

The Open Modular Façade Concept

Master Thesis



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Preface

This is the graduation report of Joep Hövels, named *The Open Modular Façade Concept*. The graduation project has been done at the TU Delft, Faculty of Architecture for the chair Design of Construction and the Chair Product Development; both chairs are within the masters variant Building Technology. The project started in March 2007 and ended in April 2008. The first tutor is dipl. ing. T. Klein of the chair Design of Construction, the second tutor is dr. ir. W. Poelman, of the chair Product Development.

The project has been very challenging and in the end quite satisfying for me and forms a nice ending of my study period in Delft. In my opinion the design of facades has a close link with architecture, which was one of the reasons for me to choose for this project. During the graduation project I learned much about facades and façade systems. I will probably start my working career in this field. This way of designing, from the product development side, was new for me and appeared to be interesting and very helpful for the result.

So in the end I would like to thank my tutors, Tillmann Klein and Wim Poelman, for their enthusiastic and committed support. As a team we developed a nice design concept based on the Open Modular Façade Concept.

Joep Hövels

Delft, March 2008

1 Introduction

1.1 Issue and relevance

Problems of current metal-glass façade systems

The facades of many utility buildings nowadays are metal-glass facades. The metal-glass façade is a system that has been successful in the architecture since the beginning of the last century. These facades consist mainly of a secondary structure connected to the primary structure of the building, with filling elements in this frame. This principle hasn't been changed since the 1930's and works pretty well; it is capable of performing all the functions of facades.

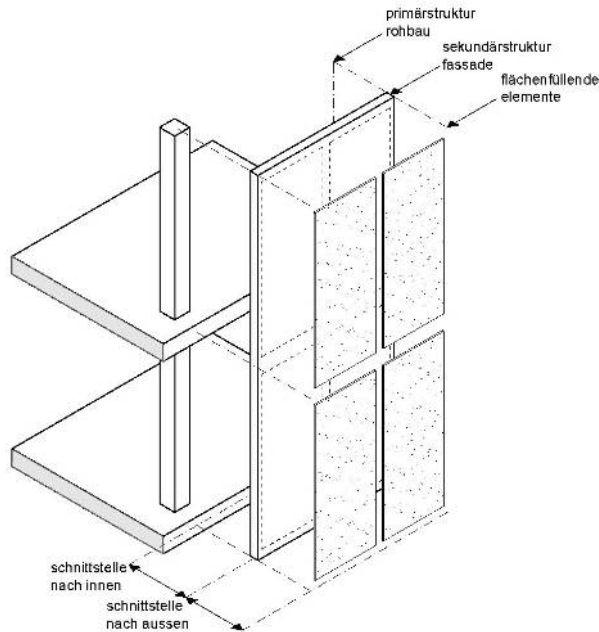


Figure 1: general layout metal-glass facades (source: [5])

But the metal-glass façade systems seem to have not much room for further development, at least in terms of energy performance and upgradeability. Since the invention of the thermal break not fundamental improvements have taken place.

Buildings from the a few decennia ago don't meet the standards of today; the insulation values are not good enough and the rooms behind the facades are not comfortable enough. In such cases upgrading the facades is very elaborate and not always cost-effective.

There is still some development in the systems, but that often results in very complex systems. Tolerances become smaller and smaller, while this is not the case for the primary structure. The systems sometimes get even too complex for the construction workers.

Future tendency

In the meantime, the demands of façades in terms of energy, user comfort and geometrical possibilities are getting higher. The regulations on energy performance and sustainability are growing; this must be solved by

Therefore the development of a new façade system may be a better solution than going on trying to continue developing existing systems. A new system will not function as well as existing systems right from the start, but after development a new system can perform better.

To catch up with the growing demands the future tendency of facades is that more functions are integrated in facades.

Facades have undeniably great effect on the inner climate. Facades influence the amount of daylight, the amount of solar radiation, the glare, air circulation and sound protection. Giving the user great influence on these factors helps to increase the comfort of the inner space.

Integration of building services and other functions enables this; besides the flexibility of the building is increased, because space for shafts and pipes will be saved. When the user demands of the system change, or the system is technically out of date, it can be easily changed. Besides that, the systems can more easily be prefabricated, so the lead time and building time can be reduced.

The existing service integrated facades (facades which have integrated other building functions) offer a just partially good solution for this: the systems integrate building services, but the design freedom which they offer is limited.

The goal of the project

Based on this the demands of a new façade system as a competitor of the metal-glass facade can be formulated:

- the façade system must offer the possibility to integrate other building functions
- the façade system must be upgradeable (technically)
- the façade system must be flexible (functionally)
- this must be accomplished without losing geometrical possibilities

The chair Design of Constructions of the faculty for Architecture developed several new façade concepts. One of them is the Open Modular Façade Concept.

Modularity should in this case not be understood as a goal, but as an instrument to make things possible. In many other products and product lines modularity can be found, offering many advantages. In facades modularity can also be seen, but it seems like the advantages modularity offers are not fully gained in the façade industry. The modular set-up in façade systems will be re-considered in order to come to a new, improved façade system, solving (part of) the problems of current systems.

The open modular facade is a concept for a façade which is (partially) built up out of modules. The used modules have different functions, and possibly come from different suppliers. The modular façade should bring outcome to the previously mentioned aspects which will be part of the program of demands; and in order to be a successful product the façade must besides that not lose geometrical potential.

The project

Summarizing, the main goal of the project is to design a new façade system, based on the rules of modularity. The objective of this system is to create a functioning, flexible and upgradeable façade, as well as a façade with geometrical potential. Applying the rules and conditions of modularity in the façade design should result in a façade system where the advantages of modularity are gained. This new façade system should be an good alternative for the metal-glass façade.

The design process will be taken from product development. Architects tend to design without a structured process; product developers on the other hand use a design process as a tool to have a structured process and to be able to review choices and decisions during the process or afterwards. Besides the process, also other tools like selection methods will be used from the product development.

Building a façade out of modules has consequences for the system and raises questions. The problems and consequences to be treated will mainly lie in the field of construction and architecture.

1.2 Research question

In accordance to the words above the following research question has been formulated:

Can by re-thinking of the modular set-up of today's metal-glass facades a new façade system be developed, enhancing the current systems in terms of upgradeability, flexibility and integration of functions?

1.3 Outline

The graduation project will be used to study the possibilities of modularity in facades and to design a modular façade system.

First to be examined are the functions of facades. Designing a new system can be a good opportunity to expand the functions of the existing product. The function analysis will be done by determining the primary function of facades, and subsequently this function will be split out into more specified secondary and supporting functions. This function analysis will play an important roll in the first part of the design process, the brainstorm.

After the function analysis of facades, the history and the current status of the metal-glass façade systems will be looked at. This must make clear the development of the system and the expected future can become clear. This determines partially what a competitive system should be capable of. Besides, this overview should reveal a part of the shortcomings of the current systems, so the new system can be an actual improvement to these systems.

One of the main goals of the project is attempting to use a modular system for the façade. Therefore modular product architecture will be studied: what are the rules and conditions of modularity, and what can be gained by applying these?

Besides that existing modular systems from other industries will be examined in order to learn from for the building industry. Those modular products can form an inspiration for the new façade system.

Apart from modular products from other industries, also existing façade systems will be studied, which show modularity on component level. What are the positive aspects of these systems, and what are the negative aspects? What elements do they integrate?

After the research, a design proposal will be done. The requirements and objectives are the result of analyses in the previous parts. The design process will be determined first. This will be done using methods used by product developers. The process will be a process of divergent and convergent steps.

The design process will start with a brainstorm based on the constraints of the product in different situations, with the function analysis as an important basis. This brainstorm should result in principle solutions. In the end one solution will be elaborated as the final design.

In the end of the project the design will be evaluated, as will the process. The product must be evaluated after the demands and requirements stated in the beginning. With the evaluation and conclusions the research question must be answered as well.

2 Facades

Since the beginning of mankind humans have been living in sheltered rooms to be protected from external influences like rain, wind and wild animals. Since the beginning of these shelters they have been changed to fulfill the demands of the inhabitants better. Shelters became buildings and the walls became facades. Facades nowadays face many demands and different functions which are determined in regulations or are stated by the users. User comfort and the energy performance of facades are getting more and more important. Facades which cannot meet the current requirements any more are removed and replaced by a new, more modern one.

In order to meet the high standards in comfort and energy terms functions are integrated in the façade. This chapter will treat a historical overview of the metal glass façade, the technical status of this system, the properties and functions of facades in general and integration of functions in facades.

2.1 Metal-glass facades

This paragraph gives a brief historical overview of the metal-glass façade. This gives insights in the development of this system and may point out the desired direction of the future of the system.

2.1.1 Historical overview

Precursors of the metal-glass facade

The background of the metal-glass façade lies in the development of the steel skeleton for buildings in the beginning of the nineteenth century. This development started in Liverpool, where industrially manufactured load bearing building components of cast iron were implemented in buildings.

Parallel to that was the development of the industrialized manufacturing of flat glass sheets. In the beginning these technologies were not regarded as architecture, but as building technology. It enabled the engineers responsible for the façade and construction planning of the buildings to separate the load bearing structure and the façade; previously this hasn't been possible because of the use of the load bearing walls in practically all buildings.

A third important development was the start of the skeleton structures for high rise. Especially in Chicago, were in 1871 after the great city fire an urgent need for building volume on large scale for dwellings, offices and retail business arose, skeleton high rise appeared to be a good solution. The ground in Chicago is comparable to the ground in The Netherlands: a non-reliable foundation. Therefore the buildings which offered a large building volume and floor area needed to be relatively light at the same time. The load bearing steel skeleton structures and the curtain wall of steel and glass appeared to be suitable. The use of iron and steel as structural elements enabled the structures to be much slender. The Second Leiter Building (Jenney) in Chicago, finished in 1891, was the first big building without the use of load bearing walls at all. Together with the use of a steel structure the lightweight facades contributed to the development of lighter buildings, which were able to be built on the relatively weak foundations in Chicago.



Figure 2: The Second Leiter Building, Chicago 1891, designed by Jenney (source: www.bc.edu)

Chicago didn't stay unnoticed by architects from other parts of the United States and Europe. This development on building technical level in Chicago was repeated in New York at the end of the last century and spread out over the whole world.

Large structures of metal and glass had been developed before these events in Chicago, though the question whether they can be classified as metal-glass facades is disputable. In 1848 in Surrey the Palm House was built by Decimus Burton and Richard Turner. This building functioned as a green house; the glass sheets were placed between curved profiles of cast iron.

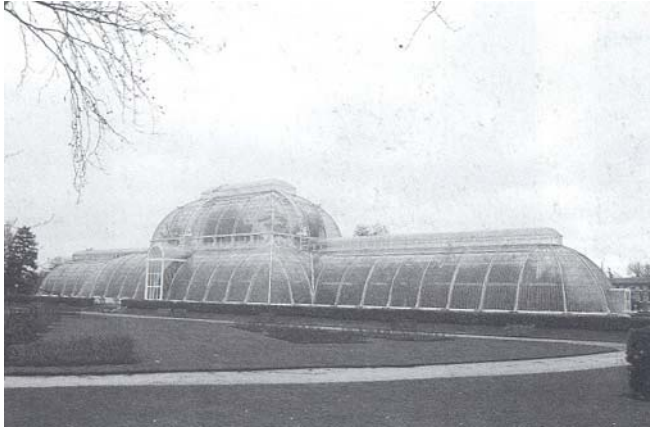


Figure 3: Palm House, Surrey 1844-1848, designed by Burton and Turner (source: [7])

Also large metal-glass roofs, used for to cover of shopping arcades and railway stations, were developed during the nineteenth century. In 1851 the Crystal Palace was realized in London. The building of this magnitude could be realized in a relatively short time because of the modular nature of the building: most of the elements were prefabricated which enabled quick assembly. This made the Crystal Palace the first large building which was built in an industrialized building way. The glass roof and the glass façade of the Crystal Palace can be seen as the precursor of the metal-glass façade as it is know today, because of the slender nature of the construction, because of the industrial manufactured elements and because of the methods of assembling the elements.

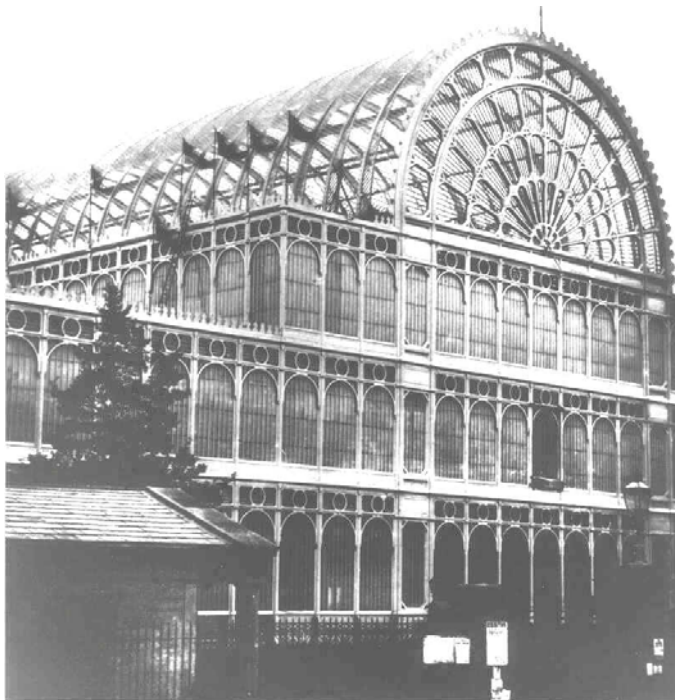


Figure 4: Crystal Palace, London 1851, designed by Paxton (source: www.ourwardfamily.com)

The first metal-glass facades

Together with the development of the steel skeleton structure and the facades build with cast iron and glass the need for inner climate control and daylight entry were important factors in the development of the actual metal-glass façade. The first offices with this kind of facades were built during the first half of the 20th century by architects as Jenney, Sullivan, Wright, Behrens, Gropius, Mies van der Rohe and Le Corbusier.

In 1903 the first example of the curtain wall was built in Giengen/Brenz by Richard Steiff as the façade of a toy factory. This façade had a post-beam construction.



Figure 5: Factory, Giengen/Brenz 1903, designed by Richard Steiff (source: www.compagno.ch)

Walter Gropius used the principle of the curtain wall on the headquarters of the 'Werkbundaussstellung' in Cologne in 1914 and on the workshop building of 'Bauhaus' in Dessau in 1926.



Figure 6: (left) Faguswerk, Alfeld 1910-1916, designed by Walter Gropius (source: [7])

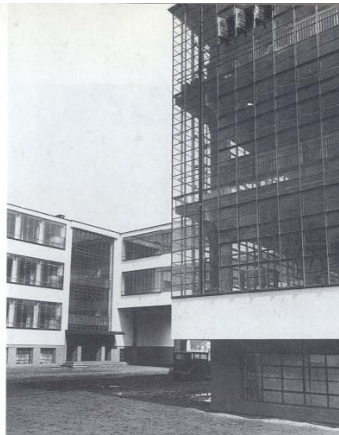


Figure 7: (right) Bauhaus, Dessau 1925-1926, designed by Walter Gropius (source: [7])

Other famous and early projects using the first curtain-wall are 'Cité de Refuge' in Paris (1933) and 'Project Centrosoyus' in Moscow (1928) by Le Corbusier. Mies van der Rohe designed for a contest in Berlin two high rise buildings with metal-glass facades from floor to floor. In spite of or maybe thanks to being ahead of his generation with this design it hasn't been rewarded as the winning design. In The Netherlands the 'Van Nelle Factory' in Rotterdam in 1930) by Michiel Brinkman and Leendert van der Vlugt is a famous example of an early curtain wall. The load bearing structure of this building is a concrete skeleton; the façade consists of non-load bearing stripes of windows of steel and glass.



Figure 8: Van Nelle Factory, Rotterdam 1930, designed by Michiel Brinkman and Leendert van der Vlugt (source: www.vannelleontwepfabriek.nl)

Jean Prouvé contributed strongly to the development of the metal-glass façade, in particular the insulated metal-glass façade. In 1938 he was the first to design a completely insulated curtain wall with various innovative details, which still are used in the current curtain wall constructions.

The curtain wall after the War until the Energy Crisis

After the war new technical inventions led to a further development of the curtain wall:

- air-conditioning installations
- artificial lighting
- industrial manufacturing of glass and glass coatings
- insulated glazing
- artificial rubbers and sealant (developed in the car and airplane industry)
- façade building in prefabricated components

In 1952 these developments led to the first high rise with a curtain wall: the Lever House in New York designed by architectural firm SOM. Some argue that the façade of the Lever House is the first real curtain wall because of the way the façade is hanged to the structure of the building. The façade is build up with post and rails of steel covered with stainless steel cover caps. The glass sheets were colored blue and green.



Figure 9: (left) Lever House, New York 1952, designed by SOM (source: www.nyc-architecture.com)



Figure 10: (right) Seagram Building, New York 1958, designed by Mies van der Rohe and Philip Johnson (source: www.britannica.com)

In the fifties other materials were applied in the façade construction instead of steel. In 1958 Mies van der Rohe together with Philip Johnson designed the Seagram Building in New York. The façade of that building consisted of post and rails made out of brass and façade panels with brass finishing.

Shortly after the war another material did his entrance: aluminum. Shortly before the Second World War aluminum had been used as a decorative material and as a façade panels. During the War fairly all produced aluminum was used in aircraft. The use of aluminum in the aircraft led to a better knowledge and understanding of the use of aluminum, which resulted in a chance for the façade industry. This better knowledge of aluminum showed the façade industry that aluminum should not necessarily be the replacement material of steel, but has in fact a better performance-price ratio. The light weight of aluminum, the good extrusion possibilities, which lead to bigger form freedom of the sections of the profiles, and the high corrosion resistance led in the early sixties to a significant growth of the use of aluminum in the façade industry. In 1975 steel profiles are almost gone and the curtain wall is almost exclusively produced with aluminum profiles.

The need for quicker assembly of big buildings arose during this period. For the façade industry this meant chances for prefabrication of lightweight elements and put in glass, panels and mechanical facilities already in the elements. The integration of elements into components was taken from other industries like the car industry. In Pittsburgh the Alcoa building is an example of an aluminum panel curtain wall.



Figure 11: Alcoa Building, Pittsburgh 1953, designed by Harrison and Abramovitz (source: [7])

The industrialization of glass led to the possibility of the production of bigger glass sheets. This possibility was taken over in the building industry by making the curtain wall more abundant in glass. This development resulted on one hand to more daylight in the rooms behind the facades, but at the other hand an increasing warmth load in the rooms. To deal with the latter glass panels with sun reflecting coatings have been developed, also taken from the car industry. During the sixties the first general awareness of ecology as a science was seen. Single glazing appeared to be a problem from this point of view. The glass industry came up with a solution to add more glass: double glazing. These panels had twice the performance of single glazing at a little more than double the price.

The development of the curtain wall from the Energy crisis until recently

The Energy Crisis of 1973 showed the western world the limitations and possible trouble of the dependence on fossil fuels. This had its consequences in the façade planning: the non-insulated curtain walls need to be insulation to make the buildings more energy efficient. Both the profiles as the panels in between the profiles have been improved since then. For the aluminum profiles a better insulation performance meant the commonly use of the thermal break. The thermal break has been introduced for the first time in the fifties by a Swiss company where it was used for military buildings where inside condensation was not allowed. After that the thermal break was until 1975 only used to improve the comfort. From 1975 and the introduction of energy performance of facades the insulators of the façade have been improved.

The glass industry developed better insulating and sun reflecting glass panels. Instead of a climate regulation or separation the façade turned into a climate resistance. The inner climate of buildings was completely taken care of by the building services and the operable window nearly vanished from the office buildings.

The development of the way the climate is kept out of the rooms as much as possible matches with the development of the box window in the late seventies. This is a double façade, with double glazing on the outside and single glazing on the inside, where the inside ventilation air is exhausted towards outside through the cavity between the two glass sheets.

In the eighties the amount of office activities grew rapidly; as a result of economic growth and automation jobs moved from the factories to the offices. Real estate developers decided about the building sites and the realization of the buildings, which meant that the developed buildings were less concerning with sustainability, user friendliness and flexibility. The quick realization and low investment costs were normative for them.

Technical development in the eighties was rather limited. In the beginning of this decennium a 'Dallas like glass building' trend was set in; this type of building has sun reflecting glass panels in front of both non-transparent (in front of the parapet for example) and transparent panels. Office buildings were becoming

dark closed mirroring boxes. The sizes of the facade pattern were increased standardized to an industrialized size of 180 x 180 cm to make the façade cheaper. Dimension, rhythm and scale disappeared as a means of design. This development resulted in a large growth in the façade industry. Because of the growth a shortage on engineering knowledge of the curtain wall arose; the knowledge shifted from engineers and architects to the system developers, and with that knowledge the power and influence on the façade development. Together with the 'Dallas like glass buildings' the invention of structural sealant glazing was from the United States introduced in Europe.



Figure 12: Example of Dallas like glass building, location, year and architect unknown (source: [7])

At the end of the eighties the need of operable windows arose mainly caused by the increasing attention for the 'sick building syndrome' and the increasing employee participation in the decision making of the companies.

As mentioned before the technical development during this period was restricted and business is more important. This has led to a more industrialized building process in order to make it more efficient: post and rail construction are less used and the development of prefabricated façade components or even super components win ground.

Another issue at the end of the eighties is the recession in the building industry, which causes a decrease in the building activities. In The Netherlands this causes a shift from the newly constructed buildings to renovation. This process is strengthened by the growing consciousness on the field of energy and sustainability: use and recycling come forward instead of consumption and demolishing.

In the first half of the nineties the metal-glass façade is pushed back and is replaced by facades which use more natural materials, like nature stone, brick and ceramics; furthermore technical materials like pre-formed metal sheets and polymer panels are used and the innovative connection of materials are important, like structural glazing and visible design constructions.

Besides that, the curtain wall has in the beginning of the nineties to deal with the pressure to design more sustainable and to save on fossil fuels.

On one hand there is the development in facades towards a heavy closed façade using materials like stone and brick; on the other hand there is a movement towards a very transparent façade, using technical materials like glass, metal and polymers, to show users of the building and passer-bys what is happening on the other side of the façade. In this trend the revision of an energy performance law in Germany (Wärmeschutz-Verordnung 1995) appeared to be very important. A positive aspect of this law was the approval to take into account the (direct) gaining of energy of sunlight in the justification of the total energy use of the building. This resulted in a façade which actively regulated and used the sunlight instead of resisting it.

New kinds of coatings were developed, among which the Low-E-coating: a neutrally colored coating, specially designed to keep the heat of the sunlight inside the room. The recession of the late eighties and beginning of the nineties actually brought innovation in the façade industry. The low level of building activities and the opening of the European borders led to new and fresh perceptions of façade design. Half way during the nineties the building activities are increasing again, especially in former East-Germany, Poland, Czech Republic and Hungary.

From the late nineties until recently the further development of the double skin facades is the most important in the development of the metal-glass façade. By the way, the origin of the double skin is not

recently, but can be brought back to the 17th century, where during the winter a second glass plane was placed in front of the window to improve the insulation. The recent double skin facades must be able to regulate the climate during the whole year resulting in an optimal comfort for the users and in a decrease in the use of energy. An important similarity of most double skin facades is the possibility to ventilate the room behind the façade naturally by ventilating the cavity between the two glass planes.



Figure 13: Double skin façade of the Stadttor in Düsseldorf 1997, designed by Petzinka (source: [1])

Recent research has shown that the double skin façade is not a good solution in all situations: the chances of overheating the ventilation air, the air in the cavity, are big. Besides that is the price of the façade much higher compared to a single metal-glass façade, more than a factor two.

In the (near) future the two main topics of the development of facades will be energy efficiency and comfort. Professor Brian Cody explains in Profile, a magazine published by Schüco¹, that in his opinion energy efficiency and comfort cannot be separated. He states that energy efficiency is often confused with reduced energy consumption; however, energy efficient architecture should be understood as a combination of minimal energy consumption, optimal comfort and high architectural quality. To serve these two goals several companies and research institutes have tried lately to develop a new kind of façade based on function integration in the façade. Examples of this type of facades and concepts are the TEmotion façade of Hydro Building Systems, The E² façade of Schüco and the façade of the Capricorn Haus of Schossig and Gatermann.



Figure 14: Capricorn Haus, Düsseldorf 2005, designed by Schossig and Gatermann (source: own picture)

¹ Profile, Magazin über Architektur 05 published by Schüco

The façade company Alcoa states that the development of the metal-glass façade, in terms of thermal insulation for example, is coming to an end and that it would be time for the next step in the development. The importance of energy reduction and sustainability to limit the use of fossil fuels and materials is growing and will be in the future, while the comfort of the rooms cannot decrease. In recent discussions prominent people in the fields of facades have stated that in the future the façade should be more adaptable to the changing of the seasons and changing of outside conditions. Klaus Daniels said during his presentation of Delft School of Design on the 10th of January 2008 that facades in the future should be like our clothes: the physical properties of the facades, such as the U-value, g-value and the t-value should change along with the different properties of summer, winter, autumn and spring. In the Schüco magazine Stefan Behnisch says in a discussion on the future development of facades with regard to energy that “thought needs to be given to whether buildings should be changed more in line with the seasons”. So this meets in fact the idea of the polyvalent wall of Mike Davies [21]; a wall that adapts itself to the changing outer conditions to optimize the inner climate and minimize the energy use. The state of the technology in 1981, the time that Davies wrote the article, was not developed so far that a façade like that could be realized. Technology now reaches a higher level, while the focus of the façade designers will move towards comfort and energy use. The realization of a façade in the direction of the idea of Mike Davies seems a matter of time.

The goal of the modular façade is the integration of functions, especially the integration of building services. Also flexibility and upgradeability play a very important part. Perhaps the next step in the development towards it lies in the development of the modular façade.

2.2 Integration of functions

Facades do have a broad scale of functions. In this paragraph different visions on the main function of a façade are treated. Eventually the design must incorporate at least the same functions as current facades in order to be a successful product. The findings of this paragraph will form an important input for the brainstorm in the beginning of the design process.

2.2.1 Façade functions

To discuss the integration of functions in facades the primary function and other functions of the façade must first be discussed. The primary function is the main function of a product. The primary function of a façade could be described as follows:

A façade forms the interface between inside and outside, regulating the interaction between the inner space and the outer space.

In this definition the word *regulating* has been chosen intentional instead of *protecting*; regulation suggests 'using the external factors for the inner space' while protection suggests 'a complete closed border between the two'. The facades of the first houses built by humans just had functions in the field of protection against the outside world. Through the course of history new kinds of functions have been added. As the definition of the primary functions already states, the façade is nowadays more of a regulator between inside and outside instead of just a protector.

The primary function describes the basic function of the façade. The primary function can be split out more specifically into sub-functions. The sub-functions consist of two categories: supporting functions and secondary functions.

Supporting functions are functions which enables the primary function. An example for a façade is insulating the façade; this function helps the façade to create an optimized relation between inside and outside in the field of temperature.

Secondary functions are functions which enable applications other than the primary functions. This type of functions is not necessarily a part of each façade. An example of this kind of functions is displaying of media. Although displaying media could be an interesting feature of a façade and could be a more familiar and common function of facades in the future, it does not directly enable the primary function in the first place.

To see what functions facades actually need to fulfill a function tree has been made. The functions listed in the tree are practically all supporting functions. Since the design aims for a new façade system the list of functions can be of help in the design process to prevent that certain essential façade functions will be forgotten. The tree will also play an important role in preparation for the brainstorm part of the design, where the façade system will be more thoroughly analyzed on the field of functions (see chapter 4 and appendix I).

This tree starts with the primary function of the façade. The primary function (1) is then split out into different groups (2) based on different fields of attention for facades. These groups again are split into themes (3) within these groups; on their turn the themes are also split in different categories (4). And finally the last category is split up into all sub-functions (5) facades have. On the next page the function tree can be viewed.

The groups after the first splitting up of the primary function are building physics, comfort, safety, energy and appearance.

Building physics

In the group of building physics the functions of the façade have been mentioned which must protect the construction from possibly negative outside influences. Failure of one of these functions could result in high damage to the construction. The functions in this group all have to do with natural or biological processes.

Comfort

This group is actually rather similar to the group of the building physics. Some functions in this group are even the same as the functions in the building physics group. The point of view however is different in this group. The user is the central point in this group. Unlike the building physics group failure of one of these functions will not lead to damage to the construction. Failure would however lead to an undesirable inner climate for the users, which ultimately would lead to unpleasant or even unusable rooms. This makes this group of functions of the same importance as the building physics group.

Safety

This category lists all the functions which protect both the users and the construction. Unlike the functions in the group of the building physics the processes in this group have to do with the strength and resistance of the façade against different outer influences. Failure of one of the functions could lead to extreme damage to the construction or even perilous situations for the users.

Energy

This group of function treats all façade functions which deal with energy saving or energy production. Regarding global developments on economic, political and environmental level this aspect is absolutely necessary to consider in façade planning. Not only because of the regulations which have been formulated the last decades, but also because of the responsibility engineers and designers have on this field. Failure of one of these functions would not immediately lead to damage to the façade or to unpleasant situations for the users, except for a possibly high energy bill, but it will indirectly influence the environment. Besides, due to stricter regulations in the future, the life span of the building will decrease in case not enough attention is paid to these functions.

