Water buffering - Outside space (French balcony, balcony, loggia, entrance gallery) - Thermal accumulative capacity/phase shifting - Ventilation/openable facade elements



Cfb), met relatively mild winters and mild summers. It rains year round with 800-900mm per year and wind comes primarily from the SouthEast direction. Another impoartant aspect is the local ecology types that occur. All these factors together form the boundary conditions in which the facade has to be developed. Figure 5 shows the relation between the faҫade and the climate.

How the faҫade system performs in terms of climate regulation, is greatly dependent on it's structural and material properties. Many aspects have already been partially covered in this

Figure 5: All functions of a facade: the climate perspecitve
(Knaack & Verkuijlen, z.d.).

research, for example the water and wind proofing in paragraph 2.2, and affect the climate performance. First, some properties of two standard cassette types will be discussed. Type one is a closed cassette, type two is a cassette with floor-ceiling height opening. They are the most extreme in their performances. Type three is a cassette with façade opening, plus a parapet, with performances in between the other two types. Finally, some exceptions in the standard cassette types will explored to accommodate to all the possible needs in the façade.

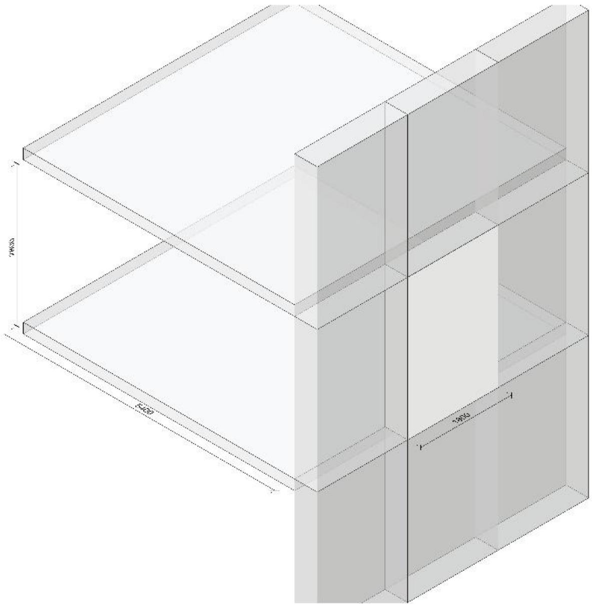


Figure 6: cassette type one (own image).

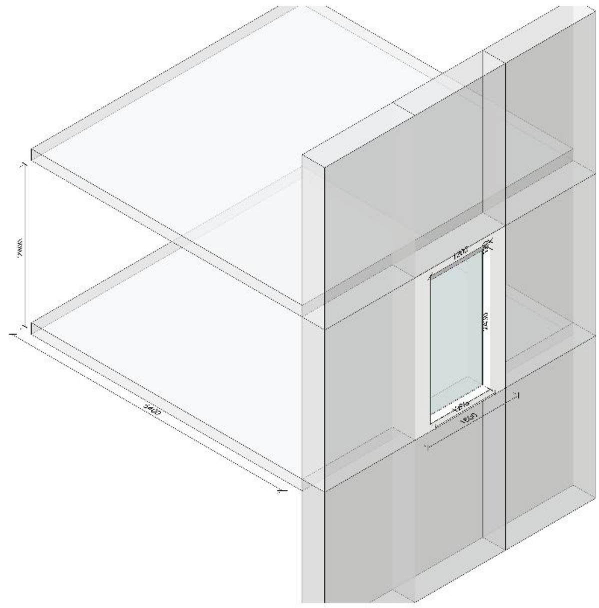


Figure 7: cassette type two (own image).

Water and wind proofing, waterdrainage

The modularity of the system requires an unconventional high flexibility between building elements. Here arises an issue, because with high flexibility of many elements come more gaps and seals that can create potential water and air leaking. These so called tolerances are also higher with biobased materials In this regard, two main sealing areas and solutions will be discussed.

The first concerns the horizontal sealing between two stacked cassettes (figure 8 on the left). This area makes use of the pulling force of the steel L-profile, pulling the cassettes onto the support structure. Both cassettes half-overlap with the ribbon. Between the ribbon and the cassette is a wool filt strip to neutralize tolerances. Additionally, are wood fiber boards placed as an extra outer ribbon along the same area on the outside. They are friction fit by custom 3D printed PLA plugs, which can be demounted by pulling out and are fully reusable.

Vertically, the sealant again makes use of the pulling forces of the connections (figure 8 on the right). Now, the X-fix connector between two cassettes pulls them together, with a wool filt strip in between.

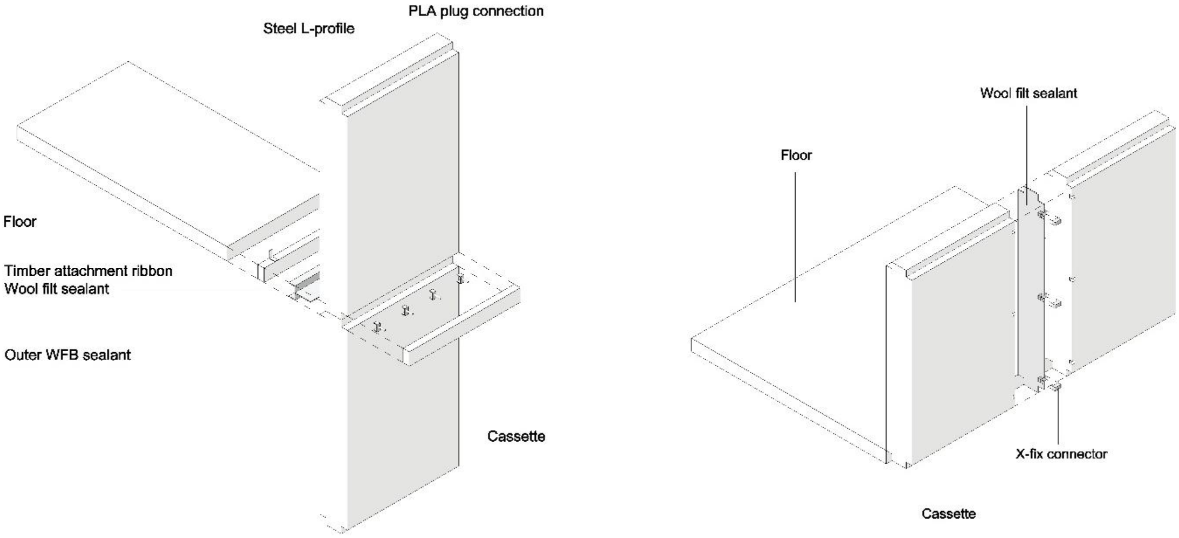


Figure 8: The vertical and horizontal sealing between the cassette modules (own image).

Rainwater drainage is facilitated by drainage pipes. Their diameter and placement is dependent on the roof type and total roof surface. An important note is that, to allow the façade system it's flexibility, the drainage pipes do not run along the façade, but through the core of the building. Likewise, this allows for potential reuse of rainwater.

Vapor diffusion en condensation

These physical phenomena can cause the development of mold, freezing of construction materials, unhealthy indoor environments and blocking of sight through windows. Therefore, it is important to see how these materials would react under the circumstances of the Dutch climate. For condensation, both cassette types are examined, since they are both affected. However, for the vapor diffusion only the closed casette is examined, since it concerns only the façade structure. The calculations are listed in the appendix (A2.3.2).

Vapor diffusion is the horizontal transportation of water vapor through a construction, caused by a difference in vapor pressure on either side of the construction. Conclusion:

- Beacuase of the high thermal resistance of the structure, surface condensation will not occur, even in the critical winter period.
- Internal condensation does occur at the critical winter period, but is not critical as such to cause any harm to the façade construction or its users.

Thermal conductivity

The main insulating materials are the straw and wood fiber boards. Thermal resistance of a façade $R_c = \frac{thickness}{\lambda}$ is measured in m²K/W. This depends on the material thickness (in meters) and thermal conductivity coefficient (λ in W/mK): straw: 0,045 and wood fiber board (WFB): 0,038 (see A2.2.2). In this case, we take HR+++ glass with a U value of 0,7 W/m²K. Additionally, has to be accounted for transitional resistance on the inner ($R_{si} = 0{,}13$) and outer ($R_{se} = 0{,}04$ façade surface. Thermal bridges due to the wood frame are here marginalized, but in the design should be optimized for thermal and sound insulation by seperation of the frame members!

Type one: $R_{total} = R_{si} + R_{straw} + R_{WFB} + R_{se}$ = 0,13 + $\frac{0{,}4}{0{,}0645}$ + $\frac{0{,}05}{0{,}038}$ + 0,04 = 7,68 m²K/W.

Type two:

This type consists of multiple façade elements in parallel, so an average insulation value can be determined. The U value of all elements need to be determined first: $U = \frac{1}{R_{total}}$. For the element with straw and WFB: $\frac{1}{7{,}51} = 0{,}13$ W/m²K. $\overline{U} = \frac{U_{window}A_{window+}U_{straw+WFB}A_{straw+WFB}}{A_{total}}$
$\overline{U} = \frac{0{,}7 \bullet 2{,}92 + 0{,}13 \bullet 2{,}48}{5{,}4}$ = 0,44 W/m²K. So the average insulation value is:
$R_{total} = 0{,}13 + \frac{1}{0{,}44} + 0{,}04$ = 2,45 m²K/W.
Type two is obviously a weak spot in the thermal resistance. The ratio of open/closed façade surface should be kept in mind when designing a building.
The façade system does not contain heating or cooling installations.

Ventilation
Ventilation is facilitated in type two only, since the grilles are placed along with façade openings. This is a common building practice, because both daylight and ventilation requirements usually concern the same spaces, like living rooms, bedrooms, offices, et cetera. Additionally, all windows and doors applied can be opened for an increased ventilation capacity. The grille used is the following:
https://www.duco.eu/nl/producten/raamventilatie/ventilatie-en-zonwering/ducotwin-120-zr-ak.
The ventilation capacity is 14,5 dm³/s/m grille.The ventilation capacity per person is about 7 dm³/s. The ventilation grill is as wide as the façade opening: 1,2 meters. This means the ventilation capacity per cassette is 1,2 • 14,5 = 17,4 dm³/s. This is sufficient for ±2,4 persons, without creating an overpressure on the grille. Determining if this is suffcient for a building, strongly depends on other aspects - like program, space plan, ventilation type (A,B,C,D) - and their design. The grille is placed above the sunscreen, preventing ventilation obstruction.

Sound
For sound insulation properties, many factors play a role and can influence the perfomance drastically. In A2.3.1 This test was exclusively done for airborne sound, since that is what the façade system primarily experiences. The required calculations displayed, as proof the performances. All information about the sound requirements and performances were used from the Bouwfysica book, chapter 11 (Van Der Linden et al., 2018). The calculation was executed for two main situations, to demonstrate the versatility:
- type one: standard closed cassette
- type two: cassette with floor-ceiling window

In short, only type one meets the minimum requirements needed for dwellings (≥ 35dB) and offices (≥ 40dB). A building with only cassettes type two will not be sufficient, and need to be alternated with type one to some degree. Situations with smaller windows will (intuituvely) have a higher insulation performance and meet the criteria as well.

Climate façade finishes
These outside finishes include two options: a green façade (including nesting boxen for birds, bats or insects), and PV panels.
The green façade finish can have multiple advantages: increased biodiversity, filtering air pollutants, buffering rainwater, decreasing temperature of microclimate and increased thermal/acoustic insulating performance. There is also the possibility to add nesting boxes between the vegetation panels (see A.2.3.2). The waterbuffering is 20L/m² façade surface at a maximum. Like in practice, they can be placed on the most top row of the green layer so that it is out of human reach. Another important factor in determining the application, is where the cassette is placed in the façade. If it is placed under a balcony or gallery, sunlight will be significantly reduced and the placement might be adjusted. This is less of an issue with railings, since they are executed in thin steel wiring.
For the PV-panels, a similar approach to the placement of nestingboxes was used. Due to the

risk of damaging the PV-panels by human activity, they have to placed somewhat out of human reach.

Daylight entry and sunshading

For daylight entry, two main window types are implemented in the façade system: the floor-ceiling window (figure 7) and the window with parapet. The floor-ceiling window is also suitable for doors. Of course, depending on which window type is used, different sunlight entrance values are established. The glass used in the façade is HR+++, which reflects a high amount of the suns heat (g=0,6).

For sunshading, a drop-arm sunscreen is chosen for multiple reasons (see ventilation paragraph for exact product). The function of the sunscreen is to obstruct any heat from enetering the building and to prevent blinding the inside users. First of all, is this a system that is placed outside, making the reflected and absorbed heat to be released to outside air instead of inside. Secondly, does this system allow for (partial) views outside. Thirdly, is there a possibility to automatically fold or unfold, making it suitable for dwelling, office and commercial spaces. The share of the total amount of energy from sunlight that eventually reaches inside, is called sunlight factor *g*. For HR glass in combination with the drop-arm screen an average *g*-factor of 0,15 can be reached (Van Der Linden et al., 2018). Since the final performance of the façade openings and sunshading is highly dependent on other design aspects as well (e.g. façade orientation, building shape and dimensions , et cetera), no specific calculations are made here. A study on sunslight entrance in combination with the sunscreen, however, does reveal the performances during all seasons of the year in the Netherlands (A2.3.3). It reveals that in summer almost all heat is blocked from entering, preventing high energy consumption for cooling. In winter it can block sunlight to prevent blinding, but simultaneouslu enter the opening and reduce energy consumption as a result of heating.

In A2.3.4 some verification calculations were executed concerning the phase shifting values and the thermal accumulation of the façade system. This shows that, although the hase shifting is more than enough (6,5 days), thermal accumulation is relatively weak with approximately 1,5 hours. This could create problems, and should be accounted for when designing a building with this system (i.e. with cooling methods).

Climate type matrix

The façade system has to offer a wide range of custom options in relation to the climate. This is realised through the variety at the component scale, and are listed below. Fundamentally, are the three types of cassettes accompanied by additional options in relation to the climate. In A2.3.5 are all options listed in a matrix.

III. The Design

See design booklet for more information.

IV. Conclusion

In this paper, an extensive research was conducted by investigating the development of a façade system using the framework of architectural tectonics. This method allowed the study to focus on three major pillars in the façade design, being the façade structure, the materials used and the study of climate phenomena projected on the façade. These three topics were linked to their respective sustainable construction paradigms, to aim for an integration of more sustainable construction practices. In conclusion, could be stated that all topics within the sustainability paradigms were touched upon in this research. The theoretical basis (chapter II) produced the general design preconditions, to elaborate a façade system in the design (chapter III). An important note is that there is not one correct way of designing a façade system with these parameters. Design is always intuitive in some part.

A relatively high degree of modularity was achieved, by a) safeguarding standardized connections types, b) examining different customizations in the climate design, c) taking

inventory on a variety of renewable construction materials and d) a consistent operation on different scales. This resulted in a coherent overall façade system.
The research covered all three required domains quite extensively, yet the final options might still be considered limited. Relevant follow-up research would be to explore more complex façade shapes, to expand the system's application field. This could include more inclined, organic or even parametric design solutions. The use of more and different biobased materials is also a field for investigation. The research result is therefor more a general design template, rather than the outcome for one specific design solution.
There is also room for optimization in the façade's accessories, like the balcony and outside gallery, which include mostly circular principles but is not optimized more for biobased potential.