Appearance

This group of functions has been mentioned as the last one, because the appearance of the façade is in fact the result of all the other functions together. However, the planner should pay attention to this group of functions considering the users, both inside the building as well as outside the building, the social and cultural context and the relation of the building with the surroundings. If this group of functions would be neglected the value of the building, both economic as well as emotional, will decrease, which would result in a shorter life span of the building.

The functions in this group could be regarded as secondary functions rather than as supporting functions, because they don't directly enable the primary function of the façade but offer extra possibilities. In my opinion this function group is essential for the rate of success of the façade that it should be considered as a supporting function. The interaction between inside and outside doesn't only mean interaction in the field of natural processes, but also the interaction on a visual and cultural level.

One could argue that this list is rather a list of façade conditions than a list of functions. I prefer to call it a function list because some functions have a certain degree in which they could be fulfilled. Calling it conditions would imply that the list would form a kind of checklist to see if they all have been satisfied. In my opinion this is just partially the case; I would rather consider it a complete list of functions which the façade must perform as well as possible. The more successful this has been done, the higher the quality of the façade system.

Literature on the function of façades

In the literature different definitions for facades can be found, although similar to the one for the primary function stated above.

In [1], by T. Herzog, the façade is described as the separating and filtering layer between inside and outside, between nature and interior spaces occupied by people. In historical terms, the primary reason for creating an effective barrier between interior and exterior is the desire for protection against a hostile outside world and inclement weather. To these protective functions other requirements have been added during the development of the façade throughout history. Furthermore, Herzog divides the façade requirements into two groups: the external conditions and the internal requirements, depending how the façade is being considered. The external conditions are specific to the location and the internal requirements govern or at least influence the internal conditions.

As a rule, the external conditions cannot be influenced by the design. They therefore form from the beginning of the building process the primary criteria for the design or more specific the façade design.

External conditions vary at every location. They need to be analyzed carefully in order to make the proper design decisions in satisfying the inner requirements.

When determining the requirements for the inner space, the use of the interior must be kept in mind. These requirements must accurately be observed during the design because they directly influence the amount of energy and materials used for the construction.

If we consider the façade as the human body's third skin (1st skin is that of the body itself and 2nd is our clothing), as has been done in [26] by M. Wigginton and J. Harris, the analogy of the design objective becomes clear: the regulation of the interaction between outer influences and our body. In [26] the analogy of the human skin and the building skin has been worked out further: the human skin, the largest organ of the human body, is a protective organ that guards against the action of physical, chemical and bacterial threats to the internal organs. The human skin adapts to temperature and humidity, can feel a breeze or the slightest touch, and can repair itself. It is waterproof and yet permeable to moisture. Taken this into view the human skin is a good model for how we would like the building skin to behave.

Wigginton and Harris argue that the skin of a building should be intelligent. This is defined as a responsive and active controller of the interchanges occurring between the external and internal environment, with the ability to provide optimum comfort, by adjusting itself autonomically, with self-regulated amendments to its own building fabric. It is assumed that, as an objective, this is achieved with the minimum use of energy, and minimal reliance on the importing of energy.

The idea of an automatically adaptable and self-providing building skin was first presented in 1981 by M. Davies [21]. In his article in RIBA Journal called *A wall for all seasons* Davies described the idea of the *polyvalent wall*. This is a building skin which is so designed that it will, depending upon user wishes and season, function as shading or heat insulation, reflect heat energy outside the building or bring heat energy into the building, and open and close itself automatically. The polyvalent wall is thus a chameleon skin adapting itself to provide best possible interior conditions.

The different, yet similar approaches which are described in the text above all argue that the function of facades lies in the providing of a comfortable inner climate while the outer circumstances are considered and used. These function definitions of facades fit the design idea, the modular façade, where units taking care of the building services will be integrated in the façade.

2.2.2 Integration of building services in the façade

The subject of integration of building services in the façade can also be found in the literature: proposals for strategies or systems have been done, attempts for integrated facades have been done and opinions and views have been stated. This paragraph will start with a short introduction on the different possible so called actors to regulate the interaction between inside and outside; after that a brief overview of climatic active facades and facades which have incorporated building services will be given; the paragraph will end with conclusions and recommendations on the future perspectives on this theme.

Different actors

For the process of regulating the climate facades can possess different actors, to perform this task. With an actor is meant an (active) instrument to influence a process. Some of these actors must be integrated in the façade by means of regulations or standards; others are optional, but are strongly desired to reach a comfortable façade. The actors in the last category are really optional, and will reach an actual improvement to the more standard options (this division between commons, options and specialties will be treated more elaborately later on in paragraph **Error! Reference source not found.**).

The function tree, presented earlier this chapter, gives an overview of the different functions a façade must have to be successful. These functions can be filled-in in many different ways and in many different combinations. For almost all the functions in the function tree different actors are possible. To make an overview of the different possibilities would be too elaborate and too wide. Therefore just a short overview of climate active facades will be given in the next part, discussing the basic principles of the facades, not so much the specific nature of the actual actors. During the design process different possibilities for relevant actors will be shown, in a stage where an overview of the different possible actors will not be too wide.

Overview of different solutions

Facades have always been more or less successful in fulfilling their primary function, the regulation of the interaction between inside and outside. To improve the regulation climatic active facades were developed. This is however not something of the last decades, but goes back hundreds of years. Traditional farmhouses had already the property of being climatic active, by adding timber shutters for their windows. In case of a weather change the shutters could be closed to improve the thermal performance of the façade.

During the 20th century the development of the climatic active façade took a bigger speed. The box window is one of the developments, which is a double glazed unit with individually operable windows on both sides to prevent overheating during the summer and cooling down in the winter. Le Corbusier developed an idea for a climatic active façade: the 'mur neutralisant'. This idea consisted of two membranes of glass, which closed of a volume where depending on the climate, hot or cold air was pushed inside. This way the wall neutralized the outside temperature and other exterior influences on the interior. His idea has however not been realized into a satisfying stage.

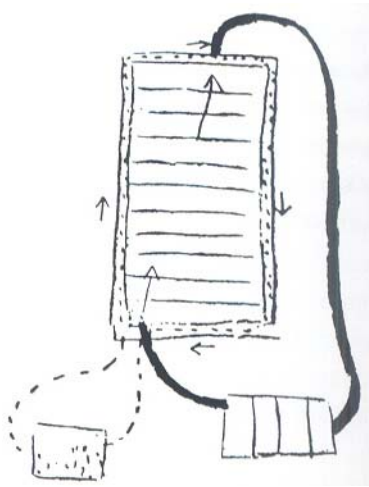


Figure 15: Mur neutralisant of Le Corbusier (source: [5])

After Le Corbusier's idea of the 'mur neutralisant' other concepts were developed where the façade played a more active role with regard to the inner climate. From the forties till the sixties Buckminster Fuller, Norman Foster and Frei Otto developed ideas to create a large environmental envelope as a façade to create an independent microclimate between inside and outside. None of their ideas were ever realized but formed the background for the development of ecological architecture in the U.S. before the energy crisis.

An important driving force for new façade technology was the already mentioned polyvalent wall of Mike Davies [21]. The basis for Davies' idea was formed by the problems which were encountered during the energy crisis in the façade industry: the metal-glass façade appeared to be not energy sufficient unless new discoveries were done. Architects realized that unlimited energy resources like the sun could play an important role in this, which resulted in architecture with glass on the south façade to get solar energy inside and a closed north façade which limits the energy losses. The use of glass would be strictly limited with this strategy.

Davies, however, argues for the development of general design strategies for energy economical buildings, in which highly insulated fabric and efficient services measures will play a major part. Because light, views and contact with the outside world is still searched for, the use of glass is still very important. Besides that, he argued, is silica which is the base material for glass, the most abundant element on earth. He saw that the success of glass lies in the combination of this material with other elements, like curtains to stop the light and the sound, shutters to reflect heat and blinds to stop glare. The polyvalent wall itself was also to be build up from different layers on a glass layer to be an absorber, radiator, reflector, filter and transfer device at the same time. The necessary energy needed to be gained by the façade itself. The wall needed to operate at a molecular level rather than at a mechanical level. To secure that the façade acts like an automatic responder to the outer circumstances on one hand and the inside users on the other hand the facades needs to have a local micro-brain and sensing nodes connected to a control

processor which carries information on use schedules, habits and environmental performance data from the users of the building.

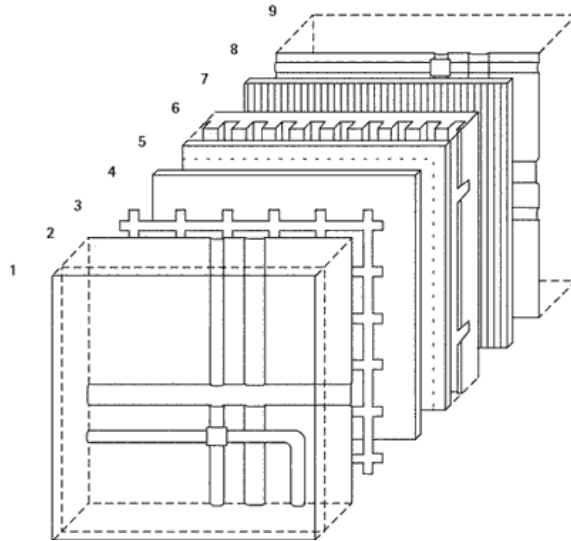


Figure 16: The polyvalent wall of Mike Davies (source: www.hl-technik.de)

Unfortunately the glass industry has never been able to realize this idea. But the idea was not without effect: it formed the basis for many new façade technologies and it could even be considered as the preliminary idea for the service integrated façade, the façade which is aimed for in this project.

Davies wrote the article on the polyvalent wall during his work period for Richard Rogers and Partner in London. Perhaps the ideas of Davies have had an influence on some of the ideas of that office afterwards. A few years later in 1986, after the publication of the article the Lloyd's Building was built after a design of this office. The façade of the Lloyd's Building is an exhaust facade consisting of a multi-layered façade structure.



Figure 17: Lloyd's building, London 1986, designed by Richard Rogers (source: [5])

According to Knaack et al. in [5] the exhaust air façade normally exists of a layer of single glazing on the inner side and a layer of double glazing on the outside; the façade of the Lloyd's building exists of a layer of double glazing on the outside in combination with a layer on the inside which consists of the sun shading screen. The working principle of the façade is that the exhaust air from the rooms is drawn into

the space in between the two façade layers. From there ducts lead the air to an exhaust point on the roof. This principle enables the application of heat recovery. The sun warms up the air in between the two layers, which also can contribute to higher savings in applying heat recovery. The exhaust air ducts on the Lloyd's Building are clearly visible on the outside.

Exhaust air façades differ from double facades in the fact that they need mechanical ventilation to get the principle working. Although the double façade has already existed since the 17th century, where during cold times a second layer of glass was placed in front of the existing windows, the use of extra glass layers possibly with a sunscreen in between can be considered as an attempt to realize the idea of the polyvalent wall. During the late eighties and the beginning of the nineties the double glass façade became popular in attempts to create energy sufficient, yet comfort providing facades. Whether the idea for a double glass façade is actually directly derived from Davies' idea is not the issue; the goal of both ideas come down to the same.

Double skin facades appeared to be most useful for buildings with high sounds loads and for facades exposed to high wind loads, where the outer sun shading must be protected and possibly to enable natural ventilation.

The fact that there are different types of double facades is mainly caused by the presence or absence of a division of the cavity between the two layers. Herzog [1] and Knaack [5] have approximately the same subdivision of double skin facades:

- Box window façade
- Shaft-box façade
- Corridor façade
- Second skin façade without interruptions in the cavity

Box window facade

This type of double skin façade consists of a façade with an interruption of the cavity in both horizontal and vertical direction.

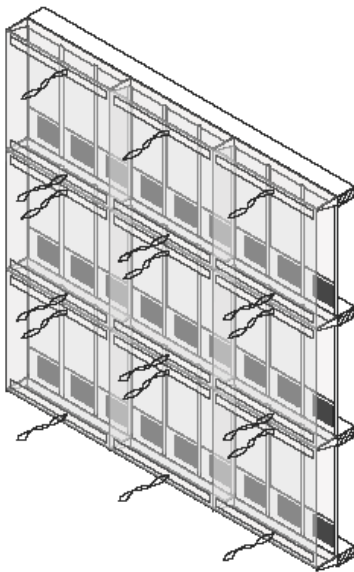


Figure 18: Scheme of the box window façade (source: [5])

Shaft-box façade

This type of façade has been derived from the same construction principle of the box-window façade. Box windows and shaft elements alternate, and the shaft elements extend across several storeys.

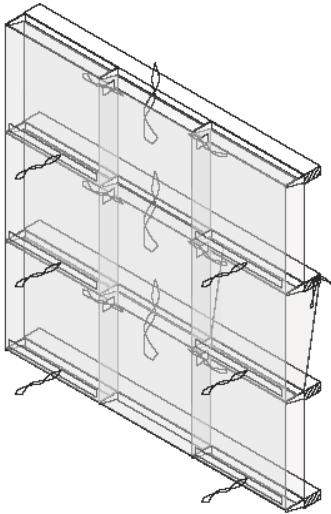


Figure 19: Scheme of the shaft-box façade (source: [5])

Corridor façade

The double façade is separated each storey, so the air is managed storey by storey. This division prevents overheating of the air in the cavity, because the air inlet and outlet find themselves respectively on the upper and lower part of the floor.

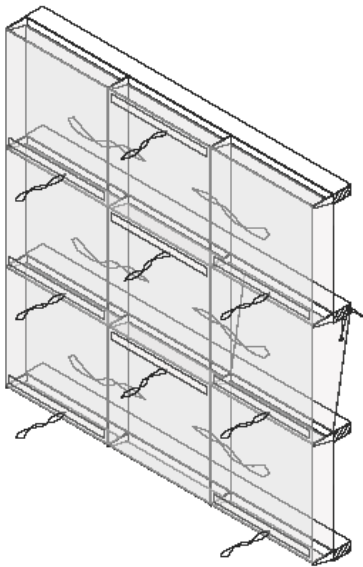


Figure 20: Scheme of the corridor façade (source: [5])

Second skin façade without interruptions in the cavity

The air in between the two façade layers functions as a buffer which envelopes the entire building. The rooms are then often ventilated mechanically.

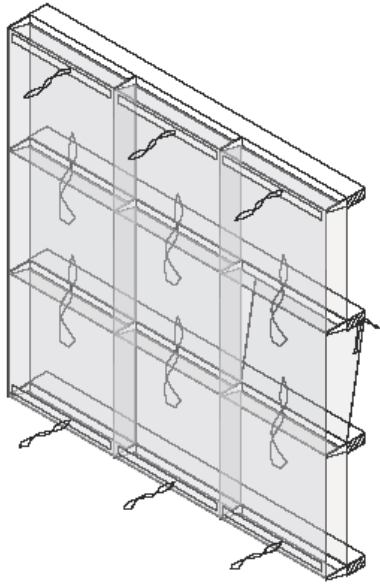


Figure 21: Scheme of the second-skin facade

The future tendency of facades is that more functions are integrated in facades. According to U. Knaack et al in [5] this is already the case since Mike Davies came up with the polyvalent wall [21]. Facades should be able to adapt themselves to changed outdoor conditions and changing user demands.

In [5] is mentioned that, next to common functions as ventilation, thermal insulation, light steering and solar protection, facades should have functions to gain energy, to store energy and to save energy. These functions can be integrated in the façade, preferably in small units, so adaptations can be made more easily, both in a functional and in an architectural way.

This trend can not only be observed in the integration of different elements in a façade; also the allocation of more than one functions to one element. An example is electro-optic layers. Usually these glass sheets transmit a certain amount of daylight. By applying a voltage, the light and/or solar transmission of these layers can be actively controlled in accordance with the prevailing light or weather conditions, either via a central building management system, or via microchips integrated into the glass skin [4].

There have been several attempts to produce service integrated facades. Some producers of these systems claim that their facades are the facades of the future, because of the high comfort level and the energy savings that can be reached. System developer Schüco developed the E²fassade and Hydro Building Systems developed the TEmotion façade. These systems can actually be the future of facades. They will be studied and analyzed more closely in the next chapter together with other systems.



Figure 22: E2 fassade by Schüco (source: Profile, Magazin über Architektur 05)

3 Modularity

The idea to search for a new façade system as a competitor for the curtain wall in the field of modularity came from the chair 'Design of Construction'. In order to find the opportunities and advantages of modular systems, modularity will first be studied. From other fields of industry, modular advantages could be overtaken. From the literature must be derived what rules and conditions building according to modularity has in order to be able to take over the advantages.

3.1 What is modularity

In order to avoid misunderstandings in the terms round modularity, some of them will be explained. The descriptions of the terms have been found in the literature on this subject.

Product architecture

K. Ulrich [11] describes product architecture as the scheme by which the function of a product is allocated to physical components. More precisely it is described as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components.

Product architecture is important because of the possibility of manufacturing firms to choose product architecture as a key driver of the performance the firm, and is therefore important in managerial decision making.

The first main two types of product architecture are integral product architecture and modular product architecture. These two extreme types of product architecture have different interfaces: integral product architecture has a complex mapping from functional elements to physical components and / or coupled interfaces between elements. Modular product architecture has a one-to-one mapping: that means that there is a one-to-one relation between functional elements and physical components.



Figure 23: Example of integral product architecture: a notebook (source: www.apple.com)

Figure 24: Example of modular product architecture: a personal computer (source: www.apple.com)

Modularity

Modularity (in design) refers to development of a complex product (or process) from smaller subsystems that can be designed independently.

Interface

Besides from the one-to-one mapping, the interface of modular architecture has another distinctive property in comparison with integral architecture: the interface coupling. Modular architecture has a de-coupled interface, integral architecture a coupled interface.

A coupled interface of two components means that when a change is made to one of the component, a change to the other component is required in order for the overall product to work correctly.

According to Ulrich [11] is a component a separable physical part of subassembly.

Types of modular architecture

Modular product architecture can be divided in different groups. Ulrich [11] divides three different types of modular architecture: slot, bus and sectional. Each of these three sub-types is modular, each embodies a one-to-one mapping between functional elements and components, and the component interfaces are de-coupled; the differences among these sub-types lie in the way the component interactions are organized.

Slot

Slot architecture means that various components in the product cannot be interchanged. A good example of this type of modular architecture is the car radio. The car radio implements exactly one function and is de-coupled from surrounding component; its interface however is different from any of the other components in the dashboard, and can therefore not be replaced by a component with another function, like speedometers.



Figure 25: Example of slot architecture: the carradio (source: www.levelelectronica.com)

Bus

In bus architecture there is a common element, the bus, to which the other components are connected; the type of interface of the components is the same, which means they can be replaced by components with different functions.

An example of bus architecture is a personal computer with an expansion card.



Figure 26: Example of bus architecture: the USB connection (source: www.cepolonia.com)

Sectional

In a sectional architecture all the interfaces are of the same type and there is no single element to which all the components attach. An example of this type is most piping systems.



Figure 27: Example of sectional architecture: a expandable piece of furniture (source: www.hennenfurniture.com)

Product change

The architecture of a product determines how a product can be changed. When a component of the product is changed, it is depending on the interface of the product whether other components need to be

changed. Fully modular products could allow components to be changed without changing other elements. On the other hand, components of fully integral products can't be changed without changing other components.

Ulrich makes a distinction in the different types of changes a product can undergo:

- *Upgrade:*

as technological capabilities and user needs evolve, some products can accommodate this evolution through upgrades. An example for this kind of change is the processor board of a computer.

- *Add-ons:*

this type of change means that users can add components to a basic unit. Those components are either produced by the same company as the basic unit, or by a third party. This type of change can also be found in the computer industry.

- *Adaptation:*

when a product needs to be used in a different environment, it might be converted. Engines can for example be converted from gasoline to a propane fuel supply.

- *Wear:*

during the usage time of a product, components may deteriorate, so replacement is necessary. Tyres on vehicles are a good example for this type.

- *Consumption:*

the difference of consumption and wear is that consumption is a typical goal of the product, while wear is not desirable. Examples of this type are cartridges for printers and copiers and film cartridges for cameras.

- *Flexibility in use:*

some products can be during the usage time be changed by the user, in order to exhibit different capabilities. An example is a camera that can be used with different types of lenses.

In my opinion the reasons Ulrich gives are not complete and sharp enough. For example, upgrade as a reason is too broad; upgrade is a form of product change, not the reason. The reasons for upgrading can be diverse, like a wish to keep up with the latest technology.

Moreover, as a reason for product change, Ulrich mentions wear. There could be a difference be made between damage and wear. A glass panel for instance is not likely to show signs of wear, but is more likely to be damaged. In addition to the above list, the following could make the list more complete:

- Damage / break down
- Change of fashion
- Change of environment
- Change in regulations
- Change of user (or user demands)
- Change of technology
- Change of awareness

Modular architecture of products enables these changes; most changes are possible with minimum change of other components. Usually modular architecture is used for the replaceable components for the types of change consumptions and wear; another popular strategy is to dramatically lower the cost of the entire product, often through an integral architecture, such that the entire product can be discarded or recycled. An example is the difference between a photo camera with an exchangeable film and a disposable camera. The camera with the exchangeable film is expensive and just a cheap part is suitable for exchange very often. The disposable camera on the other hand is a very cheap product, so it is suitable to discard or recycle after using it.

Product variety

Ulrich defines product variety as the diversity of products that a production system provides to the marketplace. Product variety has emerged as an important element of manufacturing competitiveness. High variety can be produced by any system at some cost. By having the right equipment, components with the same function could be produced in different forms, for example on user's desire. Technically this is feasible, economically however, dramatically. The equipment will be very expensive. The challenge is to create the desired product variety economically.

The ability of a firm to economically produce variety is frequently credited to manufacturing flexibility. In this context, a flexible production process incurs small fixed costs for each output variant and small changeover costs between output variants.

To customers, variety is only meaningful if the functionality of the product varies in some way. Besides technical changes, the functional change can also be a change in appearance.

A product platform contains common units and units that vary between different market segments. The units in the last category carry the product identity. This could have a relation with the building typology problem: define what units are common units and what units should be specials. A modular product or system has certain parts which are common for the whole product line. Parts carrying functions required by all customers are possible candidates for common unit modules. Parts of the product that strategically should vary to satisfy customer needs are well defined and separated from the parts of the product that should be kept as common units.

Varying in the other parts delivers the actual product variety.

In this case, the design of a new façade system, product variety and flexibility are related. Variety enables the designers to vary in the solutions made with the same parts.

To handle product variation and customization effectively, a designer should strive to allocate all variations to as few product parts as possible. In products, some parts may strongly be influenced by trends and fashion, or closely connected to a brand or trademark. Therefore, styling modules that typically contain visible parts of the product should be used to underline product identity. These modules could very well be the special units. In case of a façade system, this principle can be used to offer design flexibility to the client.

To link this with the product we are aiming for, the following question might help: what does the company wants to achieve with a modular solution? The façade company, in this case Alcoa, wants to have a system, which can be developed in accordance to the regulations, which will be stricter in the future. The company is looking for a completely new direction in facade development.

The objective of the modular façade is to achieve the above described, and to fulfill these other requirements:

- Keep the product up to date with the latest wishes of the users
- Keep the product up to date with the latest regulations
- Provide enough design freedom so that it will be used by architects.

The objective of a modular product platform is to create a strategically flexible product design that allows product variations without requiring changes in the overall product design every time a new product variant is introduced.

Instead of searching for “an optimal design for an optimal product”, the objective should be to create a strategically flexible product design, allowing product variations without requiring changes in the overall product design every time a new variant is introduced.

This matches pretty well the goals of a façade company: their products must be flexible during a longer period. By keeping some of the parts of the products and with minor changes to other parts, the product can be kept up to date for a long time.

Standardization

The definition of standardization given by Ulrich [11] is that component standardization is the use of the same component in multiple products and is closely linked to product variety. Component standardization occurs both within a single firm, and across multiple firms. The first case is called internal standardization, the second case external standardization.

Standardization can arise only when:

- a component implements commonly useful functions
- the interface to the component is identical across more than one different product

Otherwise, a component would either not be useful in more than one application or would not physically fit in more than one application.

Modular architecture increases the possibility for standardization. If a product is being created with a one-to-one mapping, thus with one and only one function for each component, it is useful to use such a component in other products or product applications.

Modular architecture also enables component interfaces to be identical across several products. Especially when the interfaces of modular architecture are de-coupled (a change of a component does not result in a change for the surrounding components); for different products an interface standard can be adopted and the same component can be used in a variety of settings.

Performance

Product performance is defined as how well the product implements its functional elements. Modular architecture allows optimization of performance characteristics of a component.

When the use of standardization is possible, the product's firm can use several companies to deliver optimized components for the product. Or, when the firm of the product needs to develop the components itself, they can be designed, tested and refined focused, without disruptions and distractions.

The choice for an either modular or an integral approach of the product is depending on several organizational issues. Highly modular designs allow firms to divide their development and production organizations into specialized groups with a narrow focus.

3.1.1 Modular vs. integral

In most cases the choice will not be between a completely modular or completely integral architecture, but rather will be focused on which functional elements should be treated in a modular way and which should be treated in an integral way.

To come to a choice of the architecture of a product the previously mentioned topics need to be analyzed. Ulrich [11] formulated for each topic a number of questions to be answered, in order to choose the right architecture (integral vs. several modular types).

Product change:

- Which functional elements are likely to require upgrade?
- Are third-party add-ons desirable?
- Which functional elements may have to be adapted to new use environments over the life of the product?
- Which functional elements will involve wear or consumption?
- Where will flexibility in configuration be useful to the user?
- Which functional elements can remain identical for future models of the product?
- Which functional elements must change rapidly to respond to market or technological dynamics?

Product variety

- Which variants of the product are desirable to best match variation in customer preferences?
- What level of flexibility of component process is available or easily obtained?
- How much advantage does minimizing order lead time for custom products provide?

Components standardization

- Are existing components available internally or externally for any of the functional elements of the product?
- What are the cost implications of sharing a component with another product?
- Where can adopting a standard component reduce development time or complexity of project management?

Product performance

With local product performance is mentioned the way a function of a product is executed, which does not influence the whole product, just a part of it. An example of this is a local product performance of a car: the seat of a car offers a certain comfort. To which extent this is done does not influence the performance of the car, merely the performance of the chair: a local product performance.

Global product performance is the way the function of product performs on product level. This can be

explained better with an example, again with the help of a car as a product: the aerodynamics of the car is a function which influences the whole performance of the car. When this is not well done, the whole car will have a lower success.

The questions that should be asked on these topics to choose between integral and modular are:

- Which local performance characteristics are of great value to customers and can therefore be optimized through a modular architecture?
- Which global performance characteristics are of great value to customers and can therefore be optimized through integral architecture?

Product development management

- How much focus and specialization is present in the organization and in the supplier network?
- Is the product inherently large and complex?
- Is the development team geographically dispersed?
- Are barriers to architectural innovation developing in the organization because of specialization?
- Has the organization demonstrated an ability to change in structure and style?

Since the project aims for a modular system, the question whether it should be integral or modular is irrelevant. The questions which have been stated here can however be of help in determining whether the use of modularity was pertinent or not. At the end of the process some of these considerations can be studied to judge the choice for modularity in this design.

3.1.2 Drivers for modularity

To find out what modularity can actually bring the product the advantages should be listed. According to A. Kamrani et al [10] modularity in product development has a number of advantages. The advantages are:

- *Reduction in product development time:*
De-coupling of the modules of the product reduces the complexity of the product and enables development of different components simultaneously.
- *Customization and upgrades:*
Modular products accomplish customer requirements by integrating several functional components interacting in a specific manner.
- *Product variety:*
Modular components are used in several product lines; combining components in different ways leads to high variety with the same amount of modules.
- *Quality:*
Modularity allows production tasks to be performed simultaneously. Thus, independent components can be produced and tested separately before they are integrated.
- *Design standardization:*
Modular design facilitates design standardization by identifying the component functions clearly and minimizing the incidental interactions between a component and the rest of the product.
- *Reduction in order lead time:*
Modular products can be made by combining standardized and customized components. This allows standard components to be inventoried, and then customization can be focused on the differentiating components.

Without having an actual façade design it is hard to judge whether these advantages are useful for façades. In the end of the process the advantages of the façade system and the modular advantages will be compared to find out what modularity brings for the façade and if that is useful.

3.2 Modular solutions in product development

Besides the general information on modularity actual products give information on the way modularity has been implemented on a successful or innovative way. The goal of these studies is to find out what can actually be learned from those products and applications of modularity? In the end of this paragraph there will also be a look at modularity in façades.

Skateboard car General Motors

In 2002 General Motors came up with the Skateboard car. The chassis contains all of the sedan's propulsion, transmission, steering and braking components within its 30 cm high frame and provides a single electronic connection to the body. Standardizing the chassis will increase the efficiency to automotive production, while enabling automotive designers to tailor model designs to the interests and needs of the consumer marketplace. GM mention that the concept of building a chassis upon which multiple designs could be placed may have application in the building industry, particularly in manufactured housing where chasses are built today to carry manufactured housing systems to the site for placement.