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Appendix

A.2.1 Structure

A2.1.1 The façade as a 2D plane and the relationship to the support structure

A2.1.2 The interscale approach

A2.1.3 Floor plan study of programs for grid dimensioning

A2.1.4 Scale 1: Building typology

A2.1.5 Connection types

A.2.2 Materials

A2.2.2 Materials table

A2.3 Climate and wellbeing

A2.3.1 Acoustic insulation calculations

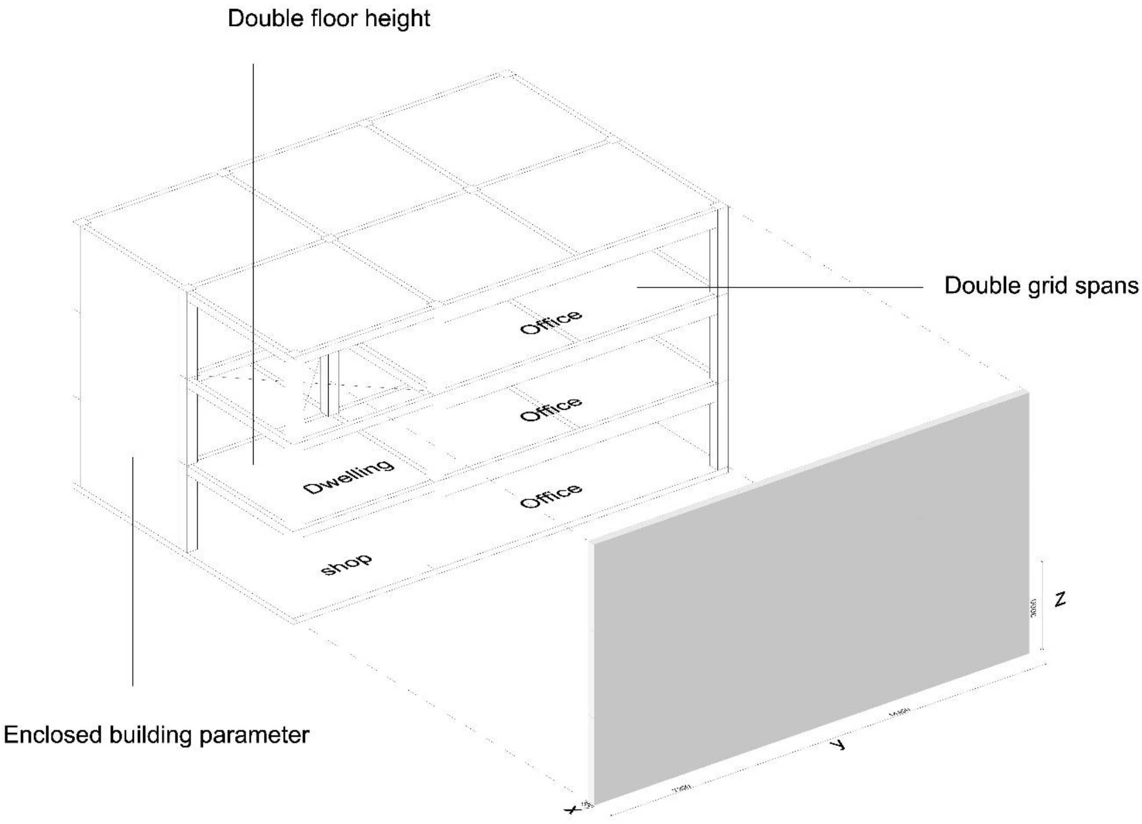
A2.3.2 Vapor diffusion, surface an internal condensation

A2.3.3 Sunlight entrance

A2.3.4 Thermal accumulation & phase shifting

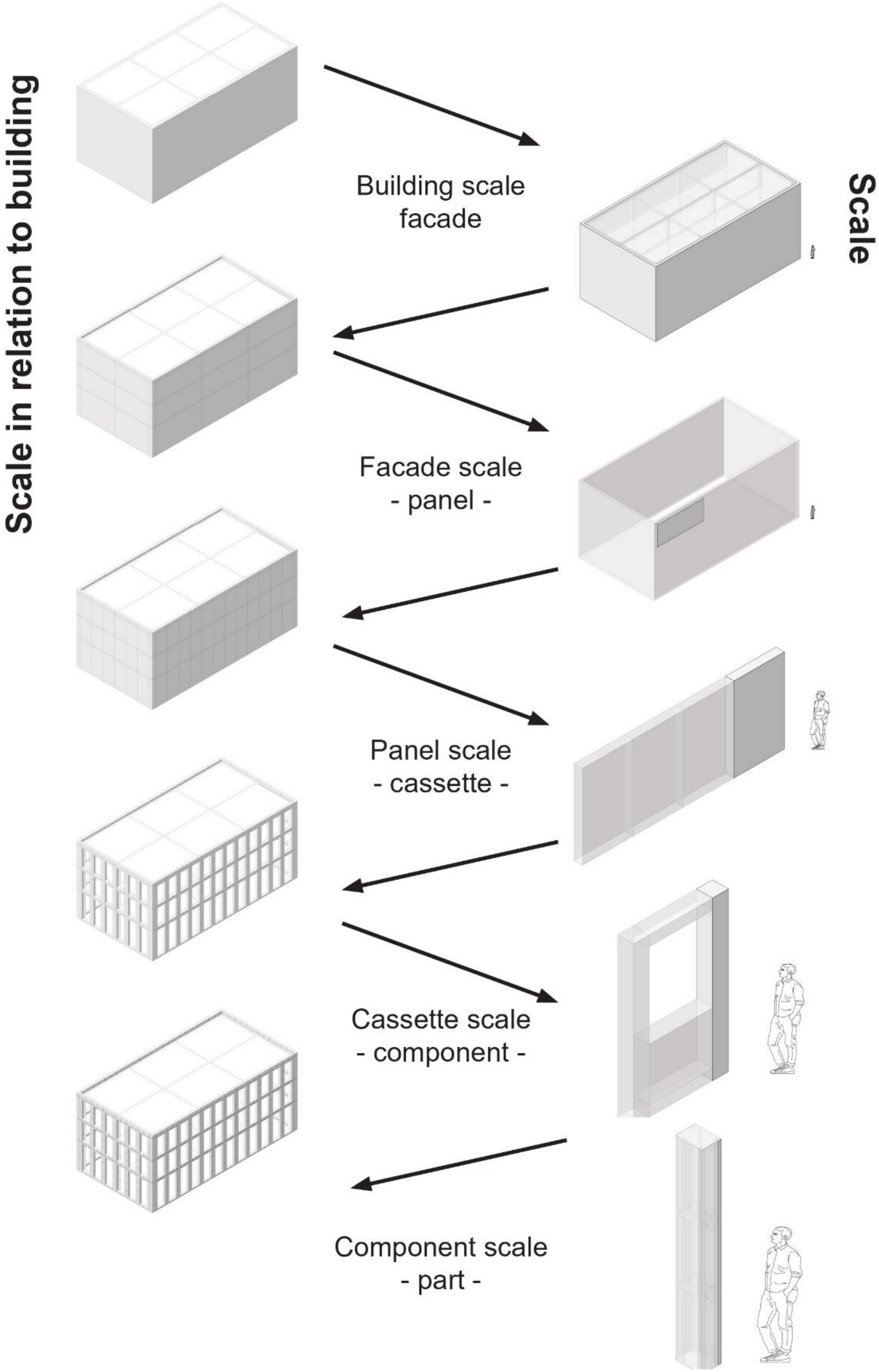
A2.3.5 climate variables in façade matrix

A2.1.1 The façade as a 2D plane and the relationship to the support structure



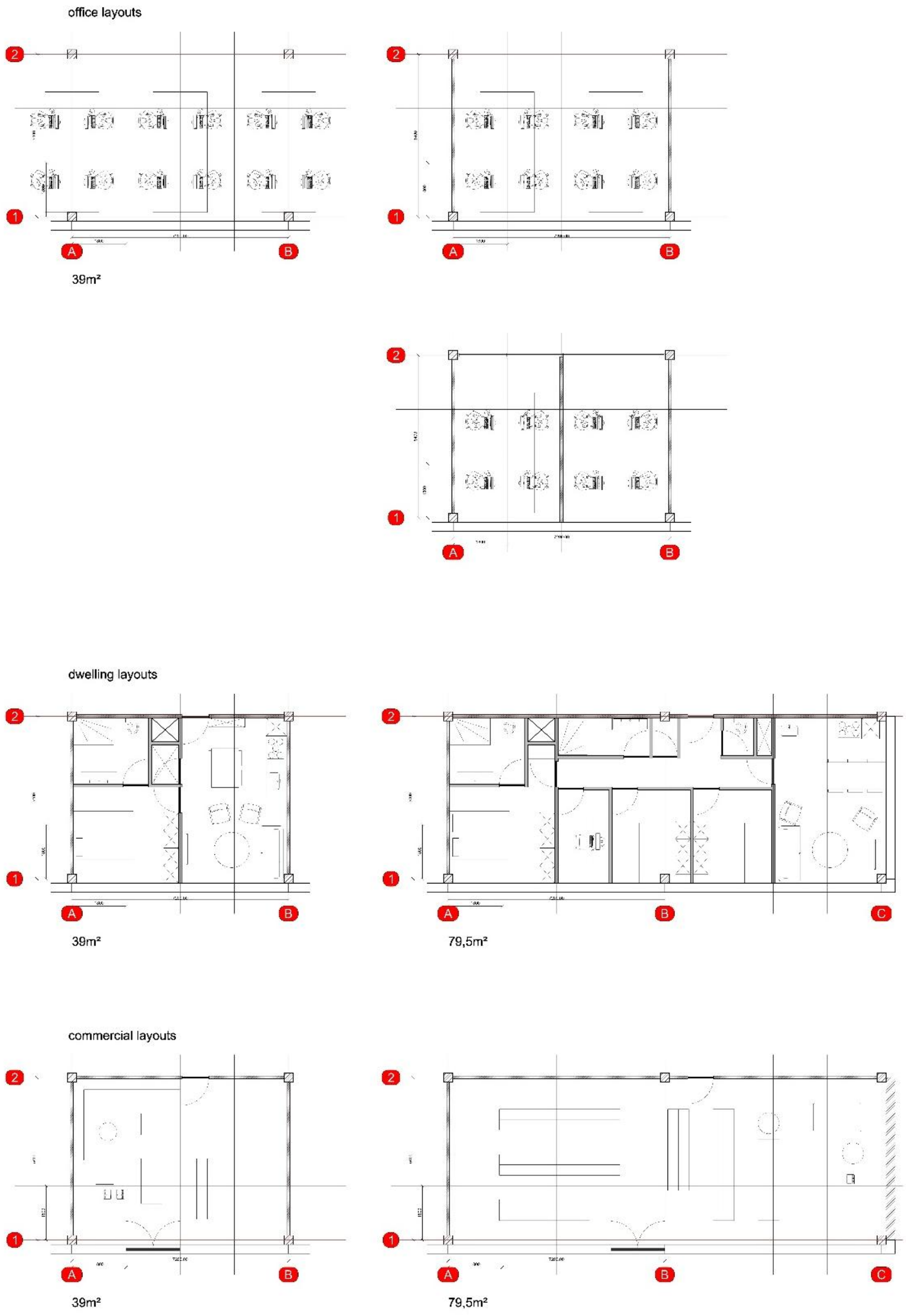
The dimensions of the façade are dependent on the underlying support structure. It should therefore be tuned to this structure. Moreover, is it crucial for the façade to also be able to adapt to exceptions in the support structure, like longer spans, voids in floor areas and enclosed building parameters. Because of floor edges and beams being the most consistent element along building perimeters, this is where the façade will mount to.