Much of the global product performance depends on the exterior casing of the car, for example the appearance, the aerodynamics and the passenger capacity. The local product performance functions depend on modular units which can be placed onto the chassis, like the chairs, the lights and the audio installation.



Figure 28: The chassis and skateboard of the skateboard car (source: www.gm.com)



Figure 29: The skateboard of the skateboard car (source: www.gm.com)

Sony Walkman

In the 1970's Sony developed the walkman. The first model, the one in the middle, is not labeled as walkman. The other ones, who have a slight difference in appearance, contain the same technique, but are labeled as walkman and were brought on the market as a new product. So Sony sold the same technique with different names and slightly different appearances.

This is also an example of modularity where the exterior of the product undergoes changes, made possible by the modular product architecture, resulting in a product which can have a long lifetime on the market.



Figure 30: The Sony walkman and its precursors (source: www.ericwrobbel.com)

Nike ID

The Nike ID shoe is an example of a highly customized product. By means of a webpage the materialization, colors and even texts can be chosen in order to create a shoe after the customer's own wishes.

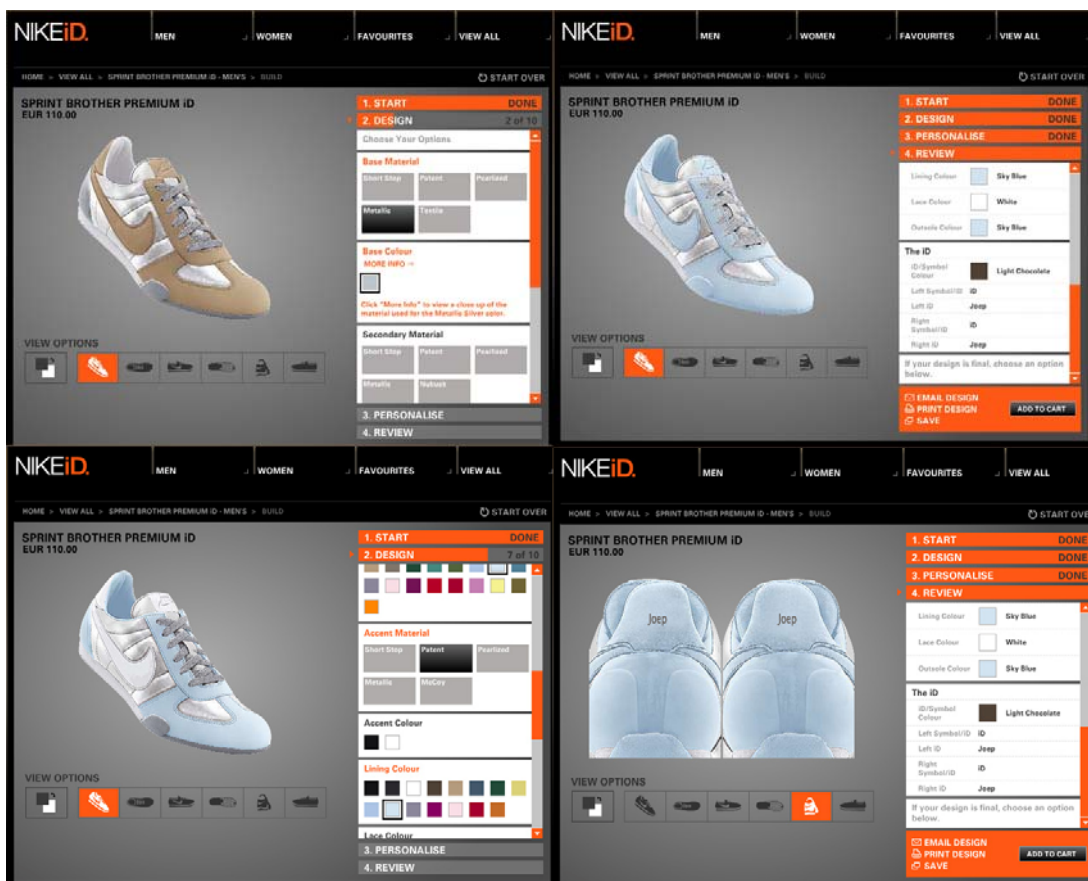


Figure 31: The Nike ID website (source: www.nikeid.com)

Computer

The personal computer is an example of modularity. The computer exhibits modularity on different levels. First of all the computer housing, the screen, the mouse, the keyboard and the speakers form different modules. They can be separated from each other without disturbing the connections (de-coupled interfaces) and they all have their own unique function (one-to-one mapping).



Figure 32: Modular example of the computer (source: www.apple.com)

The computer housing itself offers in his turn room and input for other modular units, such as the hard disk, the motherboard and the cd-rom player. When the computer housing is opened the different units can be replaced easily. Also for these units the conditions of modularity count. Taking a closer look on some of these modular units even a smaller level of modularity can be found. The motherboard can for example be extended with new or extra memory.

These different levels of modularity will be an issue in the façade design as well. More on that can be found in the next paragraph.

3.3 Modularity on different levels

Current façade systems can be regarded modular as well. Nearly all the parts of the curtain wall possess exactly one function and their mutual connections are de-coupled. This is however not the level of modularity which is aimed for in this project. Current facades are modular on element level. In [23] Eekhout distinguishes different levels of building products, based on the level of assembly and added value:

- raw material
- material
- composite
- trade material
- element
- component
- building part
- building segment
- building
- building complex

The domain of the product developer starts at the sub-element and stops with the building segment. With element is meant the smallest part of a building, created of one material or composite. Combination of different elements leads to sub-components or components. This definition of an element matches the definition of modularity in a way: elements fulfill one function and can be combined to a component, which fulfills the desired function of the combination of elements. The current metal-glass facades are composed from different elements.

Components are independent functioning parts, which are composed from elements and/or sub-components. These parts are assembled outside of the building site and are transported to the site, where they are installed.

The desired modularity level for this product will lie on the level of components. One of the goals of the new product is the function integration, especially integration of building services. Decentralized climate units as they are on the market now are prefabricated and pre-assembled components.

3.4 Modularity and facades

As already mentioned in chapter 2 a number of façade system manufactures and architectural companies has already developed service integrated facades with modular building service units. In this paragraph these systems will be examined more closely.

Existing façade systems or concepts:

- Wicona: TEmotion façade
- Schossig and Gattermann: Capricorn Haus
- Schüco: E² façade
- Cepezed: Smart Box Energy Facade

3.4.1 Schüco: E² façade

Description of the system

In principle is the E² façade, developed by Schüco, more of a concept than a product. The E² stands for energy saving and energy production. A realization of the concept has been exhibited at BAU 2007 in Munich. The mock-up presented here is in fact a conceptual realization of the concept, but Schüco is able to produce facades according the basic concept using their (newest) post-beam systems, multifunctional panels and decentralized climate units.

All opening units in the façade system have a uniform appearance. The steering of the openings of the façade as well as the ventilation systems is done by a fully automatic system. The system monitors the CO₂ level in the room, regulates the heating when the windows are open and controls the automatic night cooling. The façade profiles accommodate all the service and wiring systems and provide intuitive operating devices that have been integrated into the façade profiles.



Figure 33: Realization of the E2 facade of Schüco on BAU 2007 (source: Profil, Magazin über Architektur 05)

Goal and possible applications of the façade system

The goal of the concept is creating a façade solution that combines on an esthetical way the façade functions ventilation and air-conditioning, operable elements, sun shading and solar cells. The higher goal of the façade is to build buildings that produce more energy than they use.

Functions of the units in the façade

The reason the façade functions have been solved in a decentralized way is that the relatively high energy savings and at the same time an improvement of the individual influence on the inner climate and with that the quality of the inner climate. The mechanical components for ventilation, heating and cooling have been placed at the floor edge of the façade. This spot has been chosen because than it has the least influence on the design of the façade; this way of placing the units enables floor-to-ceiling glazing in new and renovated buildings.

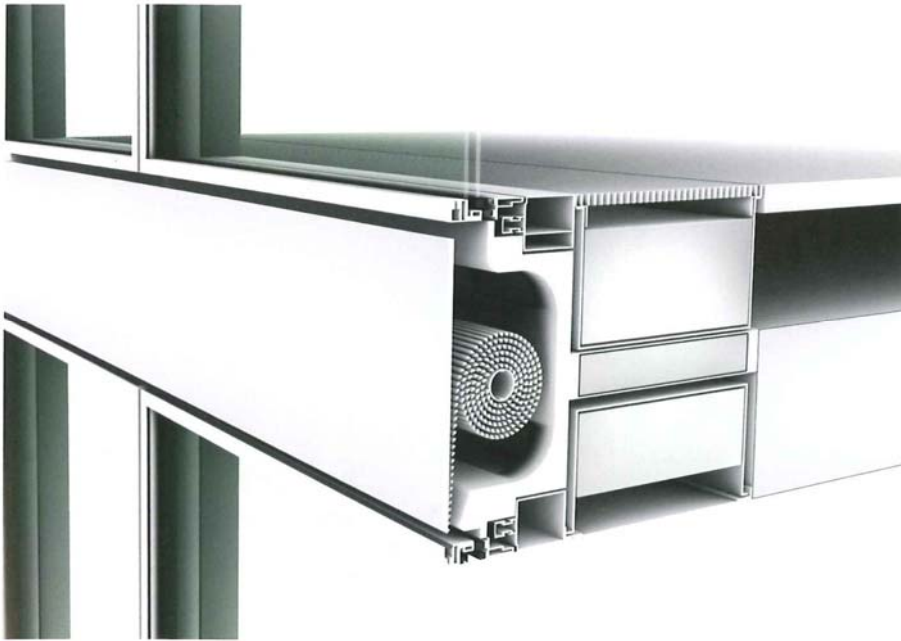


Figure 34: Section over the floor and façade of the E2 fassade. (source: Profil, Magazin über Architektur 05)

The decentralized ventilation technology performs various functions, including ventilation, heat recovery and heating and cooling of incoming air.

The modular design enables the façade to be adapted to different building types and user situations. Customized solutions can be created to enable the user to adjust their surroundings to achieve their own personal comfort level.

The energy of the façade is gained by translucent or even transparent (when the panels have been perforated) solar panels. The solar cells function as sun shading. Using these cells on all the surfaces of the building, the building will turn in its own power plant.

Schüco offers both modular systems with interfaces to enable technical upgrades and integral concepts for a multifunctional building envelop.

The sunscreen which is used in the façade is of high performance using micro louver blades. These guarantee optimal protection while ensuring maximum visibility to the outside. The sun shading can also be used at very high wind speeds and is therefore also suitable for high rise buildings.

Advantages of the system

- Sustainable by generating (PV cells) and saving energy (high insulation values)
- Integration of functions
- High comfort level because of individual control possibility

Disadvantages of the system

- Limited design possibilities due to a fixed layout
- The system combines existing elements, so deals with the same problems as the current metal-glass façade

3.4.2 Hydro Building Systems: TEmotion

Description of the system

TEmotion is claimed by its producer Wicona (part of Hydro Building Systems) to be the façade of the future. TEmotion is a synthesis of technology and emotion, developed by the façade company Wicona and the University of Dortmund.

The façade is built of a combination of glass elements in which sun shading and natural light improving elements are integrated and functional elements in which building services and solar cells are integrated. Those two elements together form an element, so the façade could be considered an element façade. The combination of the glass element and the functional element can be chosen freely to some extent, which gives the designer of the building implementing the façade some design freedom, according to the producers. The raster of the system can be chosen freely, as can the relation between the number of glass elements and functional elements. Also depending on the size of the room, the office behind the façade needs at least one functional element to equip the room with sufficient ventilation, heating and cooling.



Figure 35: (left) Outside image of a realization of the TEmotion (source: promotion material of Wicona)

Figure 36: (right) Inside image of a realization of the TEmotion (source: promotion material of Wicona)

Goal and possible applications of the façade system

The façade aims to be energy-saving and to achieve a high level of a well-being for the users. The producers also want the façade to be a bridge between building technology and personal architecture.

Other specific goals and features of the façade are:

- Making the façade modular and use a plug-in wire technology (plug & play). By that the amount of wiring in the façade is reduced by up to 60% and the designers and users can chose whether or not they install a certain functional element from the beginning; it can be decided to add or remove elements in a later stage of the user phase.
- Sustainability and self-sufficiency by using photovoltaic cells to produce electrical energy. Besides this the whole life cycle including recycling has been thought trough.
- High quality guaranteed by prefabrication
- Integrated control system; this leads to a reduction in used electronic control units. It controls the ventilation, heating and cooling system, the sun shading, the artificial lighting and the media.

Functions of the units in the façade

All components of building services which are integrated in the functional element can be controlled through a central building services management system or by the user him- of herself. In addition, the façade controls itself and reports possible maintenance requirements to the control centre. Photovoltaic

cells in the elements are used for generating energy and supplying the building installations with electric current.

For most variants the glass element consists of two glass layers. The way this element is built up can be seen in this picture. The integrated functions are mainly to regulate the light.

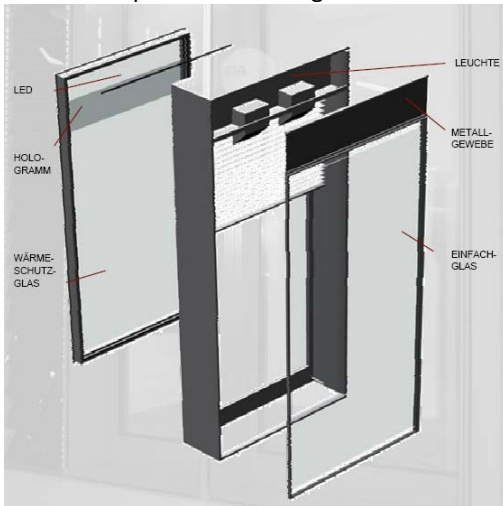


Figure 37: Element of the TEmotion by Hydro Building Systems (source: promotion material Wicona)

In the functional elements the integrated functions are:

- Heating
- Cooling
- Ventilation (mechanical and natural)
- Lighting (artificial)
- Renewable energy generating systems
- Media
- Service management system

The mechanical ventilation, heating and cooling have been combined in one element produced by Trox.

The sizes of this element are 0,30 m x 0,40 m x 1,30 m.

The size of the service management system is 20 cm x 15 cm x 45 cm.

The total depth of the façade is 45 cm.

The way the components are put together in the functional elements is shown in this picture:

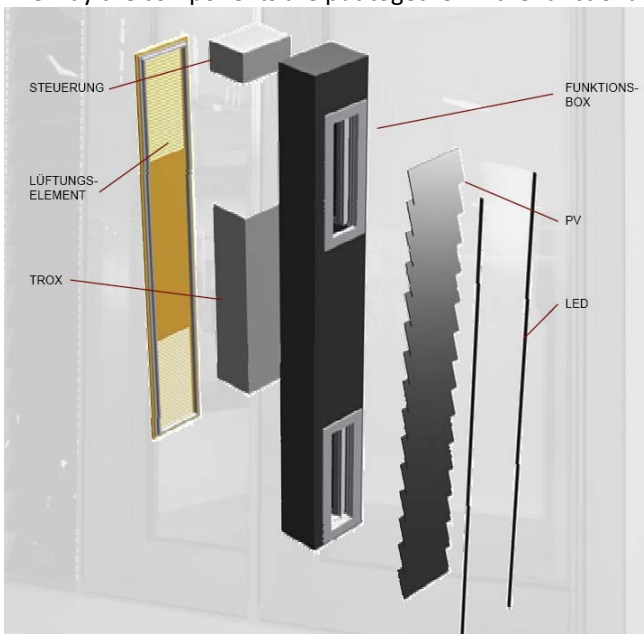


Figure 38: Component of the TEmotion by Hydro Building Systems (source: promotion material Wicona)

In November 2005 the TEmotion façade won a gold medal on the Batimat in Paris.

Advantages of the system

- Integration of decentralized climate units and other functions, like energy gaining
- Prefabrication of all elements guarantees a high quality
- Reduction of the amount of wiring compared to other service integrated façade systems
- Vertical organization of the façade functions, so easy to reach modules.

Disadvantages of the system

- Limited design possibilities due to a fixed layout; the system is an element façade that offers only six different possible configurations
- The system combines existing façade elements with existing products, so deals with the same problems as the current metal-glass façade

3.4.3 Schossig and Gatermann: Capricorn Haus

Description of the system

The façade has been designed especially for the building, an office for the Capricorn institution. The building is supposed to be a low-energy building, which has been tried to achieve by the meander-form of the building plan and therefore possible implementation of atria, and the compact building form. Besides that the high insulation values, the use of decentralized building services, heat recovery and thermal active mass contribute to an energetically balanced building concept. The façade is built up from especially produced units enabling decentralized ventilation. The façade elements are completely prefabricated and have sizes of 2,70 m x 3,35 m; they have been placed on a 1,35 m based raster as have the inner walls. The façade modules have been connected to the building from floor to floor. Each room has at least one of these modules because the inner walls can be connected to the sides of the modules.



Figure 39: Capricorn Haus, Düsseldorf 2005, designed by Gatermann and Schossig (source: own picture)

Goal and possible applications of the façade system

The façade system has been designed especially for the building and not so much as a system on its own. The goal of the façade was to reduce the use of energy by creating a façade with a sound relation between closed panels and the link between inside and outside. Behind the closed panels the architects placed a specially designed multi-function panel, the so called 'i-modul Fassade'. The panel should be able to facilitate in different functions for the benefit of the inner climate.

Functions of the units in the façade

The 'i-modul Fassade' has been developed by the architects of the building Gattermann and Schossig together with the firm Trox/FSL, so is specially designed for this building and is not a product from the catalogue. The module was based on the idea of the architects to produce a façade that helps to be free in the interior building planning by placing all kinds of building services inside the façade. The functions that have been placed inside this module are:

- Individually controllable ventilation combined with heating, cooling and air circulation
- Possibly night cooling

In short, the outside air enters the module by a closable gap on the outside of the façade and goes through a fine dust filter, a volume flow limiter, a heat recovery unit (air-air heat exchange with the exhaust air), a ventilator and a heat exchanger to the room. The air enters the room through a kind of grate in the parapet.

The exhaust air leaves the room through an exhaust valve in the parapet and goes through a rough dust filter, a heat exchanger and a ventilator to the outside.

The users of the façade can individually control the system.

The picture here below gives a complete picture of the functioning of the module.

Die dezentralen Lüftungsgeräte Serie FSL-B-ZAU

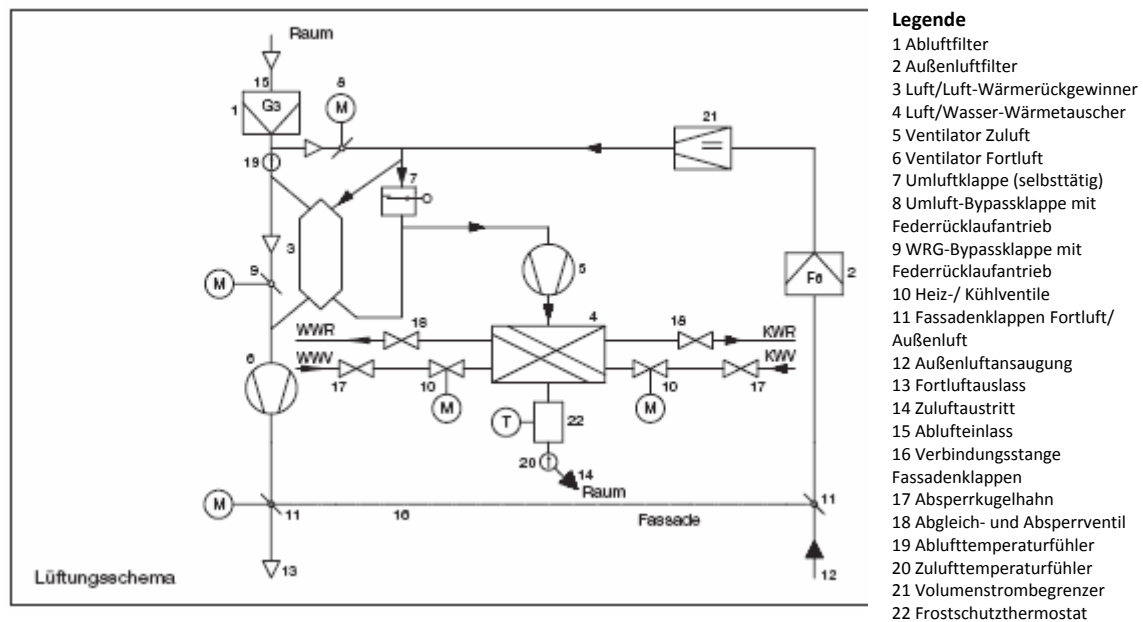


Figure 40: Scheme of the air stream of the Trox climate unit in the Capricorn Haus (source; Trox folder)

Apparently, the heat exchanger gets and hands over a cold and a warm water flow from or to an external source. The both mechanical valves and the air valves are driven by several motors, which obviously also need an (external) power source.

The developers have tried to keep the size of the i-modul limited in order to let the module merge in the façade without problems. The width of the module is 1049 mm, the height is 1065 mm and the thickness is 190 mm.

Other façade functions are not placed inside the i-modul, but are placed above and next to this module. Above the i-modul an operable window has been placed which also has a light steering function. The shelf which is placed behind this window helps to bring the incoming daylight further into the room behind. Next to the i-modul a storey high window has been placed to let the user view outside and to let more daylight into the room to reduce on artificial lighting.

In 2005 the i-modul Fassade won the "Innovationspreis Architektur und Technik 2005"

Advantages of the system

- Integration of building services and other functions in the façade zone, resulting in a free interior.

- Unique appearance of the building

Disadvantages of the system

- The façade is not so much a system, but is tailored for one specific building; it is therefore hard to judge as a standard system

3.4.4 Cepezed: Smart Box Energy Façade

Description of the system

The Smart Box Energy Façade is a façade system developed by the architectural firm Cepezed, consisting of a Smartbox and façade panels. The Smartbox is a decentralized unit which controls the room temperature and the relative humidity by combining the functions of heating, cooling and ventilation. The unit is positioned at the floor edge as an integrated part of the façade and can be combined with all kinds of façade panels. Together with the Smartbox several innovative façade panels have actually been developed to form the Smart Box Energy Façade. The façade panels are not necessarily part of the system, but they are very well applicable to it. One type of the developed panels is semi-transparent combining glass with a sheet of photovoltaic cells. Another type is high insulation glass panels.



Figure 41: Section over the Smart Box Energy Façade (source: www.smartfacade.nl)

Goal and possible applications of the façade system

The project aimed to develop an 'active' façade concept that uses active and passive solar energy and intelligence in the façade. The result is a potential 50% reduction of building related energy use at market conformable prices, combined with improved comfort.

Functions of the units in the façade

The Smartbox of the facade combines the functions ventilation, heating and cooling. The advantages of the Smartbox are:

- Heat and moisture can be regained with the heat exchanger for ventilation air.
- The heating and cooling is controlled by the heat pump, resulting in fresh air with the right temperature and humidity.
- The decentralized system makes a big system of pipes and shafts unnecessary; this also results in a saving on suspended ceilings. The absence of the ceiling makes the floor height smaller saving till 12% in façade costs.
- Installation costs are minimized by placing the system direct to the façade and using an electrical connection only.
- High energy savings by using a combination of a highly effective heat exchanger and a well performing heat pump.
- This decentralized system minimizes control losses and gives control to the user.
- The valves at the outside and at the inside part can be opened in a way that a by-pass is possible: fresh air is than blown in above the window or a bit further parallel to the ceiling. This system also enables a 100% by-pass for night cooling.

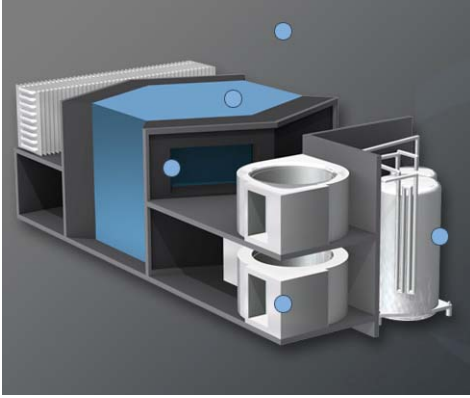


Figure 42: The actual Smartbox (source: www.smartfacade.nl)

In order to combine those functions the decentralized unit is built from several elements:

- The direction of the flows is controlled by an enthalpy exchanger (kind of heat exchanger developed by Recair). The enthalpy exchanger can regain moist from the exhaust ventilation air to bring the fresh ventilation air on the right humidity. Therefore the Smartbox only needs to be connected to an electrical network.
- The cooling and heating are controlled by a heat pump. The heat pump delivers the power for heating and cooling the space, which can be done in combination with the heat exchanger with the ventilation air.
- Adiabatic cooling is possible to save energy of the heat pump. Water supply is however necessary when is chosen to implement an adiabatic cooling device. Adiabatic cooling is cooling by vaporizing moist in the air without external supply of energy. In the Smartbox the waste air is cooled. The high effectiveness of the heat exchanger (air-air) makes it possible to cool the fresh air with the waste air (obviously without mixing the two air streams).
- Fans ensure the ventilation of the space. The energy use is low.

The maintenance costs of the Smartbox are low, air filters should be replaced once a year.

To give an idea of the dimensions of the Smartbox they are listed here:

- Width 112,0 cm
- Height 35,0 cm
- Depth 40,0 cm

The performance of the Smartbox:

- - flow: Nominal 100 m³/h
 Maximum 300 m³/h
- - power: Cooling 1900 W
 Heating 1100 W

The Smartbox has not been taken into production yet; at this moment several prototypes have been made.

Advantages of the façade system

- The use of a very well functioning decentralized climate unit (also see *advantages of the Smartbox*)
- Regular façade systems are used, so the planning of the façade is relatively free.
- The use of adiabatic cooling and heating by electricity could loose the water input in the modules.

Disadvantages of the façade system

- The façade combines the smart box with existing techniques of façade panels; problems of the current system must be dealt with
- It is possible to use the unit in one way: the building planning must be adapted to it

3.4.5 Evaluation of the systems

All the systems have a successful integration of functions, especially decentralized climate units. The units have been placed in strategically right places, so other advantages can be gained by it, like comfort (because of the right positions of air flows) and effective use of the space in front of the floor.

The disadvantage all standard building systems share, is the limitation in design. The façade systems all offer some variation, but the variations don't really differ from each other. Depending on the market the product is aimed for, this is an important feature of facades. Architects will be eager to design the façade image that they have thought through, belonging to the specific building; they won't be satisfied with images which have been determined by the industry.

Another disadvantage of the systems is that the innovation is created by combining elements and integration of functions, not in the façade technology. Therefore all systems still have to cope with the existing problems of current façade system, like the stagnating thermal performance. The systems are not revolutionary new enough to solve or to offer the possibility to solve the existing problems.

For the system to be designed in this project the integration of functions is important. As the other systems point out, the integration of functions, especially decentralized climate units offer many advantages.

The geometrical possibilities in the system are important. The façade system should offer enough variance to be interesting enough for architects. This demands is also stated in the program of demands; this feature can make the new system distinctive from the ones presented here.

Another disadvantage which is shared by all the systems is that they still have to deal with the existing façade problems, because the systems are still based on the existing systems. The innovativeness of the new system will therefore be an important evaluation criterion during the design process. Like the geometrical possibilities this could also lead to a distinctive system compared to the existing systems.

3.5 Building systems

Whether building systems like these, but also generally are a good idea has been explicitly put into words by Russell in [19]. He states his opinion on the use of building systems in a 900 pages counting book. Building systems produced by a globalized industry determine nowadays the architecture, without regarding the local tradition and values. The industrialized results seem ideal, creating standard solutions for all kinds of problems. These solutions pay homage to repetition and standardization in their appearance.

Russell shows with an example of Robert Bruno that the expression of technology can still be beautiful as long as the technology is expressed with human skill. Bruno built his own house singlehanded which, he believes, demonstrates that the use of industrialized materials can offer enormous creative possibilities if we are prepared to take them. Bruno spent years on the building site, feeling changes from hour to hour, season to season, becoming familiar with the mood of this place. He states that there is no better way to study the site as he did. His method, as he says, is in no way similar to studying site plans and climatic charts. Being constantly affected by this environment, one responds accordingly.

Russell draws a spectrum with on one end the regional approach of architecture and on the other end the international approach. Architecture that is at the regional end of the spectrum will be place dependent, rooted in the culture, related to the site and place, responsive to climate and custom, and will draw on local technologies. Architecture which is at the international site of the spectrum will be place independent, independent of local culture, free of the site (including surrounding buildings), independent of climate and will employ an international version of high technology. Many good buildings fall in the mid area of the spectrum since they attempt to reconcile the demands of context with the larger world of architectural ideas.

The systems of the previous section don't fit this profile: they could be regarded as a kind of globally applicable systems. Making the systems more flexible (using a clearer combination of standardized parts and location or client specific parts) would possibly lead to more success for these systems.

Success of the offered building systems depends on the freedom they offer. Producers of building systems take values, like local traditions, geometrical freedom and building traditions more or less into account. Like Russell states, these values are important, and therefore determine the success rate of the systems.

Again, this shows that the primary goals of the system (function integration and flexibility/upgradeability) must therefore be completed with the requirement of not losing geometrical freedom.