A2.1.2 The interscale approach



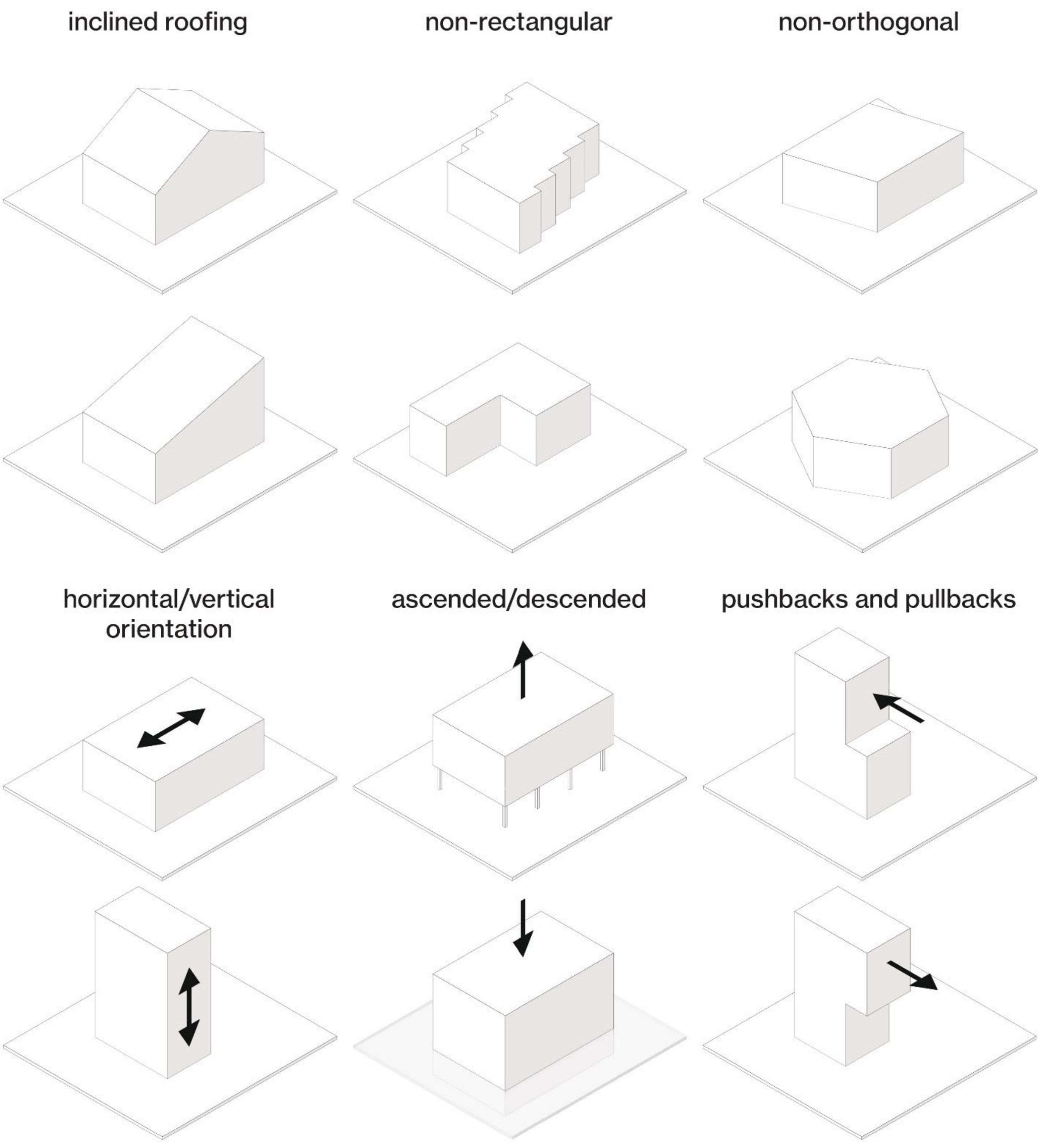
The interscale approach visualized. Ranging from interventions on the scale of a complete building, all the way down to single parts. Central in the approach is the cassette, which operates the closest to the scale of the human reach. When differentiation is created on each scale, but within this standardized system, the best modular result can be accomplished.

A2.1.3 Floor plan study of programs for grid dimensioning



A brief study of the three designated building programs and their required spatial layouts. It shows multiple possibilities per program, while all conforming to the same grid size of 7,2 meters. This ensures that one façade system is compatible with multiple building types, or that multiple programs can be mixed in one building. In this case, a grid depth of 5,4 meter is chosen, but - given the façade's flexible properties - can be any multiple of the 1,8 meter module.