In order to understand the opinion of architects an inquiry has been done among architects. The questionnaire can be seen in Appendix III. One of the architects, H. Muhl, came up with an interesting idea; he stated that the building industry should show the way their products work, instead of just showing the architects what the product could do. That way the architects could by their technology and apply it on their own ideas. A reason that building systems are not wanted by architects, he says, is that the building industry just provides the architects with limited solutions, instead of explaining the way a problem could be solved. The industry and architects can then combine their knowledge, techniques and ideas to come to innovative building systems, in the beginning tailored to buildings, but later on possibly as standard systems.

The questionnaires pointed out that some other architects mentioned the costs of building systems as one of the biggest barriers, and not so much the limited design freedom.

The questionnaire did for now not give enough information on the opinion of architects on systems like these. Just four architects filled in the question list, which is of course not enough to get an overall opinion. When the research continues, this should be investigated further.

4 Design process

This chapter forms the introduction to the design part. The process which has to be followed will be described here. The design for a façade system calls for a design structure with influences from architectural processes and also with influences from processes of product developers. Obviously the façade system needs to be implemented on buildings so the architectural values and perspectives are undeniably important for the design process and the design itself. However, since it concerns the design of a product lessons can be learned from the design process often used by industrial designers. M. Eekhout is clearly in favor of this kind of processes: in [23] he states that many building engineers and architects don't use structured design processes. They are afraid that using a methodological and systematical approach of the design will lead to a lack of creativity in the process. Eekhout also points out that many architects try to cover up a bad design process by using vague and wooly language in describing their design for an audience. I'll offer no opinion on that statement, but in general the use of a methodological and systematical design process has many advantages especially in a design process for a building system like this. Working through a process systematically leads to more control on the design process. Particularly when more processes occur simultaneously, chronological reporting leads to a clear process. It offers the possibility to track and perhaps even to revise made decisions in the process when the outcome didn't work out the desired way. A part of the purpose of this research is to judge the modular façade concept. Within that framework the use of a process is important, because the outcome of the design is not necessarily modifying for the outcome of the evaluation of the modular façade concept.

4.1 The process

According to Roozenburg and Eekels the design process consists of different steps and evaluation moments: the whole process has an alternating divergent and convergent nature. With divergent is meant that the number of solutions or ideas increases, with convergent is meant that the number of solutions or ideas is narrowed down. To converge the process an evaluation moment is necessary, to select the best ideas based on requirements and demands. In the end it must lead to one design solution.

4.1.1 The first step: associative method

The design process starts with an associative method in order to gain principle solutions or starting points from the first product idea or assignment. Associative methods use the principle of relating and connecting different thoughts. Some of these relations between thoughts are evident, but sometimes the invented relations of thoughts are not evident, but surprising. This leads to new solutions and new views on the problem; therefore this method is suitable in the beginning of the progress.

The used associative method in this process is a the most known one: brainstorming. The method lets people work together in a way that the production of different and new ideas is stimulated. To let the brainstorm be successful a number of general rules must be taken into account:

- Critics during the brainstorm is forbidden; the participants should not think about use, importance, feasibility and things like that during the brainstorm: the judgment of the ideas must be postponed. This rule is very important to prevent the participants to feel offended, so the second rule cannot be applied.
- Generate ideas freely; every participant must feel free to express every idea. The atmosphere during the brainstorm must therefore be comfortable.
- Associate further on the ideas of others; besides creating new ideas, the participants should strive to progress on the ideas of others.
- Try to think up as many associations as possible; this last rule is used to create a high association speed. The reason for this is that quantity of ideas leads to quality, and that by a high sequence of associations the critical input of participants is banned.

The brainstorm of this project was lead by a method created by W. Poelman [20] where functionalities and technologies are related based on constraints and situations in which the product may find itself.

The following scheme represents the process: based on the product idea functionalities will be thought up and will be related to potential technologies based on knowledge of technology. With functionalities is meant 'a new trick': a functionality doesn't serve any objective, except letting people wonder. By combining a functionality with a technology there is a use for the trick and the functionality becomes a function.

On the right side of the scheme the technology potentials are listed. The technology potentials or technological opportunities must be selected from a broad scale of available techniques. This part deserves much attention. This should lead to up to date technical solutions for the façade functions. On the left side of the scheme the functionalities are placed. The functionalities are during the brainstorm connected with the technologies. By doing this, the brainstorm could lead to innovative solutions for the new façade system.

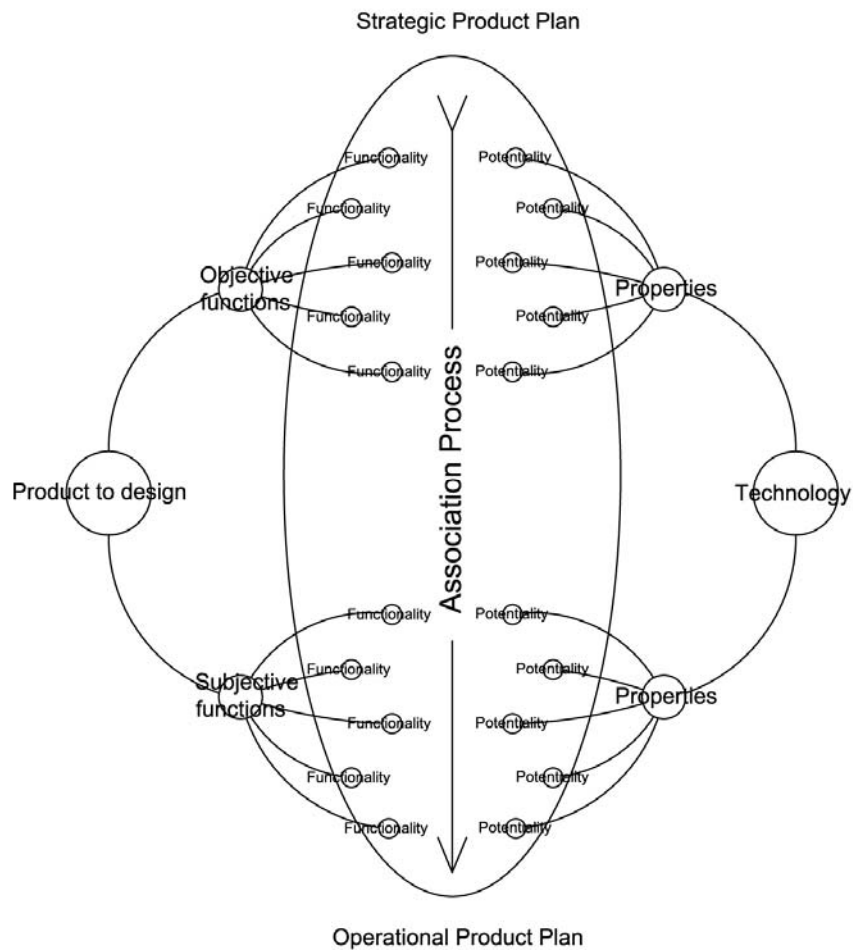


Figure 43: Product development scheme (source: [20])

As seen in chapter 2 façades need to have a broad scale of functions; these functions are separable in the categories described in the previous paragraph. Functions can be divided in three categories:

- commons
- options
- specialties

Commons are elements which are present in every product of that type. Those elements are exactly the same for the different products of that type, and fulfill generally a basic function of the product.

Options are elements which are also present in every product of the same type, but they can be distinctive through one or more properties, for example color or shape. Options enable customization, without transforming the function of the element.

Specialties are elements which are not necessarily present in every product; they are to be chosen by the customer. Specialties make a product unique, and form the reason why customers prefer this product above other similar products.

During the brainstorm this division of functions will play a role.

For a more elaborate description of the content of the brainstorm and the preparation see paragraph 5.1 and appendix I.

4.1.2 Next steps of the process

The next phase of the process is turning the functional ideas of the brainstorm into principle solutions. Principle solutions is a model that roughly specifies the so called organs of the product which built up the product so it can fulfill the desired functions. The difference between the functional solution as created in the brainstorm and the principle solution is that the principle solution shows an actual solution for the function, instead of describing it in terms of functions and technologies.

The brainstorm should lead to a number of functional ideas which are workable for the design process. These ideas have than however not been given a form or image yet. So the next step would be to actually make sketches of ideas of based on the brainstorm results. The sketches are however very basic, almost schematic.

This is obviously another divergent step in the process: from ideas from the brainstorm even more ideas will be created.

After this step the principle solution must be turned into a materialized design. With materialized design is meant the design in a more prevalent meaning of the word 'design'. Dimensions must be given to the different functional element and the spatial form must be determined.

The development of the materialized design can be built up in different steps, where each step the geometry and material are specified more. Between the different steps evaluation moments will select the best ideas to elaborate further. The design process from the principle solutions till the final design will be convergent: from many solutions

Eventually the different solutions must be brought back to one design solutions, which will form the final design. The final design should be elaborated as a preliminary design. This means that the form, materials and dimensions are clear. The product however is not ready to take into production; to bring it to that level much more research on other levels is needed: costs, production techniques, regulations, etc.

The design process as described can look like this scheme, where the design ideas are represented by circles or squares and the design steps (like development of ideas or evaluation steps) are represented by the lines.

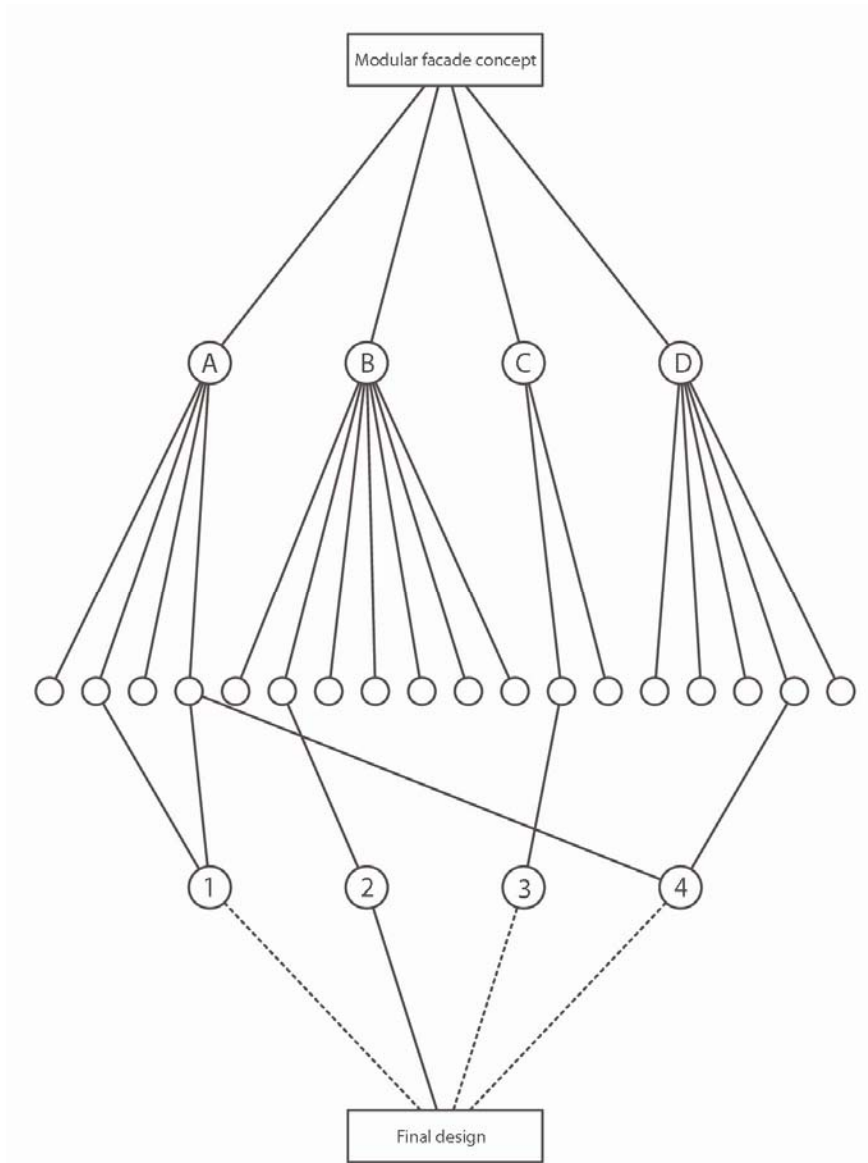


Figure 44: Scheme of the design process

In the next chapter the elaboration of the design process can be seen. Besides the content of the design itself, information on the evaluation steps during the process and the design steps itself can be found. In the end of the process the design is evaluated, as well as the process.

5 Façade Design

This chapter describes the results of the design process and the final design. At first the start of the design process will be given, followed by further elaboration of the program of demands. After that the first design ideas based on the brainstorm results and the program of demands are presented. The results after the evaluation of the design ideas are four design concepts. The selection method to choose for one final design will be described in paragraph 5.5. And finally the elaboration and optimization of the final design is shown.

5.1 Brainstorm part

In order to come to a design of a façade system that offers innovative functions and is an improvement of current facades, a brainstorm in the form of a function analysis is done. The guidance for this analysis is from the book *Technology Diffusion in Product Design* of W. Poelman [13]. In his book, Poelman describes a method for product development to determine desirable functions for a product. This is mainly done during the last described assignment, where several constraints are brought up that can happen in different situations the product may find itself in. The constraints are connected with a desired functionality, which is in the end connected with a new technology.

The assignments before the last one help to get a complete picture of the product. For example an assignment was used to find different users for the product during its lifetime. Another example of an assignment was to find positive and negative functions of the product. The results of the assignments of Poelman's book can be found in the appendix 1.

The last assignment of the method was done two times as brainstorm. First time the participants were T. Klein, W. Poelman and the writer of this report, Joep Hövels. The second time was done as at the façade company Alcoa, with employees of Alcoa, J. Scheepmaker, K.-M. Hees, A. Smit and from the TU Delft prof. U. Knaack, T. Klein, T. Ebbert, V. van Sabben and Joep Hövels. Both brainstorms appeared to be quite useful, although the results were very different. The results of the brainstorms are listed in the following section, starting with a short evaluation of the method for this project.

The results of the function analysis

The function analysis for the phases other than the application phase seems to lead mainly to boundary conditions and requirements instead of functionalities or possibilities and technologies. The difference between following this scheme for facades and this scheme for products is that the products already have a clear picture. For this façade there is not yet a design, just an idea. The example given by W. Poelman in [20] of the fire door is about improving the existing design by applying a number of changes or adding technologies. In this case it is about improving an existing design (current facades) by trying a completely new idea or system. A number of ideas from this analysis can be used in the design process, but most of them stood at the basis of the idea in the first place. The found boundary conditions however help to define the object to be designed, the modular façade.

Nevertheless, it works good to do all this exercises to get a clear picture of the design task. It helps to make the designer realize what all the aspects to consider are in the process.

The functionalities found in the function analysis are not all of the same kind. Most of the found functionalities are opportunities: they do not need to be used in the façade necessarily, but they can be helpful to reach certain goals, or to solve certain problems. The found functionalities will be kept in mind for the actual design. They are listed in appendix 1.

Another category of results is boundary conditions. The reason for this is that constraints form the basis of the brainstorm; solutions for these constraints are not necessarily concrete technologies, but can also be of conditional nature. Example:

Task	Situation	Possible constraints	Effect	Sub-system	User-system	Required functionality
2.3.1	Installation phase; construction worker carries unit	Unit too heavy (>19kg)	Not allowed to carry by one person	process	effectors	- lighter elements (<19 kg) - use tools - smaller elements - use two construction workers

The found functionalities in this case are not design solutions or techniques; they rather are design conditions. Those conditions will also be taken into account during the design process.

The third category of found functionalities is the starting points for the design. These starting points form the base for the façade layout. The starting points found in the function analysis are:

- Design a *smart component*, which allows itself to be shown: a smart box. Make this box standardized, in combination with a façade system. The box however, can also be used in other façade system. All the added values, like climate systems and energy producers, are in the box.
- Design a modular façade on a *frame basis* to put modules into or onto: the frame keeps the modules in place, and the modules inside can be put in and taken out like a drawer in a chest for example.
- A system with *self-carrying modules* (like *LEGO*): different modules with different sizes are built up. The modules are self carrying and the sizes of the modules are different, but are based on a standardized system.

Design a system that separates *design components and functional components*. This offers design flexibility (to a certain height). The design components take care of the geometric flexibility of the architect, while the technical parts offer flexible solutions for functional requirements.

Before the elaboration of the design ideas, the program of demands gets a closer look.

Obviously the basic idea is the modular façade. The background of this idea is the status of the current metal-glass facades: they almost reach adolescence. With the growing demands and regulations in the field of performance (energetic, sustainability, etc.) it is time for a new product. The design will serve two goals: firstly with the design will be attempted to develop a new façade system that as a product can be a competitor of the curtain wall system. Secondly the façade will be used to consider whether the idea of the modular façade is good and workable; so the design is in fact used as a means to evaluate the basic concept.

The fact that the purpose is a modular façade has to do with the goals of the façade itself: the wish for an upgradeable and flexible façade. A façade with the properties of easy upgradeability and flexibility will have a longer life expectation than the more conventional systems. In order to be of actual use, the façade also needs to offer architectural freedom.

5.2 Program of Demands

The program of demands describes a number of criteria which the product, in this case the façade needs to satisfy. The requirements are based on different subjects. The subjects are:

1. *The primary grounds to develop a modular façade*
2. *The rules and conditions for product modularity*
3. *The demands for a façade of an office building*

Here below these subjects will be discussed and explained to determine what is really meant and what demands the façade must satisfy in order to be successful.

1. *The primary grounds to develop a modular façade.*

The reasons to develop a modular façade in the first place are based on:

- a) a noticeable trend of function integration in the façade
- b) a wish for a flexible and upgradeable façade,
- c) without losing the potential of offering architectural freedom.

a) Function integration

From the function tree, presented in chapter 2 on façade functions, a number of functions has been selected, which at least should be part of the façade. A great number of the functions in this list are functions that all facades need to possess. The functions on the list roughly include two kinds: user functions and constructional functions. The constructional functions are of vital importance for the façade; when one of them fails the façade faces great risk of damage or malfunctioning of the primary function. An example is the impermeable layer: failure will cause damage to the construction through rotting. Eventually this will also harm the users.

The user functions on the other hand are demanded in the façade for the comfort and wellness of the users of the building. In case one of these functions fails, the façade itself doesn't face the risk of damage.

It is the users who will be harmed by this. An example is natural ventilation. When this function does not work, or the function is not available, the users will experience the disadvantage of this malfunctioning. As described in chapter 2 all the function groups in the function tree are of great importance of the façade. However, the functions that influence the construction of the façade need to be in the façade in any case, at all times. These functions will not be mentioned in the topic of function integration. The so called user functions however can be solved in the façade in a successful way, or in a less successful way. The user functions are therefore more interesting to regard for function integration. They can either be demanded (by regulations for example) or be optional. Both categories share the property that the degree of functioning is flexible. For that reason these functions will also play a part in the topic of flexibility.

The demanded user functions for the modular façade are:

- Thermal insulation
- Sound insulation
- Natural light
- Natural ventilation
- Heating/cooling
- Energy gaining and storing

b) Flexibility and upgradeability

Current systems are not easy to upgrade. Often upgrading means the replacement of the filling elements between the post and rail system by another material. This change can lead to more energy efficient facades by improving the insulation value of the element. Changing the function however is, not easy. For facades that do not have the possibility for natural ventilation for example, it takes a great effort to accomplish this afterwards.

To keep the façade up to date with the standards and wishes of clients, flexibility and upgradeability are desirable. For the functions mentioned above the need for flexibility is different. To come to a degree of flexibility for the different functions, the reasons for flexibility will be mentioned and an expectance of time before upgrading will be given.

The technical functions as described above could also have the urge to be replaced. The reason for that is when the technical lifetime of the element has passed.

For the user functions the different flexibility demands lead to the following scheme:

Performance	Function ¹	Reason for flexibility	Changing period ³
Global	Thermal insulation	Change of use	Middle term
		Change of regulations	Middle term
		Change of awareness	-
		Change of technology	-
Global	Sound insulation	Change of environment	Long term
		Change of regulations	Long term
		Change of technology	Middle term
Global	Appearance ²	Change of fashion	Long term
		Change of environment	Long term
Local	Daylight	Change of user	Short term
		Change of use	Middle term
Local	Energy gaining and storage	Change of regulations	Short term
		Change of awareness	-
		Change of technology	Short term
Local	Ventilation	Change of user	Short term
		Change of use	Middle term

		Change of technology	Long term
Local	Heating/cooling	Change of user	Short term
		Change of use	Middle term
		Change of technology	Long term
Local	Possible to change function	Change of user	Short term
		Change of use	Middle term
		Change of technology	-
		Change of regulations	-
		Change of awareness	-
		Change of fashion	Middle term
		Change of environment	Long term

¹ For all functions, the technical lifetime is a reason for flexibility. This however is not mentioned, because it is expected that the technical lifetime of the elements is generally longer than the functional, economical or cultural.

² As a function the appearance of the building has been added. This can be a reason for upgrading the façade (like the Sony walkman), but it makes no sense to mention this function as part of the function integration.

³ With short term is meant 0 – 2 years, with middle term is meant 2 – 8 years, with long term is meant 8 years and more.

It can be concluded that the period of change for the functions with local performance is generally shorter than for the ones with global performances.

The more specific demands for the aspects of flexibility and upgradeability can be gained from the table. The functions must offer the possibility of changing them for the shortest period given.

c) Offering architectural freedom

When this system eventually must compete with the curtain wall, it should at least offer the same possibilities, or the advantages of the new system in comparison with the curtain wall have to outweigh the difference in possibilities. To become popular among designers, the system should offer geometrical freedom.

2. The rules and conditions for modularity

As was described in the previous chapter on modularity there are some properties of a product to make it modular. In order to utilize the chances and opportunities, which are offered by a modular product architecture, the façade needs to possess these properties:

- First of all, the complex structure needs to be broken down into manageable units (modules)
- Similarity between the physical and functional architecture of the design (a one-to-one mapping)
- Minimization of the degree of interaction between physical components. The interfaces between the components need therefore to be de-coupled

A product can be modular on different levels. The modularity in this case refers to modularity in terms of components (sub-assemblies). Each component is build up from elements, but the product architecture of the component is left to its manufacturer. The need to change of an element of a component can be required quicker than the need to change a component. For the façade only the need to change a component has been regarded. Whether the component itself is also modular is not for the architect to decide.

3. The demands for a façade of an office building

The façade must obviously meet the demands of facades of office buildings.

Summary of the demands

- The façade must be build up out of manageable components (modules).
- Each component must correspond with one function, and not interfering with the other components. The interface between them should therefore be de-coupled.

The façade must contain the following functions with a certain expectance lifetime.

Function	Reason for flexibility	Changing period
Thermal insulation	Change of regulation	Middle term
Sound insulation	Change of technology	Middle term
Appearance	Change of fashion	Long term
Natural daylight	Change of user	Short term
Energy gaining	Change of technology	Short term
Ventilation	Change of user	Short term
Heating/cooling	Change of user	Short term
Possible to change function	-	-

5.3 Design ideas

Based on the starting points found in the function analysis, design ideas have been developed. This has been done by sketching a number of possibilities for each design idea. Because the designs are just ideas at this stage, the other two categories (boundaries and opportunities) have not been taken into account as such.

Together with the function analysis, the different product architectures played a role in setting up the designs:

- bus architecture (modules connected to a common element)
- sectional architecture (interfaces are all of the same kind, without common element)
- slot architecture (each interface between components is of a different type from others)

Nineteen different ideas have been drawn:

A. Smart component

1. Smart component placed on the outside of the frame (bus)

The interface of this idea is similar to some facades in southern European and southern American countries, where decentralized units have been placed onto the façade in a later stage. This idea however is more organized and better upgradeable. The smart component itself can also be modular and upgradeable.

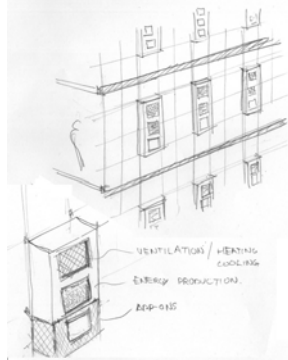


Figure 45: Component outside the frame

2. The zone at floor height is used to place smart components (bus)

The façade between the zones on the upper and lower floor can be designed after the architects wishes.

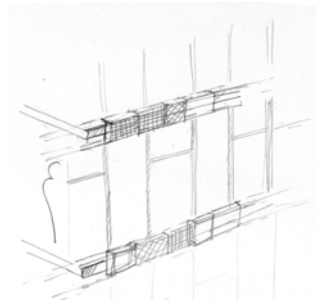


Figure 46: Component on floor height

3. The smart component forms the common unit for different modules (slot)
 The smart component or at least parts of it are likely to be changed during the lifetime of the product. The frame of the component is not likely to be changed during the components lifetime, so the sizes of the modules placed in the component are adjusted to the layout of the frame.
 The rest of the façade will than be build of parts that are likely to change throughout the lifetime of the building.

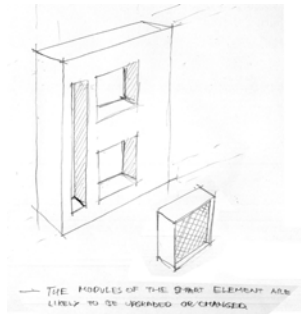


Figure 47: smart component as common unit

4. Smart component placed in prepared space as posts (and beams) (bus and/or slot)
 The smart component contains all the added value of the façade, and at the same time forms the post and beam frame for the rest of the façade. Because the posts run over the total length of the façade, the electrical wiring and other possible pipes and cables are placed inside the posts as well.
 The fillings between the posts and beams are more basic elements and those elements can be upgraded as a whole

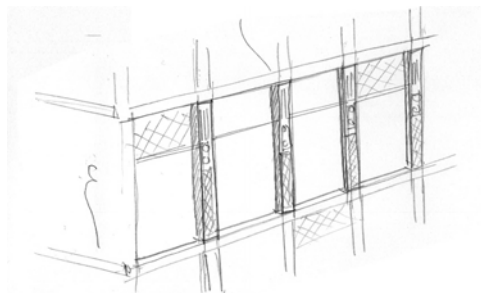


Figure 48: Smart component placed in posts

5. Smart component with all the added value alternated with more simple façade elements. The local product performance functions are solved in the smart component, the global performance are solved in the more basic façade elements.

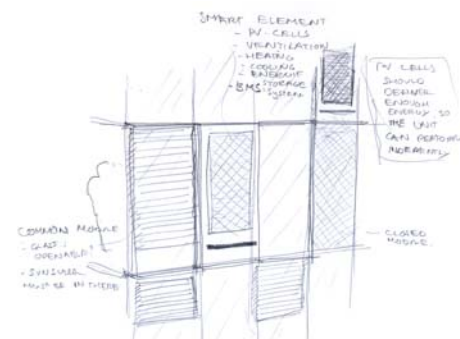


Figure 49: Smart component and basic components

B. Frame based ideas

1. Modules are placed in the frame like a chest of drawers (bus)

The frame forms the common element. The type of interface of the components is the same, so they can be replaced by components with different functions.

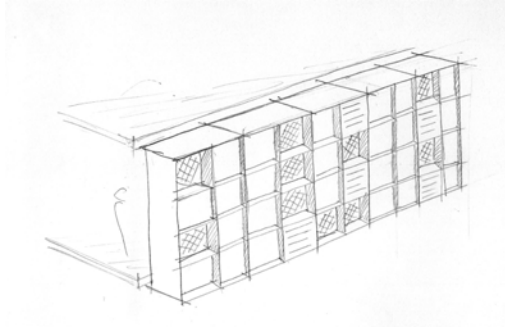


Figure 50: Frame like chest of drawer

2. The frame is adapted to the different sizes of the modules (slot)

This idea offers geometrical freedom in the x- and y-direction. Technical units will be placed into reserved spaces, while the more flexible fillings can be placed after the design of the architect.

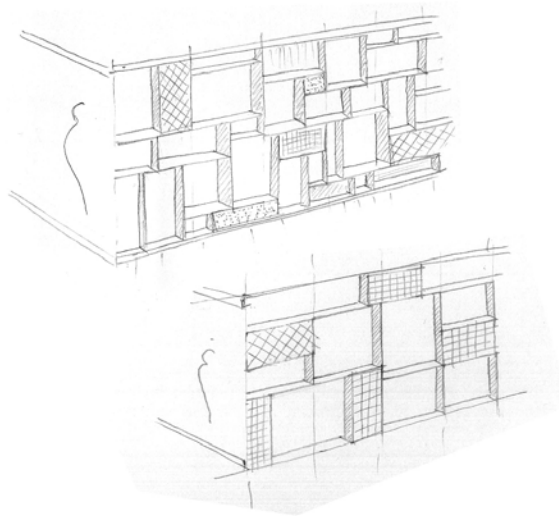


Figure 51: Adapted frame

3. The modules are connected on the outside of the frame like a backpack (bus)

By placing the modules on the outside of the frame, more plastic quality can be achieved. This may however limit the architectural freedom; the system itself is fairly expressive, so the possible different images of buildings using this system will be reduced.

The added value is in the boxes placed on the outside of the frame. By just clicking the extra volumes on, the flexibility and upgradeability is high.

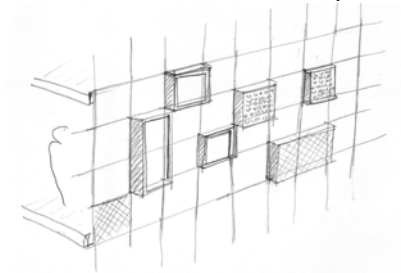


Figure 52: Modules like a backpack

4. *The frame consist only of horizontal elements (bus)*
The frame spans between the vertical elements of the structure. The modules placed onto the frame can be of different sizes, especially in horizontal direction.

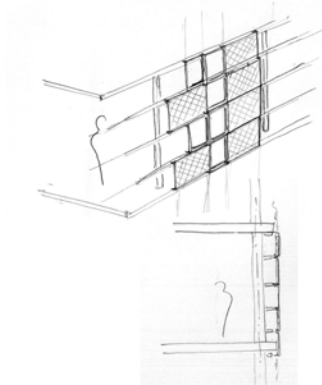


Figure 53: Only horizontal frame

5. *The frame consist only of vertical elements (bus)*
Between the floors only vertical elements are placed. The modular elements are placed. The modular elements are connected to these posts. They don't need to have the same height.

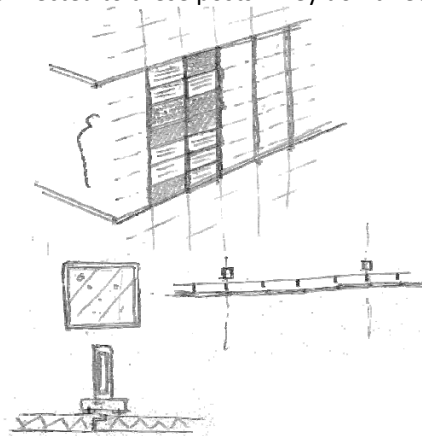


Figure 54: Only vertical elements

6. *Use a frame not spanning in x- and y- direction (bus)*
The frame doesn't need span just in x- and y-direction. This leads to a more expressive image. The form and/or the place of the modules also change. A quickly noticeable constraint is the placement of the inner walls.

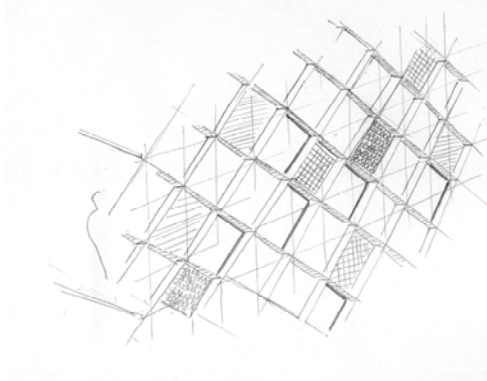


Figure 55: Frame not in x- and y-direction

7. *The structure of the building forms the frame (bus)*

The load bearing structure of the building forms the frame directly. Or one could say, the façade frame is load bearing. Either way, the modules are placed directly on the load bearing structure of the building.

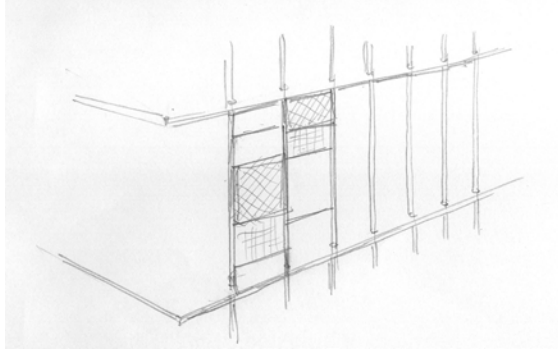


Figure 56: Load bearing structure is the frame

8. *Large, wide components connected to the structural frame with modular infill (slot)*

The large components are modular themselves, but the fillings of the components as well. This idea is a combination of the smart component and the frame based ideas.

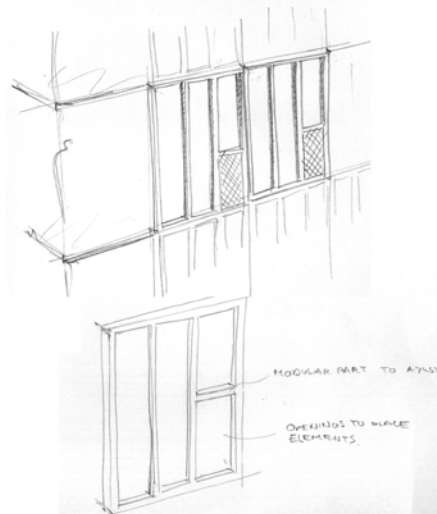


Figure 57: Large, wide components

C. *Self-carrying modules*

1. *Modules stacked like LEGO blocks (sectional)*

The modules are stacked on each other like a brick wall, or like LEGO. The modules are self-carrying, so no frame is necessary. The modules can have various functions; the flexibility rate is very big. Exchanging a modules is something to solve.

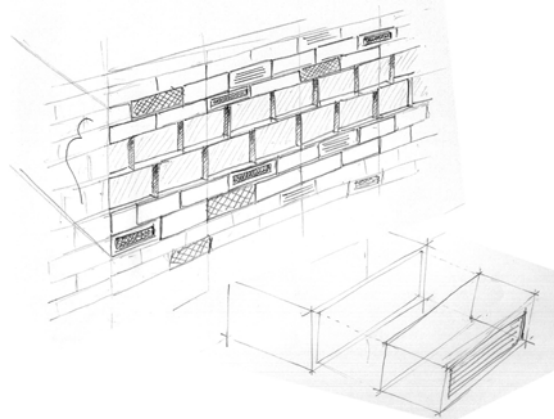


Figure 58: Modules like LEGO blocks

D. Design components and functional components

1. Distinction between freeform elements and unchangeable elements (sectional)

The components between the functional components form the free-formed elements.
The functional components are comparable to a smart component.

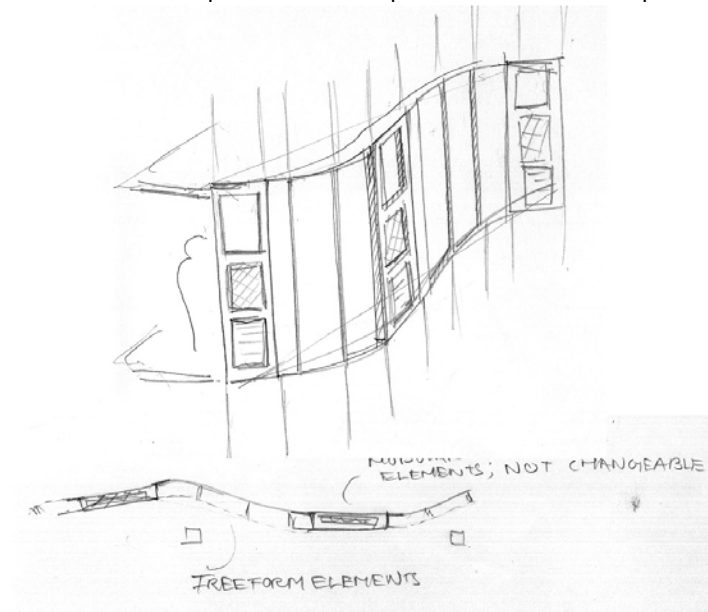


Figure 59: Freeform and unchangeable elements

2. The visible part of the façade consists of a design cladding (slot)

The inner façade consists of a layer of modular components that take care of the technical functions of the façade. The second layer of the façade consists of a skin, placed in front of the modules, to give the architect geometrical freedom. Extra functions can be given to this skin, besides the design reasons.

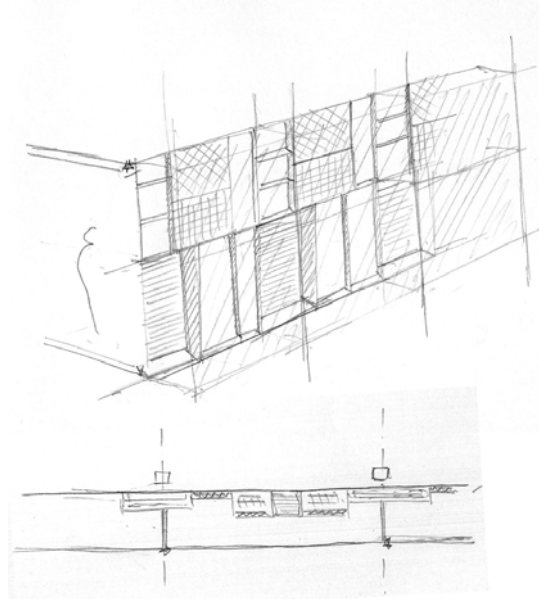


Figure 60: Design cladding

Evaluation of the design ideas

After gaining these ideas, the four basic ideas and the design ideas have been evaluated. At first all the design ideas have been evaluated separately by giving them general comments on their functioning. This evaluation step was a convergent one.

The evaluation was done by intuition, not a strict method. This stage of the design process is not suitable yet for such a method, because not all the criteria can be judged yet based on this kind of principle solutions.

By finding the advantages, the disadvantages and the possibilities the evaluation has been made as transparent as possible.

A. Smart Component

Advantages:

- The smart component concentrates all the added value. An extension or other change to this can be done by changing only one component.
- All the techniques are concentrated.
- The space between the smart components can be freely designed.
- The façade as a whole can be adapted that it corresponds with the different (functional) lifetimes of the elements.
- The smart components can be designed, tested, improved and produced independently.

Disadvantages:

- Could this be called a modular façade? This idea implies that façade in the space between the smart components doesn't differ from current systems.
- The principle of a smart component doesn't solve all the problems with current systems (global performances)
- How can extra functions be added when the smart component is pre-fabricated?
- Offers this concept design freedom, or is the smart component an inevitable component in the design that has to be accepted?

Possibilities:

- The smart component could be placed somewhere not bothering the design, for example on floor height, or as a parapet.
- The modular product architecture of the smart component facades could be adapted to the difference in the need for flexibility of different functions. The most flexible functions could for example be a part of the smart component, while the less flexible functions are placed in between the smart components. The smart component itself would then be the element with the least need for flexibility.

B. Frame based ideas

Advantages:

- High flexibility on component level
- All modules can have the same size, or can be flexible in size (when the frame is flexible in size)

Disadvantages:

- How can the frame be insulated? Existing problems around that topic cannot be solved with this idea.
- The frame is almost too important. This will not solve the basics of the problem.
- The frame makes the façade less efficient (for daylight admission for example)
- Not the optimal form per function when all functions have the same comparable space.
- How is freeform, or at least geometrical freedom offered?

Possibilities:

- The frame could be completely covered by the modules. Part of the modules could be slid into the frame openings, but still must a part of the modules be covering the frame. When the frame is covered by the modules, it can hardly influence the global properties of the façade. The façade is therefore completely upgradeable.
- Each module gets awarded exactly one function. Because not all functions need to have the same size, some modules will be bigger than others. But since the use of a frame is involved, the sizes of the modules must be standardized in correspondence with the sizes of the frame.
- A very delicate construction of a frame, which finds itself inside the building. The modules are connected with the frame through point fixings. This will make the frame less important in the appearance of the façade.

C. Self-carrying modules

Advantages:

- A high level of modularity on component level is offered.
- The mapping of the functions is very flexible.
- The building up of the façade is very easy and quick.
- It is a completely new system compared to the current metal-glass façade.

Disadvantages:

- The upgradeability concerning the global performance cannot easily be done.
- Different mappings of the functions don't lead to a new appearance.
- The system is not flexible in the size of modules.
- How can inner walls be connected?

Possibilities:

- The mapping of the modules like LEGO doesn't need to be done for the whole façade. Maybe it is possible to use just one column of stacked modules where the needed are placed inside.
- A number of modules are connected to each other with the principles of the LEGO variant. Together they form a unit of an element façade, that can be placed at once and where the boundaries form connection possibilities for walls and floors.

D. Design components and functional components

Advantages:

- This offers a high level of design freedom.
- The design cladding can also be modular in some way and can be given extra functions besides appearance.
- Functions can be given to the façade conform the client wishes without changing or spoiling the façade appearance.

Disadvantages:

- This doesn't speak for honest architecture.
- The freeform elements are hard to upgrade.
- It is difficult to make the freeform elements modular. Can this therefore be called a modular façade?
- In case of the alternation of freeform elements and functional elements: what is the difference with the smart component?

Possibilities:

- The design cladding is placed in front of the climate units, so the units can be replaced from inside. The cladding can be a media façade; the cladding should also be modular, so it can be exchanged easily.
- A design cladding could be given on component level; give each module an own design cladding with one shared feature to get the desired appearance.

The next step in this evaluation step of the design process is to choose and combine a number of potentially good design ideas. As the process scheme in chapter 4 indicates the found design ideas must be brought back to form the diamond shaped process diagram. At first the process must be divergent by gaining many ideas from the basic idea and the starting points. After that the process should be convergent by eliminating and combining ideas. These ideas must be worked out further so eventually one of them can be chosen to elaborate towards the final design of the modular façade.

Rozenburg and Eekels state in [22] that decisions based on intuition are not unthinkable in the design practice; without this kind of decisions the process will stagnate completely. Research has been done after the decisions people make in complex situations. It seems that most people incline towards heuristic evaluation rules in complex situations. Heuristic methods advance the search for a solution, but don't guarantee that a solution will actually be found. The methods always appeal to the creativity of the group or person applying them.

The way the four design concepts have been selected from 17 design ideas can also be considered as such a method. The design ideas between which a choice had to be made were not far elaborated and which made the decisions not yet complex multi-criteria decisions (a decision based on more than one criterion). By combining the best ideas and combining basic working principles four different design concepts could be formulated.

It is hard to make this step of the progress visible. Therefore the selected design ideas will be described elaborately in the next paragraph.

5.4 Design concepts

Through a method of intuitive selection described above, weighing the advantages and disadvantages, four design ideas have been picked to elaborate:

- The Design Cladding
- The LEGO Modules
- The Smart Component
- The Smart Post

These four design ideas contain the good properties of the design ideas and differ on some basic principles, so the outcome for the four concepts should be rather different. Basically the ideas differ on the properties of the structural elements and on the type of modular architecture.

The building layout

The façade concepts will be applied on a building layout. The building is for the time being not an existing building, but a modeled one. The reason for this is that the specific features and the unique character of each building should not influence the façade system in this case; it is the façade system that plays the central role here, not the building.

The building finds itself in an urban environment in the Netherlands. It will be a multi-storey building of which the façade of the third floor or higher will be planned. The third floor has still a connection with the street level, but will (technically) not be influenced by the often deviant character of the façade at street level.

The office has got a concrete structure with columns on a 5,40 m grid and a floor height of 3,30 m. The sizes of the cross section of the columns are 0,25 x 0,25 m². The floor is a predalle floor and is 0,20 m thick. The columns are being placed 0,40 m from the floor edge. In the drawing below the office layout can be seen.

There is a lowered ceiling of 0,15 m in the office to facilitate the interior lighting system and a computer floor of 0,15 cm to facilitate the sockets and electrical wiring.

5.4.1 The Design Cladding

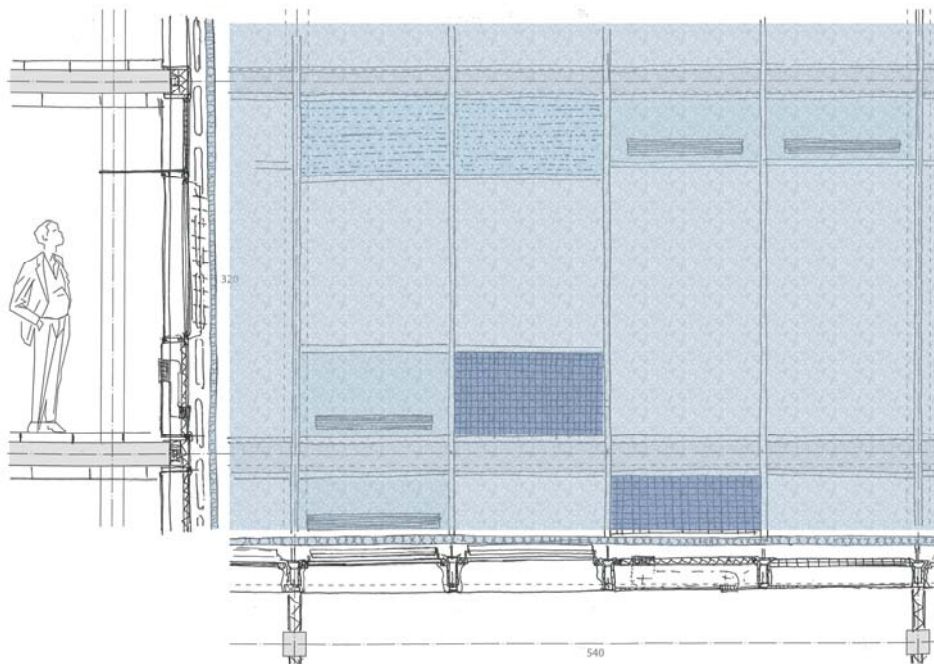


Figure 61: Sketched sections and view of the Design Cladding

Description

The facade of the idea of the Design Cladding is built up out of modules that are connected to a frame. In front of this wall of modules a second cladding is put, which is responsible for the external view of the facade. This design cladding offers the architect of the building geometrical freedom, because the cladding can be formed and be constructed after his wishes.

The frame is spanned from floor to floor with the same distances between each other. This means that the modules can have different heights, but need to have the same widths.

The design cladding can also be found on the GM skateboard car. The frame of the car contains all the elements to drive the car forward. Connected to it is the chassis, which takes care of several global performance functions, like aerodynamics, rain shield, windshield, thermal insulation and protection of the user of the car.

In case of a facade the design cladding can be built from different materials with different functions. On this picture a cladding called Sensacell is shown. That is a kind of media facade that lights up when sensors notice moving objects.

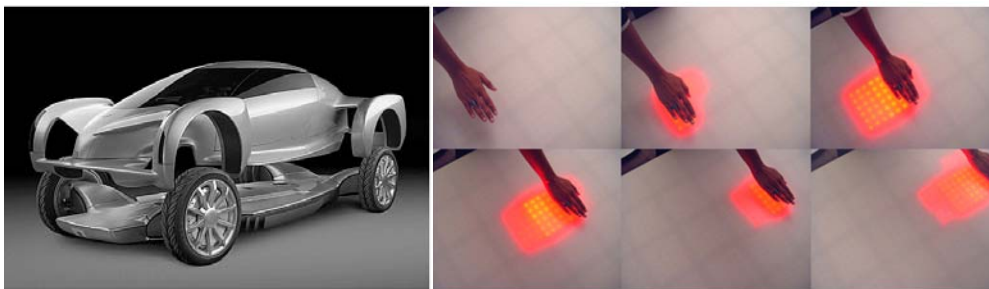


Figure 62:(left) GM skateboard car as a design cladding (source: www.gm.com)

Figure 63:(right) Sensacell as possible design cladding (source: www.sensacell.com)

Goal

The goal of the design cladding is to cover the modules behind the cladding by a layer chosen by the architect. It prevents that the modules determine the image of the facade.

Moreover, more properties can be awarded to the design cladding. The functions for the local properties are mainly taken by the modules, whereas the functions for the global properties are as much as possible taken by the design cladding. Besides the appearance of the building this could be thermal insulation, acoustic insulation or media presenting. Production of energy could also be an added value of the cladding. This way the hardly upgradeable frame is not the weak link for all global performances.

The polyvalent wall of Mike Davies [21] was described as a cladding that adapts itself to the external conditions. His idea was to produce a cladding consisting of different layers of material, each of them with his own functions. This way a self-providing wall can be created which adapts itself to different external circumstances. The polyvalent wall operates at a molecular level rather than at a mechanical level.

The design cladding can be compared with the polyvalent wall of Davies. The properties of the design cladding are different from Mike Davies' version because of the modules that take care of the local properties of the façade behind the cladding. The design cladding consisting of one or more layers is responsible for the global properties of the façade, whereas the polyvalent wall is responsible for all the façade functions. The design cladding may therefore be less difficult to realize, so the concept might at this moment be more feasible than the idea of Mike Davies. On the other hand is the façade of Davies less comprehensive than the modular façade with the design cladding.

Modularity

The modules are connected to the frame with the nature of bus architecture. The upgradeability of the local functions, the modules behind the second cladding, is large. Also the mapping of the facade functions must be able to be changed. Since the functions of the modules demand different, sometimes even conflicting properties of the design cladding, the design cladding must either be a super layer solving all this (like the polyvalent wall), or the design cladding must not be a homogeneous one and must be corresponding with the different modules behind it. Another problem arises when the modules are changed and the functional mapping changes along. In case of the superlayer this won't be a problem;

otherwise this suggests that the design cladding is modular in a way as well. An idea is to make the design cladding modular in stripes, which are connected by a kind of zippers. This is a compromise between the concept and available techniques as well.

The product variety of this concept is endless: the modules can be arranged completely free because the design cladding covers them.

Advantages

- Separation of the local and global properties leads to a well upgradeable facade.
- The design cladding offers freedom of functional mapping
- The cladding offers a free to choose external appearance

Disadvantages

- The second cladding needs different properties for different modules; this is hard to solve
- The interior needs a design cladding as well to cover the freely ordered modules.
- The connection between the design cladding and the frame appears to be difficult as well

Connection

Ideal would be that the design cladding mainly takes care of the global properties like thermal insulation. That would mean that the connection between the modules and the frame can be without regarding heat transfer from inside to outside or vice-versa. The properties of the design cladding would ideally be:

- Thermal insulating
- Sound insulating
- Weather resisting
- Transparent
- Breathing
- Wind and other loads resisting
- Offering geometrical freedom

Without worrying about possible problems and discrepancies within these demands the design cladding should possess these properties to make the concept of the design cladding working. In the above described part concept has been stated clearly without making compromises to it; after that, in trying to make the concept work, compromises to a certain extend to the concept are allowed in order to make the concept feasible and realizable with current material knowledge and production techniques. The latter is necessary in order to judge the design on feasibility and realizability.

In this attempt to solve some connection details, the modules and frame still regard the thermal insulation, so other global properties must be awarded to the design cladding besides the appearance. The modules can be clicked in the system; by an afterwards placed rail they are pressed against the frame (also to seal it off). The modules are held by the posts (by point holds), which span from floor to floor. When the modules need to be changed, the rails can be changed and be placed somewhere else on the frame. This connection is modular as well. This connection can be compared to the system of a Lunda cupboard: holes in the frame of the cupboard determine where the shelves can be put. Pins slid in those holes carry the shelves when they have been placed.

The connection between the design cladding and the frame should be without thermal bridges if possible. Besides gluing the layer against the frame, the cladding could also be embedded into the frame. When the cladding must be upgraded, damage to the cladding is not a problem: it will be recycled after use. The frame however cannot be damaged because it probably needs to fulfill its function during the whole lifetime of the building.

It could be an idea to use a kind of fabric for the design cladding, which comes in roles. They can be unrolled from the rooftop and zipped to each other. This way different stripes of cladding can be made easily and be connected modular. When the modules behind a stripe are changed, just one stripe needs to be changed.

5.4.2 LEGO Modules

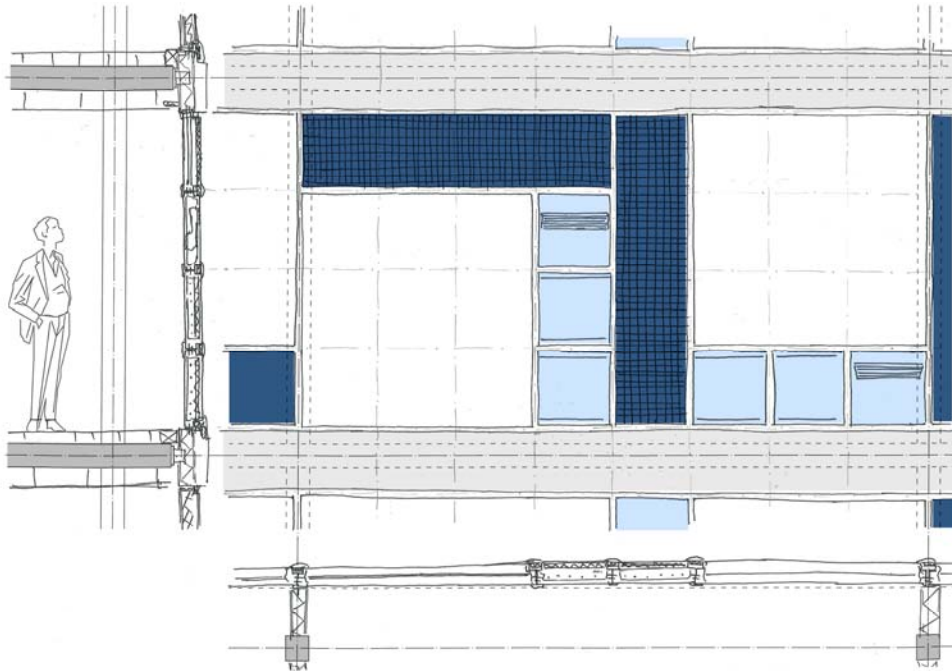


Figure 64: Sketched sections and view of the Lego Modules

Description

The idea of the LEGO modules comes from the thought of designing a variant of a modular facade without an external frame. The modules are stacked upon each other like Lego blocks or cargo containers. The modules serve one (local) function each: heating or cooling or ventilation, etc. The modules are stacked between two floors; at floor height they are connected to a closing element.

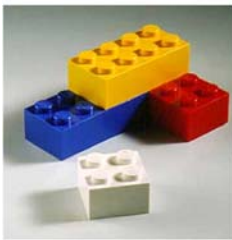


Figure 65: (left) Real Lego modules (source: www.dkimages.com)



Figure 66: (right) Container vessel (source: www.yachtingmonthly.com)

The analogy of stacked cargo containers can be made as well. The containers are connected to each other just by connection points at the corners. They have to keep their connection in rough seas and with strong winds.

Goal

The goal of this idea is to offer great flexibility in local performance functions. The modules must be able to be exchanged easily to meet with the users' wishes.

The modules must take care of the local and global performance functions. It is expected that the local performances need to be upgraded more often than the global. When a module is upgraded, the local performance is upgraded; when however the global performances are upgraded as well the facade will eventually be upgraded as a whole.

The LEGO modules are built without an external frame. This idea can be extended to a facade consisting of modules that actually forms the load bearing structure of the building. The modules need to be placed before the floor of the next storey is being built. After the completion the modules can still be exchanged to enable the user to compose and conduct the facade after his own wishes.

Modularity

This design concept can be considered very modular. The facade is built up from different sub-systems with a one-to-one mapping; all interfaces are decoupled.

The product architecture of this concept is sectional architecture: there is no common unit that connects the modules.

In order to be exchangeable the modules need to be designed in a standardized size. The standardized sized modules limit the product variety to some extent. However, the number of different possible units for this system could be endless, so the product variety will be extended enough.

Nevertheless, the modules that are usually part of the façade are commons. They are the standard units that form the product. Special units differ from project to project. These so called specialties can be ordered by the façade designer to be tailored to the building and façade; at the same time the specialties need to be of the sizes that they fit the modular sizes of the system.

The upgradeability of this concept is realized by enabling the modules to be exchanged with other modules with the same function and with each other. This way even the functional mapping of the facade can be changed.

To offer this kind of upgradeability a standardized size is necessary. This could be, as it is drawn here, quadrangular. That enables the exchange of modules in both horizontal and vertical direction.

Advantages

- High level of modularity, and therefore well upgradeable and flexible
- Very flexible in function mapping
- Building up is easy and fast
- No frame is needed that spoils the global performance
- Completely new system compared to current post-beam constructions

Disadvantages

- The upgradeability concerning the global performance cannot easily be done at once
- Different mappings of modules don't lead to very different geometrical solutions
- Many joints; hard to seal off
- Tolerances must be very small to enable upgradeability
- The connections are expensive and vulnerable

Connection

Because there is no frame to transmit the loads on the facade to the structure, the modules themselves need to take care of this. Also the weight of the modules must be carried by other modules and transmitted to the structure.

When a module is changed, the other modules must take care that the gap, which arises when a module is changed, can be spanned without making the gap smaller.

An important demand to make this concept work is that the module can be exchanged easily. The connection has therefore special demands:

- To get a module in an open gap, it must be smaller than when it is in place
- The module must be taken out when a change is required, so it must be smaller than it is when it is in place.

Of course all the other demands that count for facades in general need to be applied on this one as well.

Because of the standardized size of the modules, the points where the modules are connected to each other must be according to this size.

The modules are connected to each other by a number of bolts. The bolts are placed in every module and can be reached from inside the building. By turning them the module increases in size on the upper and right side by an out sliding piece. This piece presses the modules firmly against each other, so a sealed off gap is realized. The bolts connect the modules together in a structural way.

The sealing off on the outside is done by three parts, which can be easily clicked on the system.

The interior can be improved by a kind of interior design cladding.