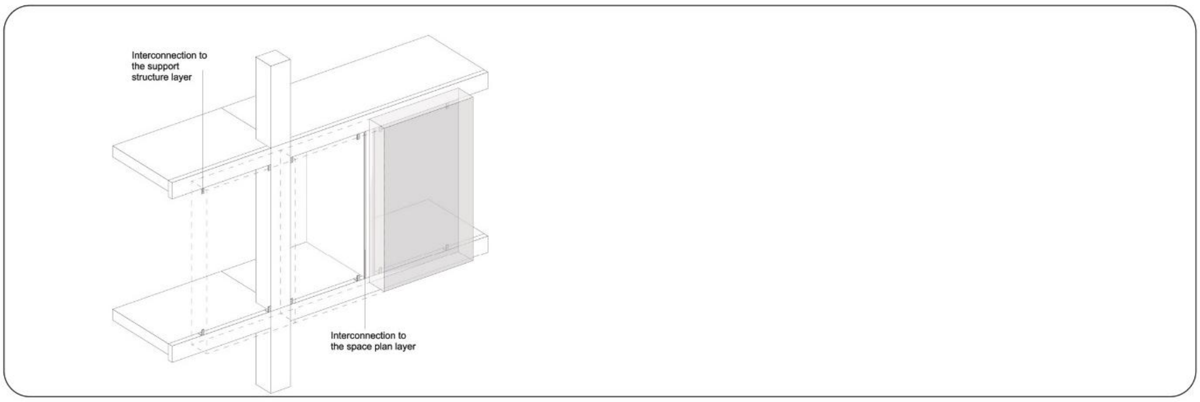
A2.1.4 Scale 1: Building typology



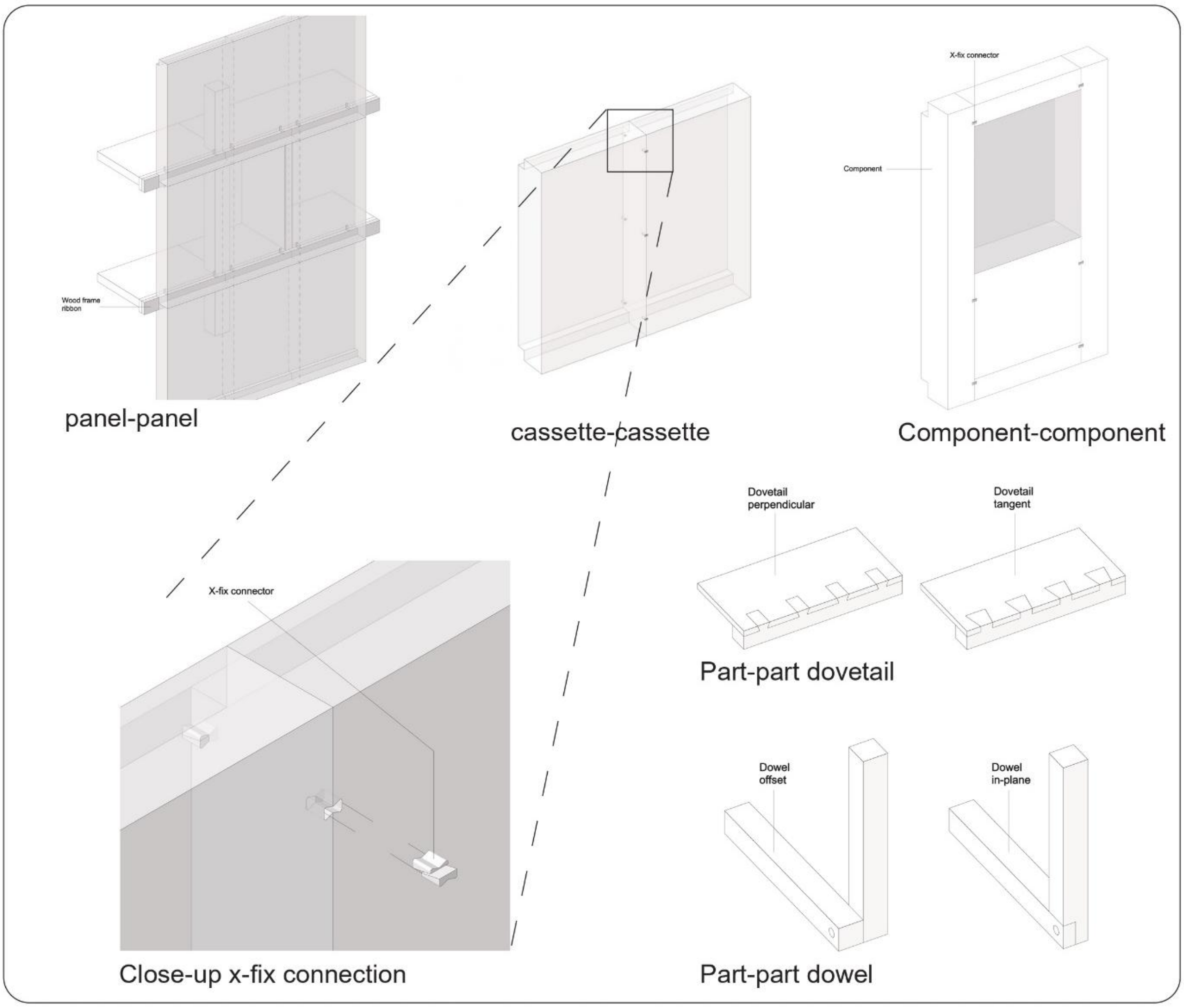
Above is a massing study to determine the application field of the system. Limited in shape for organic and inclined facades, it still allows for a variety of design options. The options vary from inclined roofs, non-orthogonal shapes to façade with set-backs or overhangs.

A2.1.5 Connection types

Interconnections



Intraconnections



The interlayer and intralayer connection types. All connections are demountable and made with renewable materials as much as possible. All connections are for structural purposes. However, the connections between cassettes and components are also for thermal, water and wind sealing. The origins of applied connection types used ranges from advanced carpentry technology , to ancient Japanese timber building practices.

A2.2.2 Materials table

MATERIAL	COMPOUNDS	AVAILABILITY/SCALABILITY	CO2 Footprint (kg/kg) Calculated with edupack	FIRE PROOF	THERMAL EXPANSION (µstrain)	VAPOR DIFFUSION coefficient (wet cup, 50% RH, 23 C) with correct thickness	Thermal conductivity coefficient (W/m K)	Av. Density (kg/m³)	Sounds insulation value (dB)	Regenerative rate (years) for at least 1m³
INSIDE FINISH										
Lemix clay boards	Clay, wood fiber, jute fiber, metycellulose	Available in the Netherlands, produced in Germany.	0,064	Class A1-S1-d0	0,01mm/m/K	Av. 7,5	0,353	1450	52 dB	Compostable, recyclable
STRUCTURAL										
Spruce wood	100% natural wood	Available in the Netherlands, Austria, Switzerland, Scandinavia and Baltic area.	0,352	120 min (with ecococon), class B-s1, d0	2-11 *10^-6	100	0,24	510	54 in ecococon	20-40
Multiplex (stabiofloor)	90% birch/poplar wood, 10 % bone glue	Currently south America/China	0,6	Class D- s2, d0	6-8 *10^-6	70	0,13	550	n.a.	Abbatoir pigs: 0,5 (approx. 28 pigs for 1m³ of multiplex). Birch regrows in 20-30 years

										and poplar in 15-20 years.

INSULATION										
Straw insulation	100% straw	Available in all of Netherlands, assembly in Slovakia	0,8	120 min Class B-s1, d0	n.a. (2mm tolerances)	1,4	0,0645	110	54 in ecococon	1
Cellulose mat insulation	Shredded Cellulose, fire resistant natural salts	Thermal: Sweden icell Acoustic: Nederland cyclin	1,22	B-s1, d0	n.a.	1,1	0,036	85 (acoustic mat) 32 (thermal mat)	45 with 50mm acoustic mat	0
Isolena Wool insulation	100 % wool	Available in Netherlands, German company	1,35	Class C or D, but retardant in wood stud construction	n.a.	1	0,037	23	50-60	50

SHEATHING										
Wood fiber board (WFB) (pavatherm)	Wood fiber , lignin	Available in Switzerland	Positive, not specific.	Class E, but retardant in wall construction	10-15	3	0,038	110	21	20-40

WATER AND WIND PROOFING										
Polytex Pro	Polypropylene microfiber, high density polyethylene (hdpe)	Available in the Netherlands, made in Luxemburg	2,178+4,71	E	Unknown, but resistant from -40 to +100 C and flexible	44,44	0,47	145 g/m²	n.a.	Not regenerative, but recyclable

OUTSIDE FINISH										

Nabasco façade tiles (10010)	Natural fibers, natural resin (85%biobased with 8010)	Produced and developed in the Netherlands	0,6	B-S1, d0	10-15	N.a.	N.a.	1700	n.a.	1 year
Chestnut shingles	100% wood	Available in the Netherlands, wood grown in France	0,3623	F-s1-, d0	2-11	n.a.	n.a.	480	n.a.	20-40
Charred wooden planks (accoya)	100% wood (Pinus radiata)	Available in the Netherlands, wood grown in New Zealand.	CO_2 negative for whole life	Class D or E, depending on thickness	0,8% from 20 °C (65% RV) dry to wet	n.a. (ventilated)	n.a.	512	n.a. (ventilated)	25-30 years (50 years service life)
OPTIONAL OUTSIDE FINISHES										
PV integrated panels	Black/dark blue	Dimensions: 1800x600cm (5 per cassette)	Supplier: Gevel zonnepanelen voor prachtige gebouwen | Solarix							
Planted facade	green	Dimensions: 555x635mm (modular)	Supplier: SemperGreenwall Outdoor – De groene oplossing voor uw gevelproject							

CONNECTORS										
Stainless Steel screws/nails	±15% chrome, ±0,25% carbon, ±15% nickel, iron, for example	Available in the Netherlands, made in Germany	s± 5-7, with roll forming, foil rolling, wire drawing,	n.a.	9-11	n.a.	25-30	7720-7880	n.a.	Not regenerative, but recyclable

	martensitic AISI 416 annealed		coarse and fine machining							
Steel connector		Available in the Netherlands, from Tata steel Ijmuiden. many suppliers				n.a.			n.a.	Not regenerative, but recyclable
Wooden dowel	Beech	Available in Netherlands, from Switzerland	0,4285	Class B-s1,d0 (in ecococon)	33-44 *10^-6	n.a.	0,15-0,17	755	n.a.	30-60
X-fix wood connector	98% Birch, 2% urea formaldehyde	From Austria, available in the Netherlands	0,582	Class B-s1,d0 (in ecococon)	6-8	n.a.	0,3-0,36	750	n.a.	20-40

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A2.3.1 Acoustic insulation calculations

This calculation comprises the airborne sound insulation test of the two relatively simple façade types:
- type one: a closed cassette of 1,8 x 2,8 x 0,45 meters
- type two: a cassette (1,8x2,8x0,45m) with a floor-ceiling height window/door (1,2x2,43m) and HR+++ glass with thickness 4-6-4mm. (window frame marginalized) including a ventilation grill.

Important additional information:
- the outside façade surface is flat, and has the same m² as the inside surface: S=5,04m² and $C_g = 0$
- The façade consist mainly of straw and wood, with wood fiber board
- The depth of the sound receiving space (inside) is 5,4 meters, and is 2,8 meters high: V= 1,8 x 2,8 x 5,4 = 27,22m³, with type two the window sill volume is added to a total of 29m³.
- The reference reverberation time for offices, commercial space as well as dwellings is T_0 = 0,5s
- the sealing is doubled and is executed well: K=1•10^{-4}
- acoustic bridges are marginalized
- The window's insulation values per octave band are based on measurements by Peutz; Microsoft Word - R 833-1-RA.doc

In this study, double pained glass was measured. I could not find acoustic insulation values for HR+++ glass.
- a ventilation grille of the window's width is used in type two. Product: Ducotwin 120 CAP AK. The height is 120mm, the length is 1,2m and the $D_{n;e} = 34$ [dB] (the acoustic insulation loss for ventilation). Weight was estimated on company information: 5 kg without sunscreen. DucoTwin 120 'ZR' AK(+)

These are the extremes: the best and worst performing cassette type. Other façade finishes – that could increase the final result - are excluded in this test.

The façade types (in this situation) consist of straw (110 kg/m³), spruce wood (510 kg/m³) and wood fiber board (WFB) (110kg/m³) (see A2.2.2).
Type one: The wood framing takes up roughly 20% of the cassette surface, making the remaining 80% a straw surface.
Type two: the window is 58%, ventilation grill is 2,9% with wood being 20% and straw the remaining 19,1%
The WFB is not placed parallel in the cassette, but over the straw-wood panels: in series without cavity. The straw panel has a thickness of 0,4m and the WFB has a thickness of 0,05m. In this coarse, the series can be viewed as one material with an average density. Thus:

- for wood-WFB counts: (0,4•510+0,05 •110)= $209{,}5\ kg/m^2$
- for straw-WFB counts: $(0{,}45 \bullet 110) = 49{,}5\ kg/m^2$ both straw and WFB have same density

Now, the sound resistant properties can be calculated for each material combination per octave band with their respective middle frequencies. It is calculated with the following formula;

$$R = 17{,}5\log(m) + 17{,}5\log\left(\frac{f}{500}\right) + 3$$

Where m is the is mass per m² and f is the frequency in Hz.

Octave band [Hz]	125 i=1	250 i=2	500 i=3	1000 i=4	2000 i=5	R_A [dB]
Wood-WFB	33,08	38,35	43,62	48,89	54,16	43,62
Straw-WFB	22,12	27,39	32,66	37,92	43,19	32,66
HR+++ glass	20	31,5	39	48	46,5	26,9
Ventilation grille	19,42	24,69	29,96	35,23	40,50	29,96
Spectrum roadtraffic noise (K_i)	-14	-10	-6	-5	-7	

Now, the total sound insulation value of the composed façade types can be calculated with the following formula:

$$R_{A;} = -10\log(\sum_{j=1}^{n} \frac{1}{S_{tot}}\left(S_j 10^{\frac{-R_{j;A}}{10}} + 10 \bullet 10^{\frac{-D_{n;e}}{10}}\right) + K)$$

n is the number of façade elements, S_j is the element specific surface area in m².

Type one:
$R_A = -10\log(\frac{1{,}008}{5{,}04}10^{-4{,}362} + \frac{4{,}032}{5{,}04}10^{-3{,}266} + 10^{-4})$ = 32,66 [dB]

Type two:
$R_A = -10\log(\frac{1.008}{5{,}04}10^{-4{,}362} + \frac{0{,}963}{5{,}04}10^{-3{,}266} + \frac{2{,}923}{5{,}04}10^{-3{,}7} + \frac{0{,}144}{5{,}04}10^{-2{,}996} + 10 \bullet 10^{\frac{-34}{10}} + 10^{-4})$ = 23,62 [dB]

Now taking in environmental factors, like volume of the receiving space, the façade surface structure and the reverberation time, the insulation value in relation to it's environment can be calculated. The formula is:

$$G_i = R_A + 10\log\left(\frac{V}{6T_0S}\right) - 3 + C_g$$

Type one:
$G_i = 32{,}66 + 10\log\left(\frac{27{,}216}{6 \bullet 0{,}5 \bullet 5{,}04}\right) - 3 + 0$= 32,21 [dB]

For traffic noise, the sound insulation value becomes adjusted. Sound insulation values, corrected per octave band for outside traffic in [dB]:

Octave band [Hz]	125 i=1	250 i=2	500 i=3	1000 i=4	2000 i=5
$R_{A;i}$	22,92	27,99	32,66	36,35	38,57
G_i	22,47	27,54	32,21	35,90	38,12
K_i	-14	-10	-6	-5	-7
$G_i - K_i$	36,47	37,54	38,21	40,90	45,12

Finally, these values need to be characterized with the formula:

$$G_{i;k} = G_i - 10\log\left(\frac{V}{6T_0S}\right)$$

$G_{i;k} = 32{,}21 - 10\log\left(\frac{27{,}216}{6\bullet 0{,}5\bullet 5{,}04}\right) = \mathbf{29{,}7\ [dB]}$

Type two:

$G_i = 23{,}62 + 10\log\left(\frac{29}{6\bullet 0{,}5\bullet 5{,}04}\right) - 3 + 0$= 23,45 [dB]

Sound insulation values, corrected per octave band for outside traffic in [dB]

Octave band [Hz]	125 i=1	250 i=2	500 i=3	1000 i=4	2000 i=5
$R_{A;i}$	19,4	23,04	23,67	23,84	23,87
G_i	19,23	22,87	23,50	23,67	23,70
K_i	-14	-10	-6	-5	-7
$G_i - K_i$	33,23	32,87	29,50	28,67	30,70

Finally, these values need to be characterized with the formula:

$$G_{i;k} = G_i - 10\log\left(\frac{V}{6T_0 S}\right)$$

$G_{i;k} = 22{,}50 - 10\log\left(\frac{29}{6\bullet 0{,}5\bullet 5{,}04}\right) = \mathbf{19{,}67\ [dB]}$

As stated in the table for insulation value per octave band of type two, is this type underperforming. Minimum requirement is 35 [dB]. This can be explained through the relative low density of the façade construction. But keep in mind, that this situation is with all ventilation grills open. Another aspect is that additional finishes like gypsum boards and cladding are not taken into account. This will also slightly increase the insulative performances.

For application around railway traffic this value should be subtracted with 3 dB, and with 2dB for air traffic.

A2.3.2 Vapor diffusion, surface an internal condensation

Methods used are from Van Der Linden et al. (2018)

Surface condensation
Surface condensation is the phenomenon where water vapor turns into water droplets on the inside surface of a façade, due to the temperature difference between inside air and the inside façade surface. Whether surface condensation occurs, is dependent on the temperature difference of inside and outside, and the thermal insulation performance of the façade. We know for type one: R_{total} = 7,68 m²K/W and type two: R_{total} = 2,45 m²K/W (see section 2.3 thermal conductivity). This phenomenon primarily happens in winter times, the following siuation is calculated: outside: -10 °C (winter), inside: 21 °C.

The formula for calculating the inside surfacde temperature of the façade:

$\Theta_{s;i} = \Theta_i - \frac{R_{s;i}}{R_{total}} \bullet (\Theta_i - \Theta_e)$ [°C]

Furthermore, to see if condensation will occur or not a factor is used. This factor should be ≥ 0,65 and is calculated with the following formula:

$$f_{ri} = \frac{\Theta_{s;i} - \Theta_e}{\Theta_i - \Theta_e}$$

Type one:

$\Theta_{s;i} = 21 - \frac{0,13}{7,68} \bullet (21 - -10) = 20,48$ [°C]

$f_{ri} = \frac{20,48 - -10}{21 - -10} = 0,98$ √

Type two:

$\Theta_{s;i} = 21 - \frac{0,13}{2,45} \bullet (21 - -10) = 19,36$ [°C]

$f_{ri} = \frac{19,36 - -10}{21 - -10} = 0,95$ √

Vapor diffusion and internal condensation
Similar to the surface condensation, can water vapor also collect inside the façade and turn into water. This is problematic, because of the risk of a) material rot (especially with bio-based materials), b) freezing of construction materials and c) a decreased thermal performance. The method of Glaser offers a framework to determine the occurrence of condensation in the structure. Here, again the situation of -10 °C (winter) outside and 21 °C inside is taken. Additionally, the relative humidity (RH) of both inside and outside are required. For outside, the average RH in winter in the Netherlands is around 85% (source= Klimaat kaart vochtigheid Nederland | Weerplaza.nl). Inside an average RH of 50% is desirable. Materials of importance in the vapor diffusion include the clay board, the wood fiber board (WFB), the straw insulation and the water/windproof membrane. Furthermore, the vapor resistance value [μ] and the thermal conductivity coefficient (λ) has to be known per material. They are collected from the materials table (A2.2.2). The method consists out of 3 steps:

1. Determination of temperature gradient through construction: $\Delta T_{m;i} = \frac{R_{m;i}}{R_{total}} \bullet \Delta T$ [°C]
2. determination of the maximum vapor pressure (p_{max}) at the given temperature of each layer: $p_{max} = 100e^{18,956 - \frac{4030,18}{T+235}}$ [Pa]
3. Determination of the calculated vapor pressure p_{cal}: $\Delta p_n = \Delta p \bullet \frac{\mu_n d_n}{(\mu d)_{total}}$
4. If $p_{cal} > p_{max}$, condensation will occur