5.4.3 Smart Component

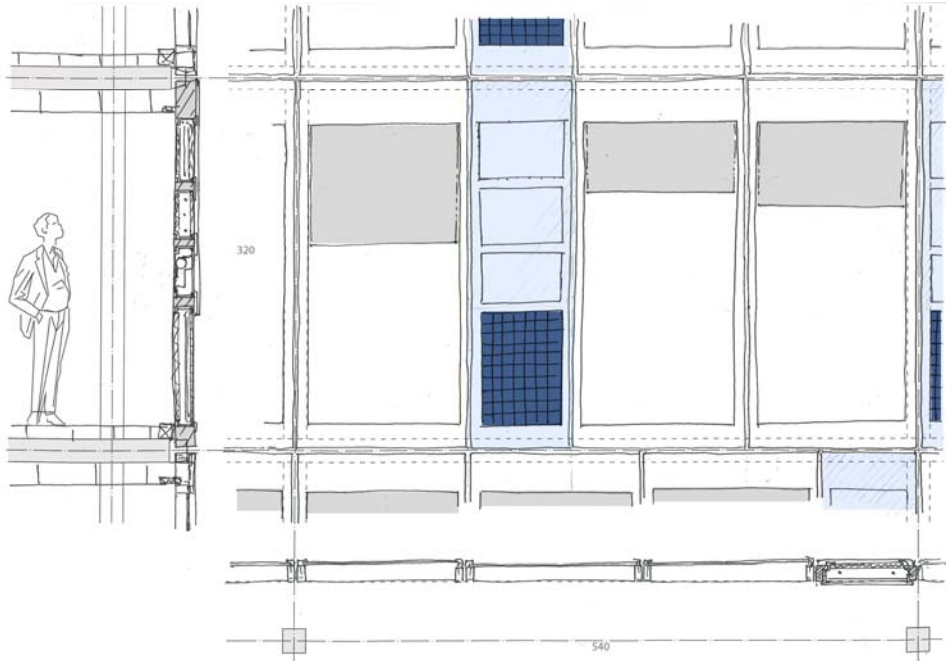


Figure 67: Sketched sections and view of the Smart Component

Description

The principle of the Smart Component is that a component with all the added value forms a repetitive aspect in the facade. Functions like ventilation, heating, cooling and energy production are placed in this element. The other more basic functions of the facades are taken care off by other modules; those modules are very much comparable with the units in an unit system facade.

The modules span from floor to floor. The idea is like a car door. The car door is a part of the exterior of the car. The door contains many integrated functionalities to improve the comfort and wellbeing of the user. The other parts of the exterior of the car contain more basic functions. The functions inside the door can be upgraded, but only by replacing elements with elements with the same function; the door is of a highly slot architecture. Furthermore, the door is very well integrated in the car and attributes to several global performances, for example the aerodynamics.

The component could also be located at floor height instead of a component spanning between two floors. In that case the component would be influencing the appearance of the façade. But like the car door, the component could have an influence on the global properties of the façade as well. This cannot or can hardly be the case if the component is on floor height.

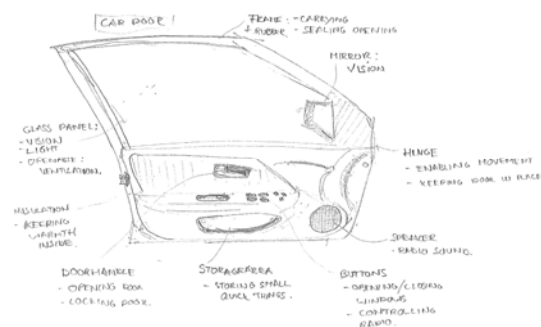


Figure 68: Car door with its functions

Goal

The purpose of this concept is to separate different lifetimes of the facade into different kinds of modules. The modules inside the smart component are likely to change more than once within the lifetime of the

building, whereas the other modules (glass for example) and the smart component itself needs to be changed less often.

Both local and global performances need to be looked after by the components. Since the local performances require quicker changes than the global performances the most upgradeable modules are part of the smart components and offer local performance functions.

Modularity

Especially because of the modules inside the smart component this facade concept can be referred to as modular. The modular architecture of the smart component and its modules could be slot, in case the openings are especially designed for the modules, of bus architecture, in case the openings are the same for all the modules.

The components spanning between the floors can be regarded as modules as well; this would be bus architecture with the structure as common element.

The product variety of this concept is big. The components can be designed independently of the smart component and functions can be added or changed to the smart component (in case of modular bus architecture).

The smart component itself can also be designed independently; it is also possible to give the module a kind of design coat in the form of a fabric.

Advantages

- The rate of flexibility meets the different required lifetimes
- The added value can be changed by changing only one component
- Geometric freedom offered; mainly by the 'basic' modules, partly by the smart component
- Mapping of the facade can easily be changed
- Smart component offers functional changes and add-ons

Disadvantages

- The global performances are hard to adapt
- The facade is just partially different from current systems
- Not all kinds of functions can be added to the smart component: daylight for example
- Is this concept innovative enough?

Connection

The components span from floor to floor and are therefore placed without a frame. That means without a frame outside the components.

The smart component consists of a kind of framework in which the modules are placed. In this variant the frame has a rather integral nature (compared to the modular nature of regular post-beam frames). This has been done because of the simplicity: in case the frame (because of the global performances) needs to be upgraded, the whole smart component must be upgraded.

The connection between the modules and the frame of the component is a flexible one. The module can be pushed inside and is clicked to the frame with the connection of a door closer. A cover cap seals the connection off. The inside of the component can be covered with a design material to make the interior look more attractive.

The connections between the components mutually are similar to connections in buildings using a unit system facade. They differ from the connections in the LEGO modules, because the demands are different. These components don't need to transfer loads to one another. Besides that are the components less likely to be exchanged often.

The tolerances in this connection are of the same magnitude as in mechanical engineering.

5.4.4 Smart Post

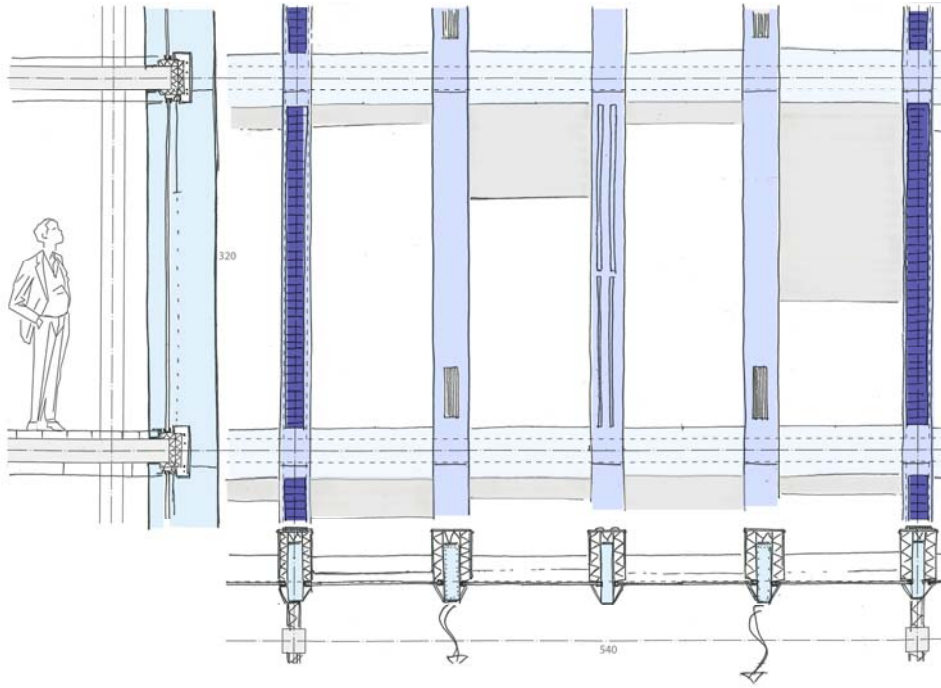


Figure 69: Sketched sections and view of the Smart Post

Description

Originally the Smart Post concept was one of the design ideas of the Smart element starting point. The Smart Post is a system with posts and beams containing all the added value. The room between the posts and beams can be filled with plates with different functions. The functions of the plates must be rather basic to make the concept work. In between the post functions like sun shading must also be placed; the driving power is placed inside the post.

The posts hold mainly functions like ventilation, heating, cooling and energy production. The posts are through going over the height of the building, so through going piping systems could be placed in the post, as well as electrical wiring.

In between the smart posts beams can be placed to give more than one function to the plate in between them. The fronts of the post can support different functions, like heating, cooling, ventilation and media.

Goal

The structure of this concept is not far from the structure of regular post beam constructions. So with this concept has been tried to achieve a facade with comparable elements as the usual post beam construction, still using the advantages of modularity.

Because the post are placed relatively often, they can be kept rather slender. Not as posts look nowadays, but they must be evolved.

The local performance functions are mainly placed inside the posts and beams. Together with the elements in between them the posts and beams must look after the global performance functions.

Modularity

Like the Smart component the Smart post contains of different stages of modularity. The modules taking care of the local performances generally have a shorter functional lifetime than the elements taking care of the global performances, so the upgradeability level is bigger for these modules.

The modules inside the posts have a nature of slot or bus architecture, depending on whether or not standardized connections have been used.

The product architecture of the elements between the posts and rails is bus architecture having the post and beams as common unit.

The product variety is limited when it concerns the possible modules inside the posts. To keep them as slender as possible, not many different types are possible to be integrated. It may however be possible to use especially designed modules like is done in the Capricorn building in Düsseldorf. The elements in

between the posts are free to choose and to design, so that leads to a high level of variety.

Advantages

- Both local and global performances can be updated easily because of the highly modular nature of the post.
- Level of geometrical freedom is high.
- System is similar to the current post beam system, but with more functions in the construction

Disadvantages

- Many posts are needed; this is expensive.
- The post and beams remain big for the time being
- Placing of modules might bother the inner walls and vice versa

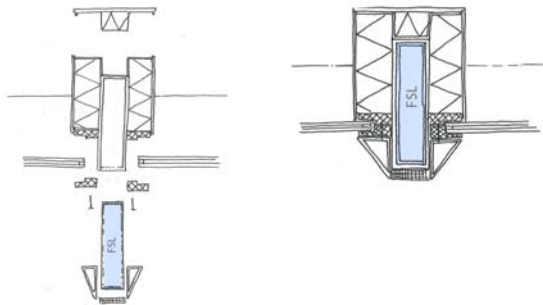


Figure 70: Sketches of the horizontal section of the post with the modular parts

Connection

Parts of the posts may run through over the whole facade in order to place necessary piping or wiring, but the structural element of the posts span between two floors. The connection of this structural element with the structure of the building is not modular, but modules can be placed inside this element. The connection of modules with this structural element is very modular, like a hard disk that is put inside a computer. The module can be pushed from inside into this case.

The size of the structural element has been determined based on the size of a FSL module. The heating, cooling and ventilation unit is considered to be decisive for the size of the module. Other functions with more flexible sizes must be able to be placed inside the module as well.

The plates and elements in between the posts and beams can also be changed from inside. They are pressed between two 'rubberish' insulating parts, which are connected to the structural case.

The front of the post has got different demands for different functions. Therefore the front of the post is a modular unit as well: it works like a front of a mobile phone which can be exchanged.

The beams are built to insulate the floor. The space in front of the floor can be used to realize a wired connection between posts, for example to provide electrical energy. Sun shading can also be placed in this space, so that function is the least as possible integrated, for the sake of upgradeability.

5.5 Design selection

These concepts have been worked out further until a scale of about 1-20. Besides that the concepts have been analyzed, described and given design possibilities.

The next step in the process would be to select one of these concepts to work out to a 1-1 scale. The chosen design must be the one with the best potential to be a successful modular facade.

The final step will be the evaluation of the final design. The results of this evaluation will also play a role in the evaluation of the modular facade concept.

The concept with the best potential must now be chosen. A suitable method to come to a well-founded choice is the cardinal method [22]. The capacity of people to process a large number of data at once is limited. Therefore most of the complex criteria decisions can not be made without a good structure. For

product development several methods of decision making have been developed. For most of the methods all the criteria will be validated separately. After that these value judgments will somehow be combined to one overall value judgment of every alternative. The criteria can be given the right effectiveness. Giving the right value to the criteria for every alternative is not without a problem; this has to do with the way the values are 'measured'. Besides that the assumptions belonging to a specific decision method should be valid for the choice situation.

Roughly two different kinds of decision methods can be distinguished: ordinal methods and cardinal methods.

Ordinal methods

According to ordinal methods, also called qualitative method, the decision maker arranges the alternatives per criterion from 'worst' to 'best'. This method is relatively simple and has the advantage that it can help the individual decision maker to come to a consistent order, even if the criteria are not accurately described. Moreover, an additional advantage is that more than one person can be involved in the evaluation procedure.

Not all criteria have the same importance. Therefore the criteria can be classified in the right order, so the effectiveness of the criteria can be judged. Since there are only qualitative properties to be judged, this method appears to be simple and reliable. The problem is that the rank numbers cannot be added to come to a final score. The numbers only give information on the rank order of the alternatives, not on the size of the effectiveness differences.

The best alternative could be selected by counting how many times an alternative was the best, second, etc. However, this gives no result in the rate of effectiveness for the criteria, so conclusions on this cannot be drawn. Besides that, counting the successes doesn't lead to a really significant end value.

Cardinal methods

According to cardinal methods, also called quantitative method, the decision maker must qualify the rate of success per criterion for each alternative. The decision maker rates the effectiveness of each criterion by appointing a value to it. The values could for example be:

9 = very good, excellent

8, 7, 6 = good

5 = reasonable

4, 3, 2 = moderate

1 = very bad

This way all the criteria are judged according the same scale. Furthermore, each criterion can be given a scale factor to express the importance of it. Usually the scale factors are chosen in a way that the sum is equal to 1, 10 or 100. Doing this, the importance of the criteria must be compared with each other, which leads to a well-founded distribution of scale factors over the criteria.

The final score of an alternative is calculated by multiplying the scale factor with the given value for the criterion; the sum of the scores per criterion gives the final score.

This method is only reliable and plausible if the decision maker is an expert in the field of the alternatives and criteria; he or she must be able to validate the effectiveness of an alternative in the right way.

Moreover, the decision maker has to validate the criteria independently, which means that the score given to a certain criterion cannot influence the score for another criterion. Otherwise, a multi criteria decision method like this one would be pointless.

Whether the choice situation of the decision maker independent is as described above should be verified. This is mainly done by the decision maker by comparing two criteria in pairs. The decision maker should ask him or herself whether he or she would:

- Accept a certain improvement in relation to criterion K, disregarding the effectiveness for the other criteria, in exchange for a certain decline for criterion L? If the answer is yes, criteria K and L are in principle independent.
- Change the importance of the criteria P and Q because of the rate of effectiveness of these criteria. If the answer is no, criteria P and Q are in principle independent.

The choice between using the above described ordinal or cardinal method and making choices based on intuition is a choice between two bad options. The choice based on intuition forces the decision maker to

simplify the problem by ignoring certain information; choice based on a multi-criteria decision method includes all the relevant criteria, of which however the assumptions are hard to verify. This last method only works if the decision maker really doubts over the choice to make. When he or she already has a preference for an alternative (based on intuition), the use of a multi criteria decision method is useless.

The choice between the four façade concepts is so complex and is dependent of so many criteria, that a multi criteria decision method is necessary to come to a good choice.

For this decision the cardinal method is preferred. The results of this method can better be compared to each other, which makes the decision making easier. Certain criteria can be given bigger effectiveness than others and the design concepts can be given an independent note. Since the decision is made with the help of experts in the field of facades and the criteria, this method seems to be the most suitable. The ordinal method doesn't necessarily lead to the selection of the best alternative, but could have two 'winners'; the results will be less convincing, because of the fact that the final score of this method is hard to determine.

To find out if the situation is suitable for the cardinal method, the question whether the choice situation of the decision maker is independent remains. To answer that, first the criteria will be determined.

The criteria are mainly based on the program of demands of the façade, described in paragraph 5.1. In order to make the new façade system innovative but realizable, two criteria have been added, which are not mentioned in the program of demands: the originality and the feasibility.

The criteria are:

- *Flexibility/upgradeability:*

Is the facade flexible and upgradeable according to the scheme of different lifetimes of elements?

- *Geometrical possibilities:*

Does the facade offer enough geometrical possibilities to the designer that it can be successful on the market?

- *Originality:*

Is the design original and innovative?

- *Feasibility:*

Is the design feasible and realistic? Is the design too complex to be realized?

Now will be looked at the two question with which can be indicated whether the choice situation is independent enough or not. The first asks if the decision maker is prepared to accept an improvement of a certain criterion in exchange for a decline for another criterion disregarding the other criteria. The answer to that would be positive. The decision maker can accept that for example the geometrical possibilities improve, while the originality is less. The scale factor of originality however is bigger than for the geometrical possibilities, so the importance of this criterion is already determined.

The second question says whether the importance of the criteria P or Q would change when one of them scores better than the other. The answer to that would be negative.

Although this is a very rough method to determine the independency of the choice method, the result is that the decision method is independent enough to use it as a valid method.

In my opinion the decision maker, in this case myself, is independent in the process: the two test questions described above can be answered in favor of the independence of the method:

- Does the decision maker accept an improvement for one criterion while another criterion gets worse? The answer to that would be yes.
- Does the importance of two criteria change when one of them scores better than the other? The answer to that would be no.

Also important is the question whether the decision maker is capable enough to fill in this scheme realistically and to make this decision. According to Roozenburg and Eekels [22] the scores of cardinal decision method only lead to useful results when the decision maker is besides independent also experienced in judging and recognizing values of a product in its field. The making of the decision has

been discussed with other persons² who have more experience in the field of facades and façade development.

The scale factors have been awarded to the criteria in order to reflect the importance of the criterion in this stage of the design process (see table below). The criterion of geometrical possibilities has been given a smaller scale factor than the other criteria, because this demand is hard to criticize at this stage; it must and will be improved during the next stage of the design process.

In this stage the originality and the feasibility are the most important; now the design ideas have been elaborated to more extensive ideas, they can be compared with already existing facade systems, to judge whether or not they are original and feasible.

The notes that can be given to the designs on the different criteria are, as is written on the right, numbers from 1 to 9.

	Flexibility	Geometrical possibilities	Originality	Feasibility	Score
<i>Score</i>	2	1	3	3	9
Design Cladding	7 (14)	9 (9)	8 (24)	4 (12)	59
LEGO Modules	8 (16)	6 (6)	8 (24)	7 (21)	67
Smart Component	6 (12)	8 (8)	6 (18)	8 (24)	62
Smart Post	7 (14)	8 (8)	8 (24)	8 (24)	70

The Design Cladding scores high on the criterion *Geometrical possibilities* because the second cladding of the façade can be chosen in a way that it meets the wishes of the architect completely. This is at the same time the reason why the concept scores bad on the feasibility part: the second cladding should be a transparent, breathing, watertight and insulating material to enable the modules behind the cladding to perform their tasks. It will not be easy to find a material with all those properties; further research would than be in the field of material science instead of façade design.

In contradiction with the Design Cladding the Lego Modules score not so well on the geometrical possibilities. Different layouts of the modules don't lead to really different appearances. This could be done by varying the modules more, but that would probably not be feasible. The Lego Modules are essentially different from current façade systems, so their score on originality is high.

The Smart Component scores high on geometrical possibilities. The concept requires next to the use of a smart component the use of regular façade systems. The geometrical possibilities would therefore be comparable to today's systems. This is at the same time the reason that the concept scores low on originality. The concept is not essentially different from existing systems.

The Smart Post's critical point is the flexibility: although modules can easily be changed from the posts, the properties of the post determine roughly the nature of the modules which can be integrated. On the other three criteria this concept scores very well: the concept is different from current systems in essence, but the façade is actually a post-rail system. The geometrical possibilities and the feasibility are therefore well solved by the system.

Although the differences are not big, according to the scheme the Smart Post is the most promising concept.

The eventual choice was the *Smart Post*, mainly based on its originality and fundamental differences with current systems.

The Smart Post offers more possibilities besides the ones described in paragraph 5.4.4. The posts can for example possess a load bearing function as well; the posts form not only substitutes for the façade posts, but also for the vertical elements of the load bearing structure. The posts can be prefabricated completely

² The persons taking part in this decision making: Prof. U. Knaack, Dipl. Ing. T. Klein, Dr.ir. W. Poelman, J. Hövels

forming the cases for electrical wiring and vertical piping. The post offers a possibility to slide one or more modules inside per storey to offer a different scale of functions for the room behind the façade. The wiring and piping must facilitate the function that is placed inside, so the connection must be comparable with the USB-connection of a computer. The post can be more than one storey high.

5.6 Elaborating the Smart Post Concept

According to Roozenburg and Eekels, after the principle solutions, which describes and shows the intended behavior of the product in a roughly sketched and shaped design, the materialized design comes. Here the roughly determined and designed concepts must be designed further into real designs. The level of the design concepts can be regarded as the beginning of the materialized concepts. The layout of the design and the basic ideas have roughly been determined, and the spatial and formal properties are shown. By optimizing these concept the materialized solution should roll out. Optimizing will at first be done by taking a closer look at the layout and the principle, and by consulting manufacturers of the climate units. After that the principles of the connections must be worked out and the façade layout and dimensions must be determined.

5.6.1 Modular hardware

The possible integrated modules

In order to use modularity and modular hardware in the façade, the actual modules for the façade need to be studied. The functions of the façade post must be determined to make a choice in the modules. The fact that the room behind the façade has an office function is modifying for the functions which are placed in the façade. Besides that, the office behind the façade has certain demands which prescribe the capacity of the modules in the façade.

The functions

The modules must take care of the local properties of the façade. The functions carrying these properties need to be placed inside the posts in a flexible way. The global properties of the façade must be taken care off by the whole façade. This kind of properties has a bigger lifetime than the local properties and therefore need to be less flexible.

Possible local functions in the façade are:

- ventilation
- cooling
- heating
- heat recovery
- lighting (interior)
- energy production
- displaying media
- storing energy
- extending inner wall

The first three functions must at least be able to be part of the façade, the others are optional.

In the modules that are offered on the market, heating, cooling, ventilation and heat recovery are often combined in one unit. This is mostly the case for, for example Emco and Trox units, shown here.

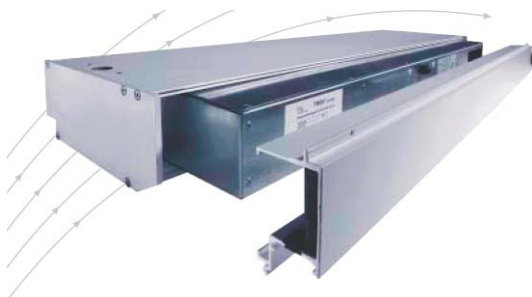


Figure 71: (left) Trox FSL ventilation unit (source: Trox product folder)

Figure 72:(right) Inventer ventilation unit (source: www.inventer.de)

The other one is a unit of Inventer: this unit heats and ventilates, and has a heat recovery function with a high effectiveness. The advantage of these units is that no water input is necessary. Providing an electricity and internet connection enables the system to make a false ceiling and a computer floor unnecessary. The units of Inventer are for now just used in the house building industry, not yet in the utility building industry.

The media façade here shown is the Uniqua tower in Vienna, where LED's have been placed on the façade, creating different images. Media facades are very well realisable with the system.



Figure 73: Uniqua tower with media façade, Vienna 2004, designed by Neumann and partner) (source: www.barco.com)

Flexibility and connections

The connections between the modules and the façade must be flexible depending on the flexible lifetime of the modules. The modules themselves consist of elements which need to be replaced every now and then. The flexibility of the parts of the modules will however be a matter for the suppliers of the modules. So far in this research the lifetime of the modules, or actually the functions of the modules, has just been expressed in long term, middle term or short term. To design the right connections and give the modules the right place in the façade post, a more specific lifetime must be awarded to the modules. A way to find this out is to interview the producer of this kind of decentralized ventilation units.

Research by interviewing companies

The text above is in fact a summary of the part of the program of demands dealing with the modules of the façade. There are however many open ends, because at some points information is lacking. The information which is not there is mainly about the functioning of the modules. This information will be collected by interviewing producers of decentralized ventilation units, because that kind of unit should be placed into the façade anyway. Of the several companies that produce decentralized ventilation units for facades Trox/FSL is one of the most famous. Trox/FSL is therefore the company that will be approached.

Before interviewing Trox/FSL and possibly other companies, the product catalogues will be studied, because probably many questions can already be answered by doing that.

In order to understand how the decentralized climate units can be integrated in the façade, more should be understood of them. Therefore Trox, one of the most important players on this market, has been contacted. To give an idea of the working of a climate unit the information that is given on the Trox website [d] for standard product, the FSL-B-100, has been studied.

The information gained from the brochure and the conversations with the façade companies can be found in appendix II. Here the most important findings for the design are presented.

- The number of the ordered units must be in the order of a few hundred to make specially designed units cost-effective.
- The units need to be connected with the electricity net (230 V) and with four water pipes (2 warm, 2 cold; both have one supply circuit and one return circuit). The pipes are comparable with pipes used for regular radiators (Ø15 mm)

- The depth of the modules is at least 20 cm to enable the heat exchange; the other dimensions can be varied. The units of the Capricorn building give a good indication of the dimensions of the units with a ventilation, heating, cooling and heat recovery function.
- The technical lifetime of the units is about 24 years (the manufacturers of the vulnerable parts guarantee this lifetime). Vulnerable parts are the moveable parts, like the ventilators and valves. These elements are placed so (they often are slid into the unit as a module) that they can be maintained or changed.
- According to the representative of Trox the Netherlands the advantages won't lie in the saving on the energy use of the building installations: comfort costs energy. The representative of Trox Germany doesn't agree. According to him the future development of the units can contribute considerably to the energy savings of buildings.

For the Smart Post can be concluded that at least electrical and water connections are necessary in the post. The connection of the units can be made flexible, or is already flexible. This corresponds very well with the concept. When in the future changes in the desired media for the modules will occur, the system should offer the possibility to adapt the media.

The flexibility that is offered by the system to change the climate unit with another one is probably not necessary regarding the technical lifetime of the units and regarding the wish of the users to replace the unit with another more modern one for example. The German representative gave as a reason for this that changing a unit for another one is not customary, so it won't be probable that that will be a demand or a wish in the future. Perhaps the current incorporated systems don't offer the possibility to be exchanged with other modules; changing modules is looked upon as not possible, so there is no wish for this.

From a project size where 100 modules or more will be used specially designed units are cost-effective. For the Smart Post this could mean that there can be a series of specially designed units (designed for the specific demands of the Smart Post), but only when the Smart Posts will be available as a standard product. Otherwise the choice for specially designed modules or standard modules will depend on the project size.

The fact that certain parts of the decentralized units must be reachable for maintenance or replacement speaks up for the Smart Post: the modules can be reached easily on a suitable height from inside the building.

Solar panels and accessories

Besides decentralized climate units the Smart Post could offer the possibility to gain energy in the façade. When energy is produced by Photo-Voltaic cells certain units are necessary besides the panels.

Solar PV-cells need to have the photo-voltaic panels themselves to produce energy, a battery to store energy and an electrical converter from a direct current to an alternating current. The photo-voltaic cells deliver a direct current, while an alternating current is necessary for the net. The lifetime of the batteries is about 20 years and the sizes vary from 125 x 207 x 401 mm to 214 x 488 x 819 mm (batteries from Mastervolt). The sizes of the converters vary from 313 x 187 x 819 (also from Mastervolt).

Clearly these elements could very well be integrated with the Smart Post, possibly after small changes in size.

For the more information on the decentralized units and the solar energy system see Appendix II.

5.6.2 Optimizing the design

Most important features of the system are the modules which are integrated inside the posts and the media running through the posts over the whole height of the façade which provide the modules with input. On these pictures of models of the principle solution these two features can be recognized. Furthermore, the system is a post and beam system that offers connection possibilities to different kinds panels and sun shading. Grid and height of the system depend on the specific building.

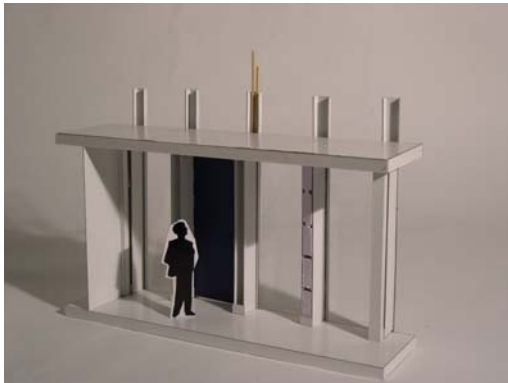


Figure 74: Model picture of a schematic 1:20 model with the principle

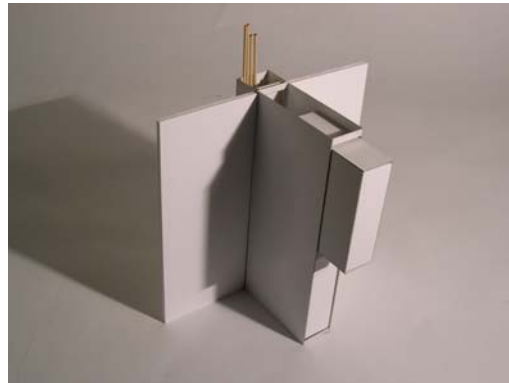





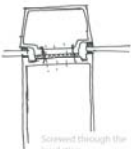


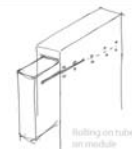






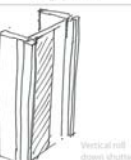
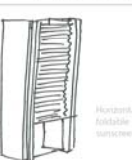


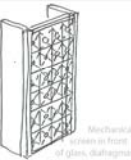
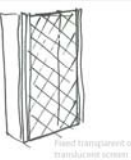

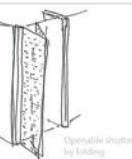



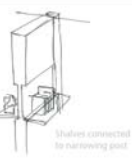





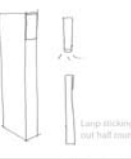
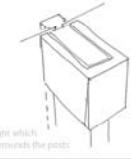




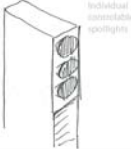


Figure 75: Model picture of a schematic 1:5 model with the principle

Morphological map

To find out the possibilities the system offers, a morphological map has been chosen. This principle has been based on the theory described in [22] by Roozenburg and Eekels. The actual goal of a morphological map is to find all the theoretical possible combinations of solutions for problems. Many ideas are generated for a number of problems. Each single solution can subsequently be combined with other solutions. This way the number of possible combinations can go up very quickly. This number of combinations can be kept under control by selection for each problem only the best (for example three) solutions. This limits the number of the combinations drastically.

The best combination can eventually be drawn in the morphological map by connection the solutions by a line. This give a clear insight in the chosen solution.

For the Smart Post the morphological map has been drawn with a number of solutions for some of the local product performance functions. The result is shown in the following pictures.

		Components				
Parameters	Connection Post - cap	 Regular single connection	 Clickable system (modular)	 Double regular connection	 Screwed through the insulation	 Wide single up/down double connection
	Connection Post - module	 Sliding over rails	 Hitting on tube on module	 Secondary construction to which the modules slide	 Module with shawtes hung up on rails	 Fixing module on one point and fixed
	Sun shading	 Horizontal louvers	 Vertical louvers	 Horizontal roll-down shutter	 Vertical roll-down shutter	 Horizontal foldable sunscreen
		 Fixed sunshading (three-sided)	 Electrochromic glass	 Mechanical screen in front of glass, diaphragm	 Fixed transparent or translucent screen	 Operable shutters
Components						
Parameters	Sun shading	 Operable shutter by folding	 Sliding horizontal louvers	 Sliding vertical louvers		
	Storage interior	 Inside post when there is no module	 Shelves connected by narrowing post	 Shelves in between the posts	 Full stand	 Shelves on the sides of the posts
	Artificial lighting	 Large openings at side and front	 Opening on front and sides, light placed a bit back	 Lamp sticking out half round	 Light which surrounds the posts	 Lights behind a translucent front
		 External solution	 Spot towards ceiling	 Both spot lights, ambient and for working ambient	 Individual adjustable spotlights	 Asymmetric arm with light bulb
		 Front with bars to let through the light				

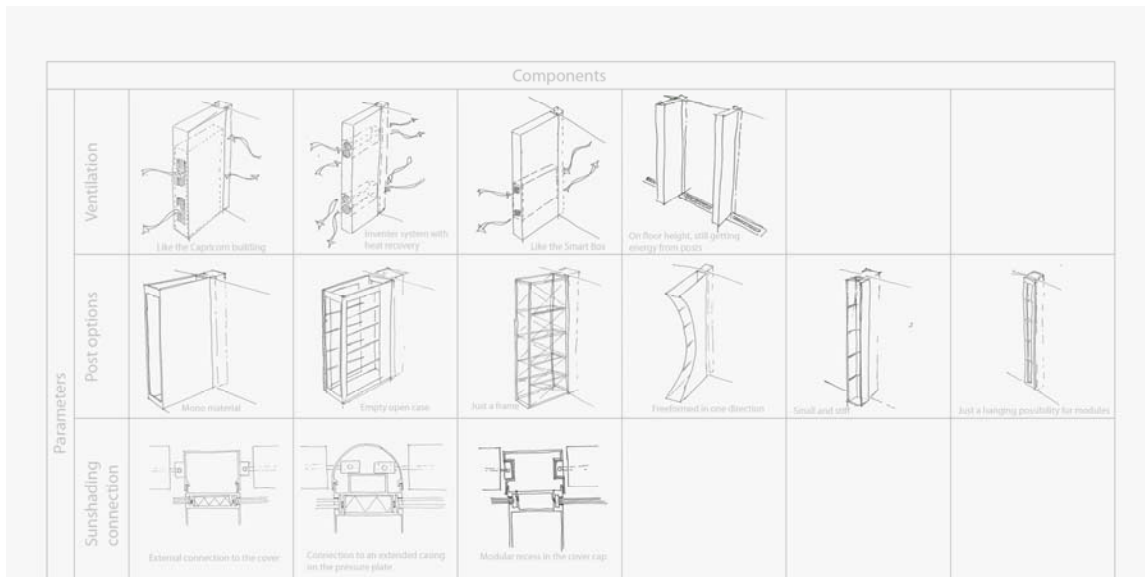


Figure 76: Morphological map (in three parts)

Because most of the parameters in the morphological map are local product performance functions it is hard to give the best solutions: the integration of all the solutions is possible. Whether a solution is better or not depends on the situation (for example the wish of the architect or the specific building properties). The morphological map was therefore not used to select a design or a design direction. However, it helped to show the possibilities of the system. Besides it gave an idea of the flexibility of the system.

Design principle

The primary idea was to let the modules enter the post from the rear side of the post, on the inside of the building. In developing the concept further on this has been converted into the principle of modules entering the post from the side. The reasons for this are:

- The modules can be more easily connected to the plugs which connect with the media.
- The modules don't need to cover the whole length of the posts now to connect to the plugs. Instead of that wires can be used to connect them. In addition, instead of one module per modular height, more modules can be installed.
- There is no problem with the connection of inner walls to the rear end of the post when the modules are replaced on one side.

The following picture shows the principle of modules entering the post from the side. The posts are in this example a little over three metres high, so the space between the two floors and their finishes is three meters. The post could be divided into 6 (for example) modular heights of in that case 50 cm. Modules of different dimensions can be placed inside, but the modules must at least have fixing elements based on this grid.



Figure 77: Possible sizes of the façade posts

All media enter the posts and once inside they are distributed over the post to the desired modules.

- For the air an inlet and an outlet possibility have been created. The inlet air is at 2,20 m, the outlet air is at 0,90 m (seen from the inside of the room; inside the post the air streams cross, so the outside will be the opposite of the inside).
- The electricity enters the post on one spot and can then be divided into four connection possibilities. The electricity is placed on a height of 0,60 m.
- The water for heating and cooling of the air enters the posts on one position at a height of about 1,20 m. The water enters the posts by four pipes.

The places of the media in the posts have been chosen for the sake of the climate units.

G. Kuder, a climate engineer, has given this advice; this distribution of the media is the most beneficial for the climate units and the comfort level.

The media that are offered are electrical connections: 230 V for the energy, and data, to signal the different actors and have a connection with the central building management system. The offered connections are both input and output.

The delivery of the media air and water is more elaborate than the electrical connections, so the flexibility of distribution over the posts is harder. This means that there is at this point only one way to integrate a ventilation unit, unless the needed media are different; it could be possible that a ventilation system doesn't need water to heat or cool the air, but just electricity. In that case other configurations are possible.

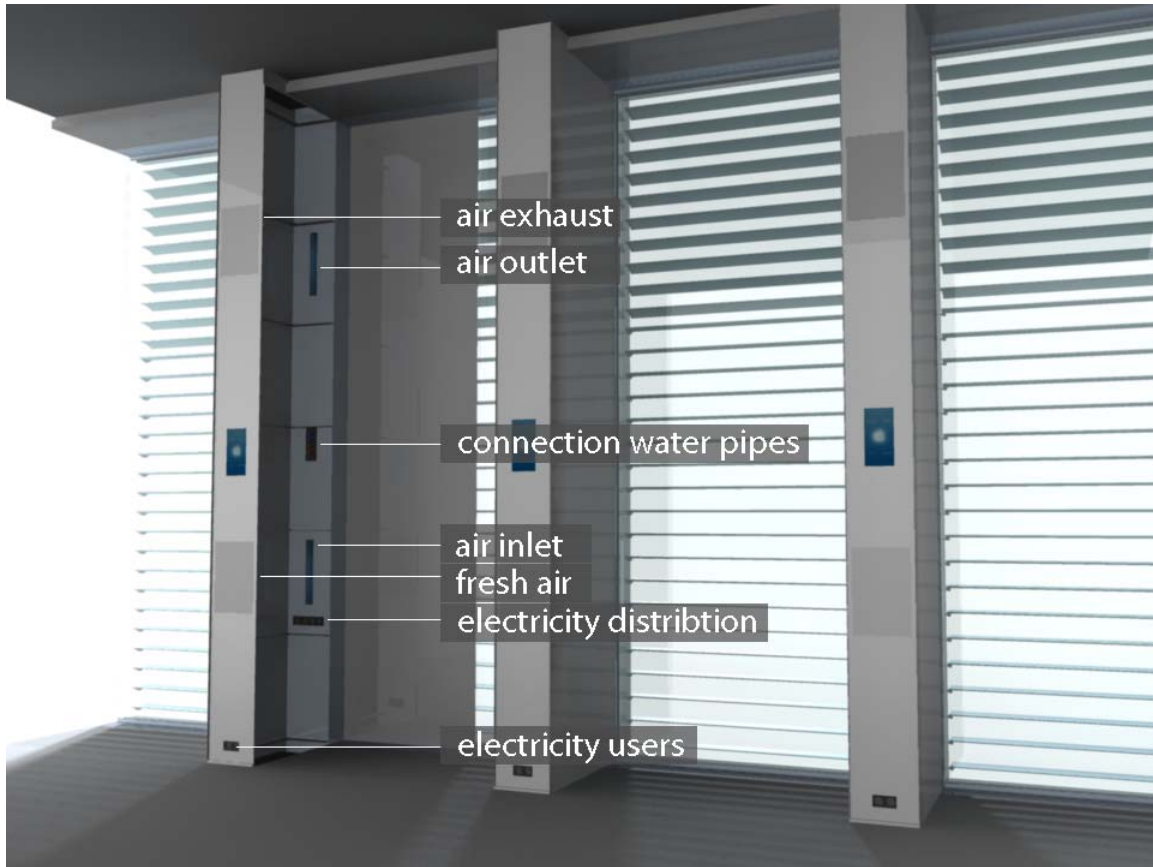


Figure 78: Layout of the media of the facade

Because the ducts for hot and cold water are expensive and difficult to insulate, it might be more wise not to offer a possibility for a climate unit in every post. The places where this has to be done must be predetermined during the building process after discussing it with the client and climate engineer. An option could for example be to place a climate unit in every second post.

In total, the system is possible to offer integration of modular units in three ways:

- the modules inside the posts
- the panels in between the posts
- the sun shading

All three modular levels can be provided with the media they need, or they can deliver the media as output. This provides the system with the possibility to integrate panels and units of many different kind, like solar panels and electro chromic glass; the sun shading could very well be cladded with sun shading as well, because the system offers an easy connection with the media. It is know that the connection of solar collectors, producing hot water, with the water pipes is difficult. This system offers an relatively easy connection with the water pipes outside.

The main characteristics of the façade system

To make this possible a number of characteristics or key elements is necessary. These key elements must be part of the system to be able to offer the above described possibilities.

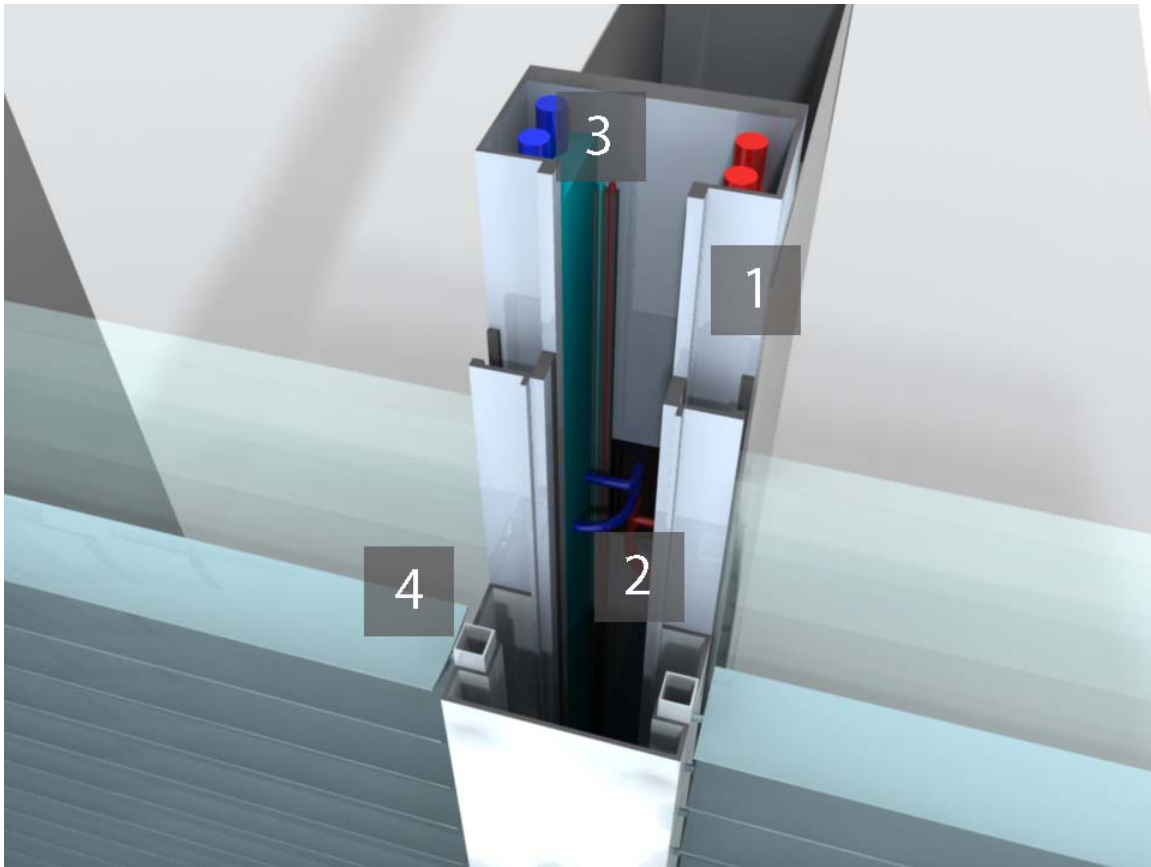


Figure 79: Four of the six key elements of the system

1. *The backbone of the system.* This part provides the post with the desired structural properties (to withstand wind loads and hold dead load of the façade) and provides a connection possibility for almost all the other parts of the façade: the panels, the pressure plates, the cover cap, the interior parts, the modules inside.

The backbone runs through over the whole height of the building, and offers the media to run through it. Because the backbone is an open profile, the dimensions of the elements must be quite big. The element is open so maintenance is possible to the media inside the profile. The opening amounts about 10 cm.

2. *The transfer element.* Providing the media with the possibility to go from outside to inside and back. The transfer elements can be prefabricated and that way they can be given all the properties they need.

3. *The media pipes and wires.* They are placed inside the backbone elements. The water pipes need to be insulated well against cold and hot outside temperatures. The insulation of the pipes consists of two parts so maintenance on the pipes is still possible. Hot and cold water have been separated from each other. The electricity finds itself against the back wall inside the profile. This way it is easy to add more cables to the posts if necessary.

4. *The modular connection for the sun shading.* Different types of sun shading can be placed inside this reserved area of the cover cap. The propulsion of the sun shading must be solved in this area as well. The post provides it with the desired media input.

The possibilities of the sun shading depend on the cover cap, so the designer of the cover cap must take into account that the sun shading must be attached to this element.



Figure 80: The last two key elements of the system

5. *The plugs to connect the modules to.* The plugs inside the posts must offer the possibility to attach the modules in an easy way to them. For the success of the system these parts are very important. The actual design of the connections should be done by specialists in this field.

6. *The user interface on the inside.* The elements on the post can be individually steered and controlled from the inside. Besides it can monitor the status of the system and the room climate. This item has a connection with the central building management system, so besides the individual regulation it enables automatic steering of the modules.

The construction and dimensions

Apart from these key elements the system needs elements to take care of other façade functions. In the following vertical and horizontal sections the other façade elements can be viewed.

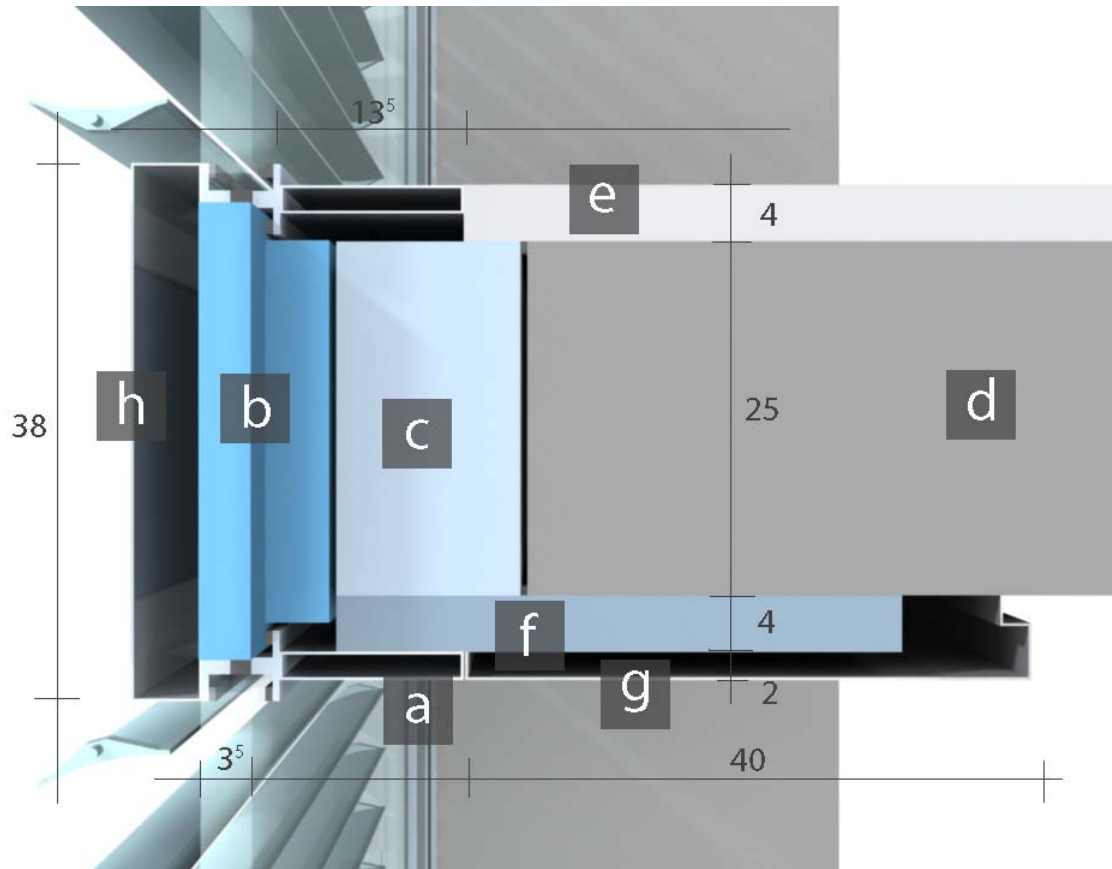


Figure 81: Vertical section of the construction on floor height

- a. *The rails.* The rails are actually rails from regular metal glass façade systems. They are now shaped more slender to give the façade a more elegant look. Together with the backbone element and the pressure plates the rails hold the façade panels and take care of an air and water tight connection. The rails can be placed wherever desired to give the façade a horizontal interruption. The depth of the rail is 13 cm just like the façade posts.
- b. *Sandwich panel.* To protect the floor and the panels in front of the floor the sandwich panel is put in between the rails and the façade posts. This way an air and water tight connection is created.
- c. *Insulation of the floor.* In front of the floor an insulation panel has been placed. The tolerances of the concrete floor can be caught by this panel.
- d. *The concrete floor.* The floor is a 25 cm high predalle floor. On top of the floor is a 4 cm high floor finish. The floor is just finished by a top layer, not a computer floor; the other side of the floor doesn't need a ceiling. Although this might give acoustical problems inside the room, as a concept the post should make the use of a computer floor and false ceiling redundant.
- e. *Floor panel.* In between the posts floor panels have been placed. They assure that the floor finish doesn't have to be poured in between the posts. The panel can be cut on site so the tolerances of the floor can be caught.
- f. *Fire panel.* To prevent fire from passing one floor to another floor this panel has been placed to cover the space in between the rails and the concrete. The panel is 4 cm high.
- g. *Folded metal plate.* This plate covers up the fire plate and gives the interior a nice finish. It is placed in between the posts.
- h. *The cover cap of the rails.* The end of the floor is covered by an aluminium cover cap. This cap is placed on both the rails and gives the façade a nice finish. The total height of the floor including finishes is 38 cm.
- i. *The sun shading.* The sun shading is in this case built up out of louvers. The louvers on the upper part (upper meter) of the façade turned upside down compared to the louvers on the lower part of the façade (lower 2 meters): this way the direct sunlight is blocked from the users eyes, while still indirect sunlight enters the room. The view of the users has not been blocked.

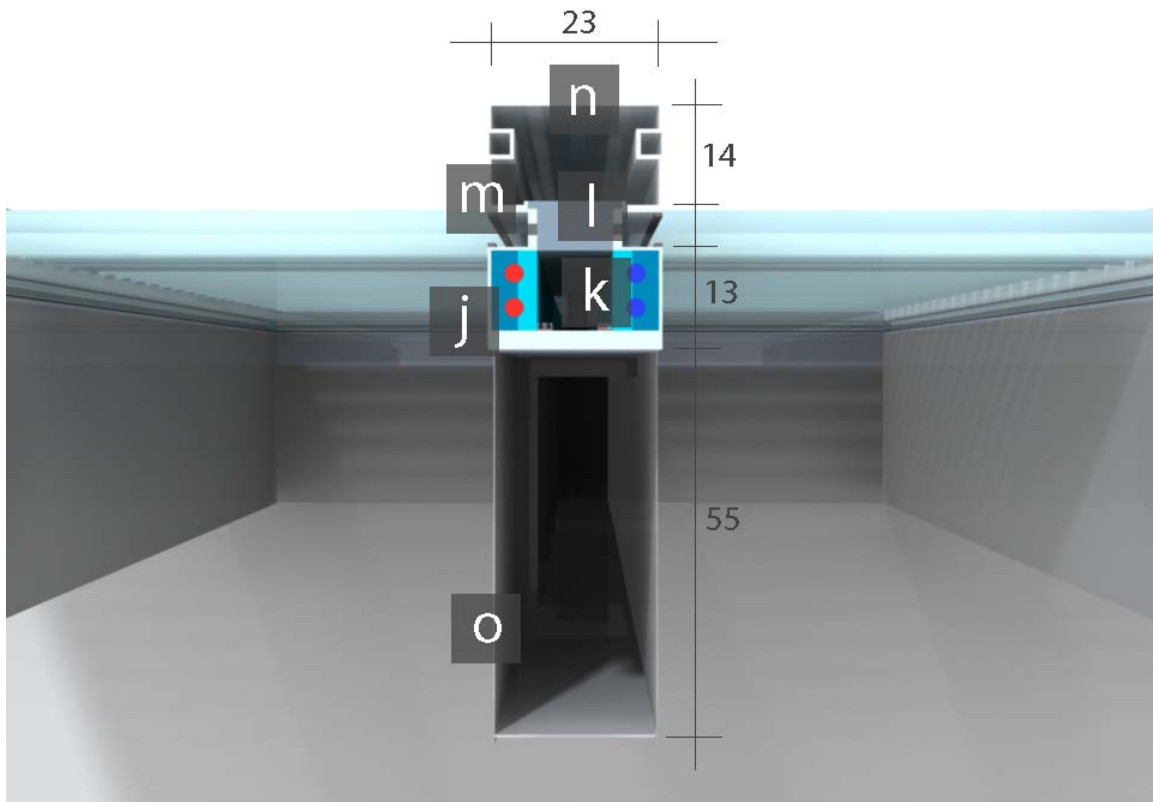


Figure 82: Horizontal section of the façade post

- j. *The backbone of the post.* The most important element of the post. This element enables all the other elements to be fixed. The walls of the profile are 0,4 cm thick and the back wall is 2 cm thick. This is necessary to provide the post with enough stiffness.
- k. *The media.* The media run inside the backbone element.
- l. *Insulation of the post.* To continue the thermal line of the façade inside the opening of the post an insulation part has been placed. This part provides a going through of all the media. To enable maintenance to the media behind it, it can be taken out easily.
- m. *The pressure plates.* The panels of the façade are pressed between the backbone and the pressure plates. Instead of one piece in regular system, this post has two pressure plates. This is necessary to still be able to open up the space inside the profile.
- n. *The cover cap.* The cover cap is connected to the pressure plates like in regular post-rail systems. The depth is 14 cm so the cover cap has enough space to offer a connection for the sun shading.
- o. *The modular housing.* In this area the modules can be placed and connected to the media. The size of the housing has been determined by the existing modules at this moment.

Exterior design

The image of the façade which is created by this construction can be seen on the next pictures. Because of the dimensions of the posts the vertical elements are decisive in the façade. This exterior design is just an option, not the only solution.



Figure 83: (left) Exterior view of the façade when it is constructed according the previous principle

Figure 84: (right) Another exterior view

Interior design

Because of the strong presence of the posts inside the room the interior design is very important. The interior design can be freely designed in terms of material of the sides of the posts and image of the user interface. For now, as an example image the interior design of the post could be like the Apple computer.



Figure 85: Reference image of the interior of the façade post (source: www.apple.com)

The Apple computer has rather nice, clean-cut sides. The front of the computer is special: it has a homogenous character but at the places where something special happens the homogenous character is alternated with a subtle change. The edges of the front are nicely covered by the sides.



Figure 86: Possible image of the interior

This picture shows how the front of the post could look. The sides here are also clean-cut. The front lies a little back in respect of the sides, so the edges can't be seen. The places where the air enters or leaves the room can hardly be separated from the front of the post; still the front of the post should not interfere with the functioning of the modules behind it. The user interface should only light up when in use and should otherwise also be hard to distinguish. The material of the front is a bit more shiny than the sides of the posts.

Another interior design feature of the posts could be the integration of artificial lighting. During the daytime the posts should strive to let as much light in as possible so the lights don't need to be turned on; this should of course be realized without letting the room be overheated. When not enough light can enter the room the post should be able to provide the room with enough light.

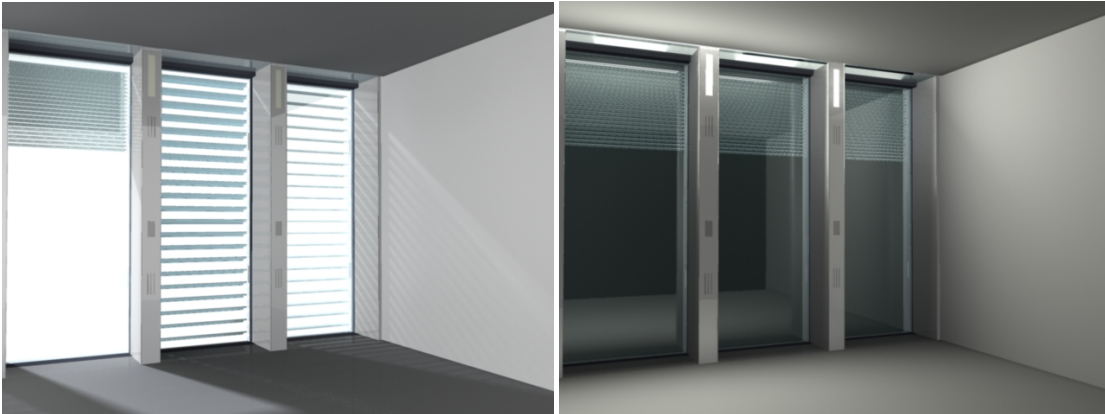


Figure 87: Light steering function of the façade during the day

Figure 88: Artificial lighting function of the façade during the night

Advantages of the system

What do the principle, the construction and the design bring? The advantages of the system are listed here:

- The post offers the possibility to integrate different modules on different levels. Besides that it is very flexible: integrated functions can be changed in a late stage of the process, even during the user stage.
- The interior is kept free of installations and transport of media. This saves considerably on building height, because no false ceilings or computer floors are necessary. It also offers great

- flexibility in the building planning, especially the floor plan. No holes are necessary in the floors, except for people transport and possibly water and waste water.
- The engineering and the testing of the elements have already been done even before the planning of the façade: both the modules as the system can be prefabricated. This advantage has also been mentioned in the literature as a typical advantage of modularity.
 - The installations are very well accessible, without much disturbing the users of the room; besides the layout of the post makes their position and function quite clear. Also this advantage is mentioned as a typical modularity advantage, made possible by a de-coupled interface and a one-to-one mapping.
 - The installation of the modules is fool proof. Probably not every person can install the modules, but after a short explanation or with a simple manual the modules can be installed or removed. It is comparable with installing new hardware in a computer.