At 21 °C p_{max} = $100e^{18{,}956-\frac{4030{,}18}{T+235}}$ = $100e^{18{,}956-\frac{4030{,}18}{21+235}}$ = 2485,6 [Pa]

At -10 °C $p_{max} = 100e^{18{,}956-\frac{4030{,}18}{-10+235}}$ = 284,1 [Pa]

First, the vapor pressure of both inside and outside can be calculated:

p_i = 0,50 • 2485,6 = 1242,8 [Pa]

p_e = 0,85 • 284,1 = 241,5 [Pa]

Facade layer	t [m]	λ [W/mK]	R [m²K/W]	ΔT [°C]	T [°C]	p_{max} [Pa]	μ	μ t [m]	Δp_n [Pa]	p_{cal}
Outside air					-10	284,1				241,5
R_e			0,04	0,16			-	-	-	
					-9,84	287,7				241,5
Water proof membrane	0,00045	0,47	0,001	0,04			44,44	0,02	23,6	
					-9,8	288,6				265,1
WFB	0,05	0,038	1,32	5,29			3	0,15	176,7	
					-4,51	435,2				441,8
Straw insulation	0,4	0,0645	6,2	24,86			1,4	0,56	659,7	
					20,32	2388,0				1101,5
Clay board	0,016	0,353	0,05	0,20			7,5	0,12	141,3	
					20,52	2413,20				1242,8
R_i			0,13	0,52			-	-	-	
Inside air					21	2485,6				1242,8
Total			7,73	31				0,85		

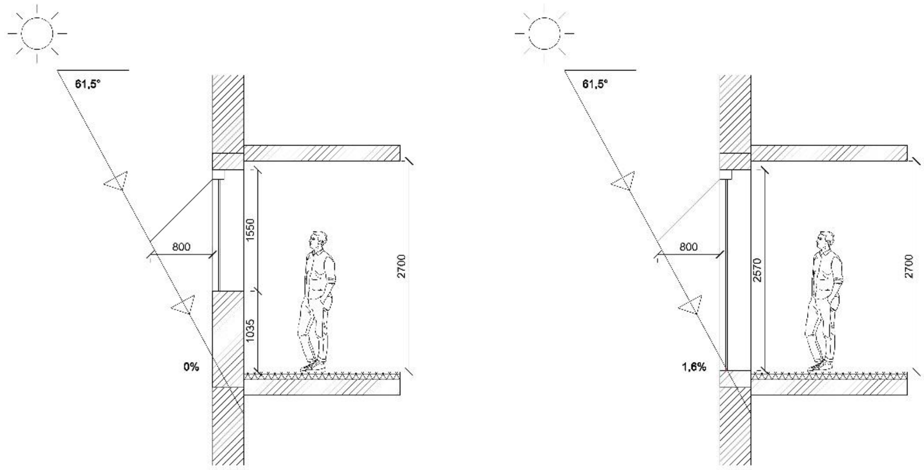
As visible in the table, slight condensation can occur under the WFB during winter. This, however, is not necessarily critical. For wood or wood-containing materials, the maximum allowed condensation should be around 0,1-0,2 kg/m² façade (Van Der Linden et al., 2018). To calculate this amount, the following formula is used:

$$g = 60 \bullet 24 \bullet 3600 \bullet (\frac{\Delta p_{in}}{R_d \bullet \sum\mu \bullet d_{in}} - \frac{\Delta p_{uit}}{R_d \bullet \sum\mu \bullet d_{uit}}) \bullet 1000 \text{ [g/m}^2\text{]}$$

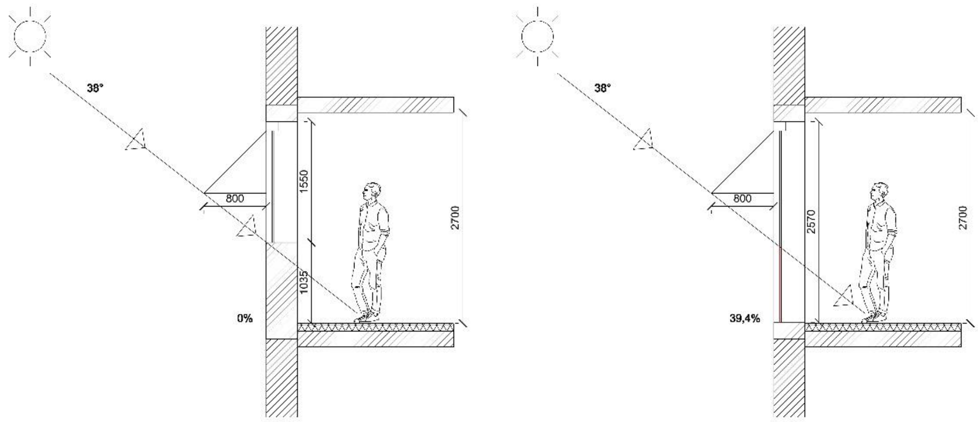
$$g = 60 \bullet 24 \bullet 3600 \bullet (\frac{1242{,}8 - 435{,}2}{5{,}3 \bullet 10^9 \bullet (0{,}12 + 0{,}56)} - \frac{435{,}2 - 241{,}5}{5{,}3 \bullet 10^9 \bullet (0{,}15 + 0{,}02)}) \bullet 1000 = 46{,}7 \text{ [g/m}^2\text{]}$$

$46{,}7 \leq 100$ [g/m²] √

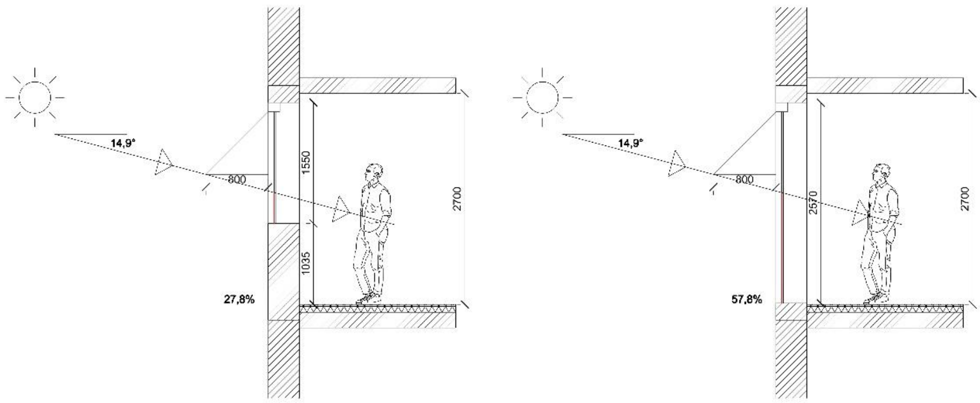
A2.3.3 Sunlight entrance



Summer situation



Spring / autumn situation



Winter situation

In this sunlight entrance study, the drop-arm awning was examined in three situations (summer, autumn, spring and winter in the Netherlands) with the two cassette types upon it's light obstructing performance. This performace indicated that in the summer - when sun power is at it's highest – almost all light is blocked in both cassette types. In the spring and autumn, it depends on the cassette type. Here, the floor-ceiling window does receive some light and heat, whilst the window with parapet does not. In the winter season, both cassette types receive the largest surface area of sunlight and heat. Source of sunlight entrance angles: Weerman, H. (z.d.). *Zonnestand per maand in nederland*. Geraadpleegd op 11 januari 2025, van https://weerman.nu/voorbeeld-pagina/zonnepanelen/zonnestand-per-maand-in-nederland/

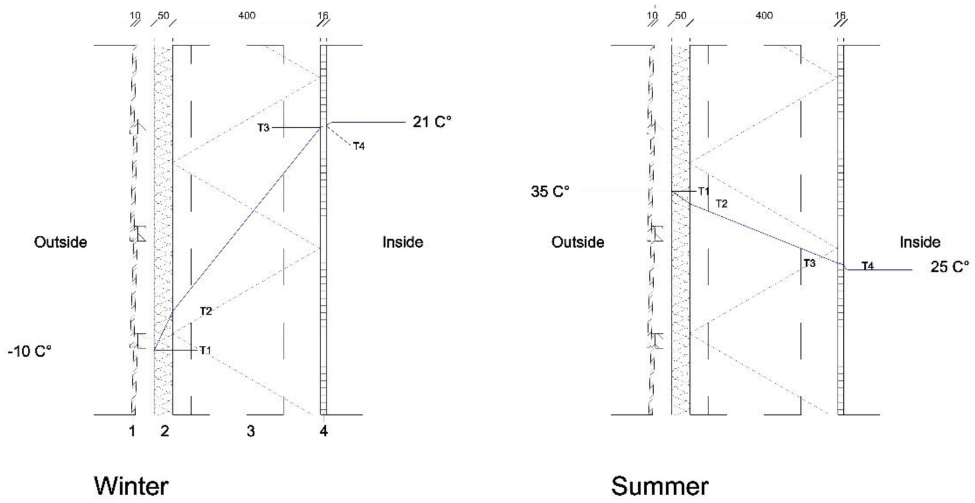
A2.3.4 Thermal accumulation & phase shifting

Thermal accumulation is the capacity of a structure to store heat over a longer period of time. This is of importance for façade construction, since it determines for a large part the indoor climate and heating or cooling demands. Two variables play a large role: the mass of the construction and the placement of insulation. First, the temperature progression through the façade is visualized. Then, the thermal accumulation and the time to heat up the façade system is calculated. Two extreme situations are calculated for:
- outside -10 °C and inside 21 °C (December), with heating installation of 500 W/m²
- outside 35 °C and inside 25 °C (July), with maximum radiation of 870 W/m² on east/west façade

Information from materials table, unless otherwise stated below.

Material	Thickness [m]	Density [kg/m³]	Specific heat capacity [J/kg•K]	U value W/m²K
Clay board	0,016	1450	1100	22,06
Wood-straw panel	0,4	0,1•510+0,9•65,5= 110 av.	0,1•1880+0,9•2000=1988 av.	0,16
Wood fiber board	0,05	110	2100	0,76
Shingles	av. 0,015	480	1880	n.a.

Sources used:
- Tabellenboekje Klimaat ontwerp TE3 - Bouwfysica tabellen en formules Klimaatgegevens - Studeersnel
- Strobouw nederland. (2019). *Stro kenmerken: Alle cijfers op een rij* [Dataset; PDF]. Strobouw Nederland. https://vakgroepstrobouw.org/wp-content/uploads/2019/04/Stro-kenmerken-SBN-april2019.pdf



Temperature progression through facade in winter and summer situation

In the calculation of the temperature progression through the façade, the shingles are not included since they are separated by a ventilated cavity. However, they do absorb and reflect some of the projected heat. This is in proportion to its mass. The mass is about 10% of the full façade construction, so 10% will be subtracted. Further heat transport by radiation and convection are marginalized.

Winter	T_1 = -9,84	$T_{WFB} = -7{,}2$	$T_2 = -4{,}51$	$T_{wood-straw} = 7{,}9$	T_3=20,32	$T_{Clay\ board} = 20{,}42$	$T_4 = 20{,}52$
Summer	$T_1 =$ 34,95	$T_{WFB} = 34{,}1$	$T_2 = 33{,}24$	$T_{wood-straw} = 29{,}2$	$T_3 = 25{,}22$	$T_{Clay\ board} = 25{,}2$	$T_4 = 25{,}17$

To calculate the accumulated heat per façade material with the following formula:

$Q_{acc} = \rho \bullet c \bullet d \bullet \Delta T$ [J/m²]

ρ = density, c = specific heat capacity, d = the thickness of the material in the construction and ΔT is the temperature progression of the material relative to starting situation. The results are extrapolated below:

Winter

Accumulated heat per material Q_{acc} [J/m²]	
Clay board	$7788{,}7 \bullet 10^2$
Wood-straw panel	$1565{,}75 \bullet 10^3$
Wood fiber board	$3234 \bullet 10^1$
Q_{total}	$2376{,}96 \bullet 10^3$

q = 500 Watt – 10% = 450 Watt

Time required to heat up the façade: $\tau = \frac{Q_{total}}{q}$

$\tau = \frac{2376{,}96 \bullet 10^3}{450}$ = 5282 seconds = 1,48 hours.

Summer

Accumulated heat per material Q_{acc} [J/m²]	
Clay board	5104
Wood-straw panel	$3673{,}82 \bullet 10^2$
Wood fiber board	$1051{,}05 \bullet 10^2$
Q_{total}	$4775{,}91 \bullet 10^2$

q = 870 Watt – 10% = 783 Watt

$\tau = \frac{4775{,}91 \bullet 10^2}{783}$ = 610 seconds = 10,167 minutes.

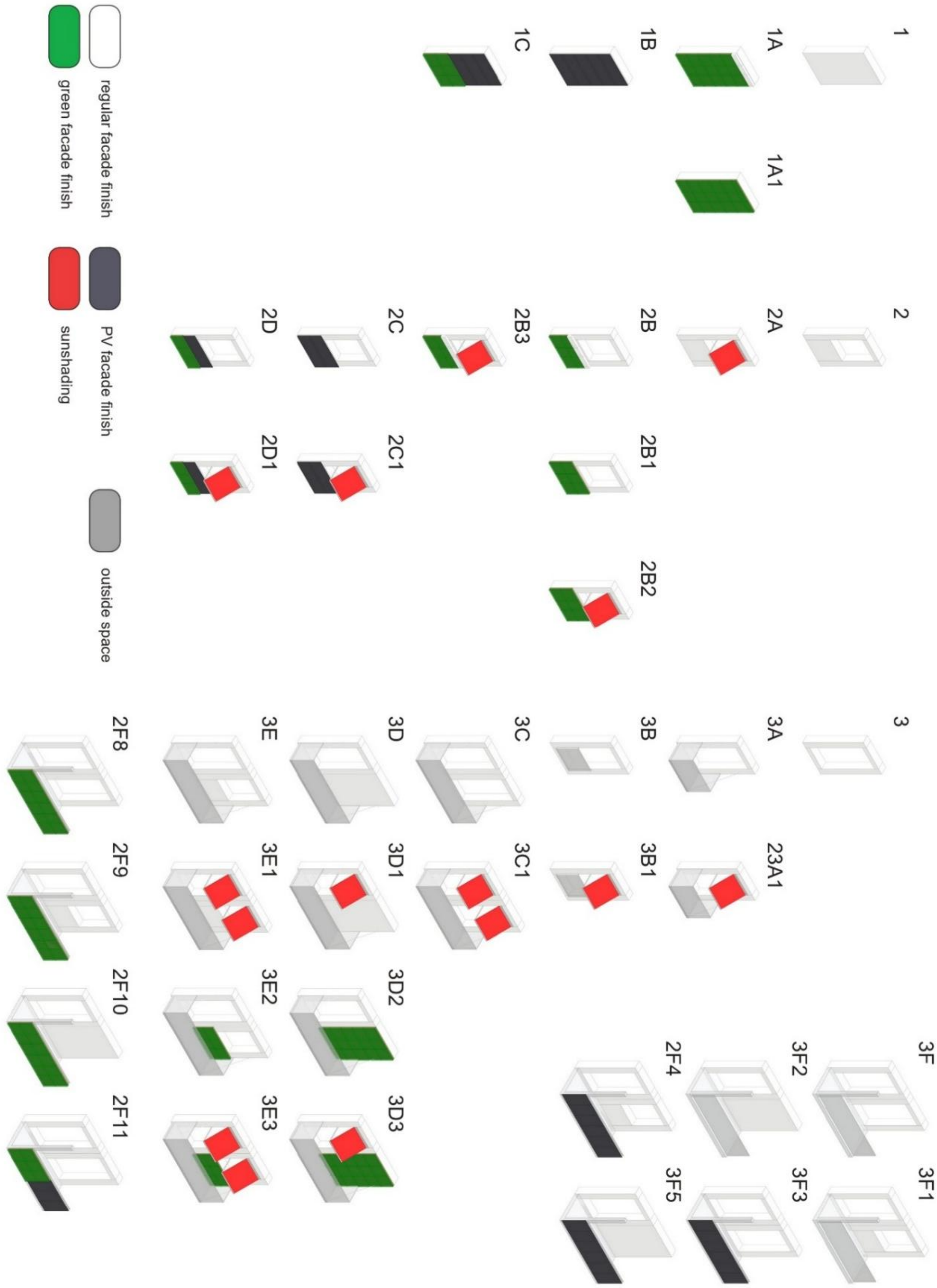
Phase shifting time

However, this calculation does not take the thermal conductivity coefficients of the materials into consideration. These determine how much heat can flow through the construction at once, in W/m² . The formula is as follows:

$f_{phase} = \frac{d \bullet \rho \bullet c}{U}$ [s]

$f_{phase} = \frac{0{,}016 \bullet 1450 \bullet 1100}{22{,}06} + \frac{0{,}4 \bullet 110 \bullet 1988}{0{,}16} + \frac{0{,}05 \bullet 110 \bullet 2100}{0{,}76}$ = 563054 [s] = 156 hours = 6,5 days

A2.3.5 climate variables in façade matrix



A matrix showing all climate design options for the façade. The more options, the more the façade system can be tailored to the user's specific demands. Nevertheless, it is all based on the same façade system. The different regular façade finishes are excluded here.