Disadvantages of the system

Besides the advantages the disadvantages are important.

- To be able to integrate all the desired modules, the size of the post becomes rather big, over 20 x 50 cm in section. Because of that the post can become too decisive elements in the appearance of the façade.
- The media of the modules run outside. Next to an advantage this is also a disadvantage because of the weather circumstances it needs to be protected from.

Opportunities and possibilities

The opportunities of this system lie in two categories: the product nature: what kind of product should it be?

The product could be a ready made system. It is prefabricated completely and only small changes are possible to the product.

The other option is that the product is relatively free to design product; only the seven key elements of the system as it is shown here are part of the product.

Both options are possible and offer different possibilities.

Ready made system

When the product is a ready made product, it should be a catalogue product. Only small changes are possible, like the modular units inside and onto the post. The cover material of the post on the inside and on the outside can vary, just as the form of the cover cap. And building specific demands can be chosen, like the façade grid, or the height of the posts.



Figure 89: Change of interior parts: wood instead of aluminum



Figure 90: Change of interior parts: glass instead of aluminum

The different choices could be made by the client discussing it with the climate engineer and architect, or even with a website, like this one. Different options can be chosen, based on the previous input, and in the end a system and a price roll out.

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Selecteer één of meerdere criteria

Model: 307

Carrosserievariant: CC

Versnellingsbak: Handgeschakeld

Brandstof: Benzine

Motorisatie: 1.6-16V

Min. prijs: € 30.000,00

Max. prijs: € 40.000,00


Model: Versie: Kleuren: Extra's: Samenvatting

Stel uw eigen auto samen

Resultaat

1 Model(len), 1 versie(s), Vanaf € 30.923,00

Verder



307 CC

Afbeelding is niet type-specifiek en kan afwijken van uw selectie

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Figure 91: Example of catalogue product: put your own car together (source: www.peugeot.nl)

When the product is a ready made catalogue product, the market would be as follows:

- because of the integrated nature of the system it is very suitable for refurbishment projects.
- the prefabrication and easy composition of the system can make it a suitable product for project developers.
- for medium size offices the product can be interesting because of the high-tech image of the product, without having the costs of engineering it.

Relatively free to design

When the product would be a system consisting only of the six key elements, obviously more variation is offered. Besides the variation possibilities of the first option, the variation consists of variation in sizes of the posts. When the decision is made to integrate smaller modules, the posts can be made smaller.

- The system can also be applied horizontally instead of vertically. This will affect the detailing of the connections, however the key elements will not change.
- perhaps the posts can be made load bearing. This would result in a completely free interior (for relatively small spans).

The market for this option differs from the first one mainly by the price of this option. Obviously the option of the free to design system is more expensive than the prefabricated one. The project size must therefore be large enough to let this option be economically.

Besides, because of the greater design freedom, architects will be more interested in this option than in the catalogue option.

The product as a relatively free to design product matches the idea that the industry offers a technique to the architects, so the advantages of the product can be used, while the architect can adapt the product after his or her design ideas. In that case the six key elements are important to offer to the architect.

6 Design evaluation

The project has two aspects which have to be evaluated: the designed product and the design process on one hand, and the overall idea on the other hand. The product will be judged on the way they fulfill the demands and requirements from the program of demands. Besides that the way the product should behave in order to be successful can be predicted based on findings from the literature.

The process will be evaluated based on the design results during the process and based on the end result, which could prove that the made choices were the right ones. Different steps of the design process can be reviewed separately.

The overall idea of the modular façade is harder to evaluate. This will be done based on the findings in the literature and most of all based on the design results. The research question in the beginning, which must be answered in this context was:

Can by re-thinking of the modular set-up of today's metal-glass facades a new façade system be developed, enhancing the current systems in terms of upgradeability, flexibility and integration of functions?

6.1 Demands and requirements

The design result is the Smart Post façade, which has been designed after the following program of demands. To see what has been tried to achieve within this project the program has been repeated here.

The program of demands as is described in chapter 5 consists of three aspects:

- the primary grounds to develop the new façade system:
 - o flexibility of the system
 - o upgradeability of the system
 - o integration of functions
 - o geometrical possibilities
- modular conditions
 - o one-to-one mapping of all the modules
 - o decoupled interfaces between modules
 - o product broken down into manageable units
- façade demands in general (see the *function tree*)

In the next paragraph the design result will be judged with the program of demands. The specific advantages which are gained for each aspect of the program will be discussed.

6.2 Design result

6.2.1 The primary grounds to develop the new façade system

Flexibility

The system provides flexibility during the design process and during the user stage by using modularity in three ways (modules inside the posts, panels and the sunscreen); the posts deliver media input to different modular units connected to them. Therefore the modules can be chosen freely after the wishes of the designer and the user. Even after completion the modules inside the posts can be changed easily and the new modules can be connected with the system according to the same connections.

The system is now tailored to climate units, which determine the locations of the air and water input by their functioning and sizes. This limits the flexibility of the layout of the functions to some extent. On the other hand, the system can be designed and tailored to other (possibly smaller) climate units as well, without changing the overall principle.

In general, the system is not necessarily a completely ready-made product; the principle solution and the technology can also be offered to clients; this way the system offers great flexibility in the design stage.

Upgradeability

The upgradeability of the system also goes back to the modularity in three ways. The modules inside the posts can be exchanged and upgraded very easily, comparable with exchanging hardware parts of a

computer. This principle offers the possibility of replacing existing modules by other newer modules, or by modules with another function.

The other modular parts, the panels and the sun shading, are more difficult to exchange and upgrade. The way of fixing these units is comparable with the way this is done for the current metal-glass façade.

The media input is placed inside the backbone element of the post. By removing the cover cap the pipes and cables which deliver the media are easy to reach. The façade can therefore easily be upgraded after the completion of the building by adding, removing or changing the media input.

Also interior parts can be changed and upgraded rather easily. The interior parts of the post are an important part of the interior of the room. By changing the outer layer on the side of the posts the appearance of the posts can be changed.

Integration of functions

By offering media input in the post for modular units in three ways many different functions can be integrated in the system. Besides the decentralized climate units, many other functions are possible to be integrated using the provided media. Even functions which deliver media to the posts can be integrated, using the same infrastructure as the media input to deliver the output.

Integrating decentralized climate units results in a building where can be saved on the central building installations. Besides the savings on the central building installations the ducts and pipes underneath each floor can be saved, which saves eventually on building height; no false ceiling is needed so each floor wins about 40 cm in height. The same counts for integration of artificial lighting.

Geometrical possibilities

A number of parts of the post is necessary to enable the principle of the system. Other parts are not necessary, but are optional or are offered as different possibilities, or even as customized parts. This is an important aspect of modularity: using a combination of standard elements and special elements, enabling product variety without the need to offer only customized parts.

As already mentioned for the flexibility, the product doesn't necessarily need to be a ready-made product, but the principle and technology can be used to design a façade. This façade can then be made specifically for a building and be tailored to the wishes of the designer. This quite increases the geometrical possibilities.

6.2.2 Modularity demands and conditions

In the design of the product the modular conditions and requirements, like they have been stated in the program of demands, have been taken into account in order to gain the modular advantages. The advantages of modularity should therefore be recognizable in the product.

The advantages of modularity are:

- *reduction in product development time*; the engineering of the system has already been done when the choice is made for the system in the design process of the building. The principle of the system can be used in different forms, so research of the technology doesn't need to be done anymore; just different forms of the special elements must be offered.
- *customization and upgrades*; distinguishing special parts and standard parts in the facade system leads to the possibility of offering clients systems which are designed after their wishes. By the standard parts the technology and principle of the system is maintained. The standard part or principle in the façade system can be the backbone element to which the other elements have been fixed. Customization is enabled by offering design freedom in the other parts of the façade (e.g. the cover cap, the panels, the sun shading).
- *product variety*; this advantage has a close relation with the previous one: separating special parts and standard parts offers great variety. The variety advantage can however also be achieved by making all the parts standard (in that case the façade system would be a ready-made system); using different combination of standard parts delivers different variants of the product. The biggest advantage of variety is to achieve many variants by combining little standard elements in different ways.
- *quality*; the pre-engineering of the system leads to a higher quality of the products than a system which needs to be engineered every time before using it. Prototypes of the modules can be tested before they are taken into production.
- *design standardization*; this is mentioned as an advantage of modularity. The fact that parts can be standard and other parts can be special has already been mentioned several times for other advantages.

- *reduction in order lead time*; the standard elements of the façade can be pre-manufactured and inventoried. This will save time in the order lead time.
Besides saving time in the order lead time, the building time can be saved: the installations don't need to be built up inside the building anymore, but can be done simultaneously with the façade in a very easy way.

6.2.3 Façade demands in general

The way the system works is comparable with standard post-rail facades: panels are placed between post and rails which form the secondary structure. The secondary structure is connected to the primary structure of the building. Regarding this the façade works like regular systems, but the specific properties of the system add advantages and possibilities to the post-and-rail system.
The advantages and possibilities will be discussed by looking at the five main topics of the function tree.

Building physics

One of the problems of current facades is the development in the thermal performance while the demands are increasing. The thermal insulation of the façade post and rails is still realized by a thermal break like is done nowadays. However, there is more space inside the posts, so this aspect can be improved; new materials or new techniques can easily be applied.

Comfort

The possibility to integrate modules inside the posts enables functions inside the posts which have a positive influence on the user comfort. Decentralized climate units, which are able to cool, heat and ventilate can be integrated, so the façade regulates the inner climate actively without the use of other installations. By letting this happen decentralize the climate can be controlled more easily according to the users individual wishes. This high level of influence on the inner climate results in a high acceptance of the climate; when because of extreme circumstances the inner temperatures exceed the desired temperatures the users will accept this exceeding. Of course this cannot happen too often.
The climate units are installed in a vertical organization. The air inlet and exhaust can therefore take place in the optimal way. This principle also contributes to the optimal comfort.
Besides climate units other functions can be integrated to increase the user comfort. Artificial lighting can be integrated to provide the room with light instead of the regular lighting in a false ceiling. The lighting can also be controlled individually by the users.

Safety

The safety aspect is no different as the safety of metal-glass facades; all the demands for this will be fulfilled at least as good as the current façade systems.

Sustainability

Also for this topic the thermal performance is important. Sustainability and environmental protection is one of the most important reasons the demands for thermal performance increase. As said in the building physics part the thermal performance hasn't been improved yet, but can easily be improved because more space is offered in the posts.

Besides this possibility the system offers an easy way of integrating energy generating panels like PV panels and solar collectors. The energy in the form of electricity or heat can be delivered to the media inside the posts.

Suppliers and manufactures of decentralized climate units claim that the use of these units will save energy compared to the use of a central climate system. Decentralized units won't heat, cool or ventilate a room when it isn't used. Besides, heat recovery can be applied; energy can be gained back from the exhaust air. Heat recovery can however also be applied with central climate systems.

The possibility to upgrade the system leads to a façade with a longer lifespan. The façade can be kept up to date with the latest wishes and regulations. Obviously facades with a longer lifespan are more sustainable.

Architectural composition

The system offers almost the same possibilities as the current post-rail facades. The posts of the Smart Post System are bigger, so the vertical element is expressed more in the façade. By the variations of the

special elements architects are offered freedom of design. This has been described in the geometrical possibilities part.

The post can be an important contribution to the interior design. The function of the post can be extended by using it for interior goals, like storage rooms of book shelves in between the posts. Also the appearance of the posts on the inside can be changed by adapting the form and choosing the desired material, texture and color.

Interior design

6.3 Impact of the design solution

Other advantages and possibilities that the system brings and which are not possible to assign to parts of the program of demands are listed here.

- A problem mentioned by the façade industry is the difficulty of today's building systems to put together: the tolerances are getting very small and the construction workers are not always skilled enough. So there is a desire for simple, so called 'fool prove' systems, which can be easily assembled. This system satisfies this demands. The modules can be installed very easily. As mentioned in the part on upgradeability this also counts for upgrading the system.
- A possibility of the system could be to work the façade post out as a load bearing part of the primary structure of the building. In that case the building plan can be totally free of elements. This will however need further research because there are many problems to solve, for example the differences in tolerances of the façade and the structure.

6.4 The disadvantages of the design solution

Besides these advantages and possibilities the system also has disadvantages. The disadvantages are:

- The dimensions of the posts; to be able to integrate the desired modules inside the posts, the post become rather big. This results in a strong vertical organization in the façade. Also the depth of the posts is big; this costs square meters in the façade zone, because the posts take in space, but also because the space in between the posts is hard to use. A counter argument is that the integration of climate units in the façade saves on space for the central ventilation system; and because false ceiling is needed to cover the pipes and ducts room height can be won.
- The media that deliver the input to the modules run outside the building. Next to the possibilities and advantages this principle offers, this is also a disadvantage because of the protection and insulation they demand. The outside part of the façade is vulnerable.
- The buildings that can be clad with this façade system have a limited height. The vertical media transport, especially the water transport is the key factor in this. When bigger heights are to be spanned, the pipes need to have bigger dimensions and need to be fixed better. Also the pressure to let the water run over the whole building must be higher, so that might give a problem with the water pressure inside the climate units. Delivering the media in a horizontal way could than be a better solution.
For now, the buildings that are suitable to clad with this system go up to four floors.
- The capacity and reach of the decentralized climate units are limited. The building depth is therefore limited to about 2 x 7 meters. Extra cooling and heating capacity can be acquired by thermal active mass. This however weakens the concept of the media inside the posts.

6.5 The design process

The design process has been taken from product development. Designing according to this more or less determined process works very well for a program like this one. The process consists of different design stages and evaluation moments, whereby it is an alternating divergent and convergent process. First step has been the brainstorm to generate a number of ideas; the second step was to generate small design concepts out of these ideas; the third step is to bring these small concepts back to a limited number and elaborate them to design concepts; the fourth step is the choice for one of the concepts and work that one out as the final design; the last step is to evaluate the final design. The different steps of the process will be evaluated in this paragraph.

6.5.1 *The brainstorm*

The brainstorm was done by using the method from W. Poelman [20] where functionalities are being created based on constraints that can rise during different situations where the product may find itself in. The brainstorm delivered many conditions for the product, and besides that, four ideas were developed, which were used as starting points for the design. This shows that the brainstorm is a successful first step, and that the brainstorm in this form works. In the example given in the book [20] an existing product is improved, an intelligent door closer. This makes generating constraints and different situations the product may find itself in easier: the product has already a clear image. For this project was aimed for a new product. The image of existing facades and the knowledge of modularity lead to very workable ideas.

6.5.2 *Generate small design concepts*

Out of the four starting point of the brainstorm 17 small design concepts have been developed. Each idea was drawn and described on just one A4 sheet. This also worked well. Clearly this was a divergent step in the process where ideas were created based on ideas consisting of two lines. As a result some of the design concepts didn't differ from others. This is no problem in my opinion: also slight difference are worthwhile to look at.

6.5.3 *Develop design concepts*

The many design concepts must be brought back to a smaller number to elaborate the ideas further. The 17 small design concepts have been brought back to four design concepts. The evaluation of the small design concepts is done based on intuition. This method works well during this stage of the process. A difficult multi-criteria decision would not be suitable yet. The disadvantage of making the choice based on intuition is the difficulty to provide insight into the decisions. The choice has been made by judging the ideas on the criteria from the program of demands and the innovativeness of the ideas. Still, this way of deciding works well. As Roozenburg and Eekels state [22]: the design process will stagnate without decisions based on intuition. This way of judging the ideas leaves the opportunity of combining ideas, or adapting ideas based on findings from other ideas. When a number of designs would have been chosen strictly according a multi-criteria decision method some possibilities would have disappeared. The development of the design concepts went well. The four ideas have been worked out by describing the concept and finding analogies from other industries. Furthermore, the ideas have been worked out as 1:20 sketches.

6.5.4 *Working towards the final design*

The choice for the final design was made by using a multi-criteria decision, a cardinal selection method. This enabled the concepts to be evaluated based on different criteria. The criteria were taken from the program of demands, filled up with the innovativeness and originality. This way of selecting should lead to an objective decision. It would be better to let more than one person fill in the scheme to make the most objective choice. In this case the Smart Post has been chosen as the best concept. In my opinion it worked out well, but perhaps the other options are worthwhile to look at as well.

The optimization of the design went well. The morphological map which has been made, was meant to be another divergent step. In fact, it was more a way of finding out and displaying different possibilities within the same system. Although the intention was different, this was very helpful.

The last part of the process was used to develop the design to a conceptual product. Another option would have been to take a closer look at the building process. The choice is however been made to develop the product one step further. The reason for this is in fact to have a more satisfying end result. The next steps of the design process should be done in deliberation with mechanical engineers or façade manufactures.

6.6 Recommendations

The product that has been developed so far is not so much a finished project, but rather a concept. In order to make it a product more research and development must be done. In this paragraph the future actions and research directions concerning this product will be discussed.

6.6.1 Future research

To turn the concept in a realizable product more research on certain topics is necessary:

- The modules which are integrated: the layout of the façade posts is for a big part determined by the modules. The modules that are integrated must therefore be defined more precisely. The layout of the façade now has been determined by data on standard available decentralized climate units. Perhaps the available modules are not suitable, so special units will have to be designed. This doesn't only count for the climate units, but also for the other functions, like artificial lighting and energy provision.

Besides, no calculations have been made on the inner climate and comfort to find out what units are necessary and whether they are suitable to use without additions.

- The façade planning itself; the façade layout and detailing has been determined roughly, but the requires refinement. The exact dimensions of the profiles (depending on the climate units must be determined). Besides the influence of the climate units on this, the production technique (probably extrusion) is important for that.

The posts can be offered in different forms; not always all the different options are desired to be integrated. When the façade designer wants to have a less elaborate system, the posts could be executed smaller. In the future these different possibilities can be developed.

The choice between two different organizations of delivery of the media can be reviewed again: vertical or horizontal. Both offer certain advantages. The choice for the one or the other has however influence on the façade design.

- The connections between the modules and the system; the connections between the modules and the system lie more in the field of mechanical engineering than in the building technology field. The connections are however vital for the success of the product, because they enable the upgradeability and flexibility. Also the plugs inside the backbone of the posts must be developed. The modularity on the other two levels (besides the modules inside the posts) must be provided with media. The connections of these modules and the media also requires further research.
- The organization of the media have now been in a vertical way. Another good option would be to let the water run in a horizontal way, more insulated. The electrical energy and data could still go up vertically. The advantages of this principle is that the depth of the post can be reduced by this principle, and the water pipes can be insulated better. The water pipes enter the posts behind the backbone. The water pipes should not really enter the post, but should be lead immediately into a module on floor height. The distribution of the water then takes place inside the module, which results in the limited depth of the posts. The following picture shows the principle.

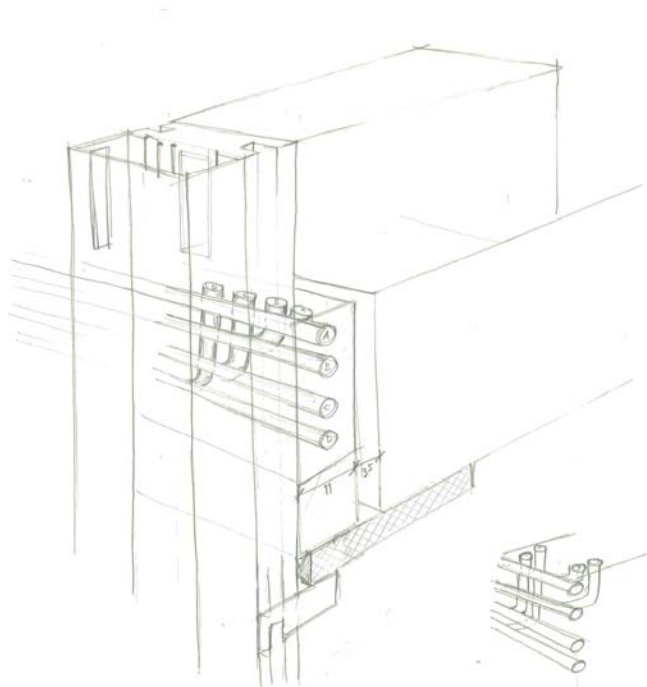


Figure 92: Possible horizontal organization of the pipes

- The advantages of the post don't change by this principle, but the concept of the vertical organization is weakened a bit; with the horizontal organization the interior cannot be kept free of installations completely because the water must go upstairs somewhere. Therefore the final solution doesn't show the horizontal solution. However, the horizontal organization of the water could be better than the way it is done now, but this needs extra research and will also partially depend on the best way to let the water enter the module.

6.6.2 Other unclear aspects

Besides the aspects which are directly related to the design of the product there are other aspects that need further research. Because the different nature of this façade system compared to current metal-glass facades those aspects or processes need to be studied.

- The market; there are already some ideas mentioned for which market this system might be interesting (refurbishment, medium size office buildings), and a view architects have been asked for their opinion on façade systems in general, but no thorough research has been done for this aspect.
- Building process; because of the integrated nature of this system (façade system and building services) the standard building process changes. The façade and the installations are now placed at the same time, where it were two separate actions.
Besides, the engineering of the system has already been done. Combined with the more simple assembly process, this will save considerably on the building time. This also needs to be confirmed.
In addition, what are the involved parties in the building process and during the engineering of the system?
- Related to this is the responsibility of the façade elements: the producer of the climate units or the façade builder who delivers the whole system. This is a complicated problem which needs to be studied.
- The costs; At first glance the façade system may seem more expensive than regular systems. This is probably true, but the total building costs may be decreased by using this system:
 - o By using decentralized climate units instead of a central system with ducts underneath the floors the total building height will be increased. This saves considerably on façade surface, building volume and a central climate system, thereby on building costs.
 - o The upgradeability of the façade increases the lifespan of the system. Hence, the investment costs of the system will be spread out over a longer period.
 - o Because of the pre-engineering the preparation time of the façade system can be reduced; the time and costs of engineers can be saved.
 - o The completion time of the building services is shorter because of the easier assembly of the modules; again, this saves money on the working hours.

This must however be confirmed by further research. The costs of the system was mentioned by the questioned architects to be the most critical point, so for the future of the system this aspect is important to investigate.

7 Conclusions

The research question from the beginning was:

Can by re-thinking of the modular set-up of today's metal-glass facades a new façade system be developed, enhancing the current systems in terms of upgradeability, flexibility and integration of functions?

Based on the evaluation from the previous chapter the following can be concluded:

- The designed product, the Smart Post, meets the requirements from program of demands;
- The Smart Post Concept distinguishes itself from the previously discussed service integrated facades by being a post-rail façade; the façade is thereby more innovative and offers more geometrical freedom;
- By applying the conditions of modularity on component level the advantages of modular product architecture can be gained;
- The followed methodology in the design process works well; it resulted in structured process where decisions and progress is easy to find back.

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Appendix I: Preparation assignments before brainstorm

The other assignments of the process of W. Poelman in [20].

Assignment 1

Define for product-line:

- Main properties
- Market and business functions
- Market and business needs
- Market and business values

This assignment is probably not useful for facades in this stage of the progress; it is mainly focused on company functions and market functions.

Assignment 2

Describe three technical functions and three emotional functions of a product.

The function list of facades made before consists of emotional and functional functions. The emotional functions are written down here.

- | | |
|--------------------------------------|---|
| - Relation with surroundings | - Communication with outside |
| - Geometry | - Provide outside view |
| - Texture, color and materialization | - Provide Comfortable sound level |
| - Communication with inside | - Provide comfortable humidity |
| - Provide privacy | - Provide comfortable inner climate |
| - Reflect building typology | - Provide right amount and quality of light |
| - Provide visual comfort inside | - Appearance |
| - Playing with light | |

Assignment 3

Describe three positive and three negative functions of a product

The function list written before describes all the functions a façade need to have; these could be considered as the positive functions.

The negative functions are:

- Barrier for daylight
- Space taking
- Fresh air barrier
- "Catching" rain
- "Catching" wind
- Limits outside view
- Use energy and materials
- Barrier for aerial view
- Killing birds

Negative functions can also be the side effect of mean functions:

- The need of a façade being wind tight results in difficulties around façade openings.
- The fact that a façade needs to be safe, results in the effect that façade materials block daylight.
- Insulation causes a wider façade, taking more space.

Actually, almost all negative side-effects result from mean functions. Is it possible to lose the negative functions, keeping the mean functions?

Assignment 4

Describe three individual and three collective functions of the product

- | | |
|---------------------------|-------------------------|
| Individual | - Experience of privacy |
| - Experience of esthetics | - Experience comfort |

- Experience protection
- Use as a play wall
- Collective
 - Sealing family territory
- Free communication
- Coziness
- Enable activities

Assignment 5

Describe three present and three future functions of a product. Taking the examples in consideration, this could also be formulated as 'what actions does the product require now, and in the future?'

Present

- Façade design
- Negotiation with (local) government
- Providing little inconvenience with placement

Future

- Maintenance
- Cleaning
- Providing an easy disassembled construction
- Upgradeability

Assignment 6

Describe three needs and three values related to a product.

Needs	Values
Enable natural ventilation	Fresh air; Being able to control inner climate
Insulation / cold – warmth barrier	Comfort; Energy saving
Provide daylight	Connection with outside; Visual comfort; Energy saving
Keep intruders out	Safety (feeling); Privacy
Transmitting loads	Safety
Protection against pollution	Visual (clean façade); Safety (toxic loads)
Sound insulation	Comfort; Privacy
Blocking direct sunlight	Comfort (overheating and glare)
Appearance	Visual comfort
Prevent damage	Visual comfort; Safety
Water resistance	Comfort; Visual comfort; Safety (water damage)
Wind tightness	Comfort; Safety
Fire protection	Safety

Summarizing values:

- Fresh air
- Control inner climate
- Comfort
- Energy saving
- Connection with outside
- Safety

- Privacy

Apart from these values connected to needs, it could be interesting to come up with values for users without being connected to a certain need.

Assignment 7

Describe three kinds of identity for the DMU of the product.

Kind of image	Actual situation
- Image by him-/herself	Standard, well productive
- Image by others	
- Image aimed for	Innovative, not standard

This is a difficult task. What is in this case the image by him-/herself? Him or her is now the client, in this case the façade company. The image aimed for is the innovative, not standard modular upgradeable façade.

Another possibility is this:

Image by him-/herself (client)	Modern, but standard
Image by others (designers)	Modern, standard
Image aimed for (purpose)	Innovative

Assignment 8

Which lifestyle should apply for the product?

	No	Little	Yes
Wealth		X	
Progressiveness			X
Nonchalance	X		
Independency		X	
Sportive	X		
Social consciousness		X	
Environmental awareness			X
Modesty	X		
Soundness	X		
Intelligence			X

Co ordinance with assignment 7, the following can be concluded of important features and properties:

- Progressiveness
- Environmental awareness
- Intelligence
- Innovativeness

Assignment 9

Which achieves of emotion could be applicable?

	No	Little	Yes
Form			X
Color		X	
Smell		X	
Feeling		X	

Sound			X
Movement		X	
Technical features			X

Next question is how to let all achieves of emotion be applicable for the product; or at least come up with ideas about how they could.

- Form: trivial; designwise should the form be attractive
- Color: trivial; designwise should the (combination of) color be attractive
- Smell: fresh air; no 'smelly' materials; give somehow the outside air a certain smell, for example a forest smell.
- Feeling: soft/organic materials could be used; when for example furniture is integrated, the façade could be used as a direct 'feel' object; Warm area: in some swimming pools there are warm cuddle walls: "knuffelmuren".
- Sound: no sound should get in from outside (unwanted); façade itself should not produce any unwanted sounds; no sound from inside should get out; possible to let the façade produce wishable sound, like background music.
- Movement; from safety point of view the façade should not move visible under loads; movement of certain parts could reflect the season (or daytime) in which we are present; movement of certain parts enables the façade to differ in functions during time; moving things could be used to collect (wind)energy; movement of elements could reflect flexibility towards different situations.
- Technical features: these features could reflect the applications the façade offers; visible technical features can also be out of date soon, because they are not timeless.

Assignment 10

Define at least ten different users of the product.

Users	Possible attributes to the users in relation to the product.
Primary users of the building (in case of an office building: working adults)	<ul style="list-style-type: none"> - comfort - influence on climate - safety - good appearance
Secondary users: <ul style="list-style-type: none"> - passer-by - users of surrounding buildings 	<ul style="list-style-type: none"> - safety - good appearance
Fire department	<ul style="list-style-type: none"> - safety
Construction worker (completion)	<ul style="list-style-type: none"> - safety - easy to handle
Service engineer (maintenance)	<ul style="list-style-type: none"> - safety - easy to handle
Window cleaner	<ul style="list-style-type: none"> - safety - easy to work with - cleanable materials
Architect (design)	<ul style="list-style-type: none"> - freedom, flexibility - enabling nice detailing
Climate engineer	<ul style="list-style-type: none"> - freedom, flexibility
Structural engineer	<ul style="list-style-type: none"> - not too much weight - an insulated structure - fire safety
Security organisation	<ul style="list-style-type: none"> - safety

	- resistance against intruders
Supplier (of possible in fills)	- flexible connections
Building owner	- good energy savings - good appearance - comfort
(Local) authorities	- safety - good appearance

Assignment 11

Define the core function of the product and as many as possible supporting functions.

Core function:

Being a barrier between outside and inside

Supporting functions are those functions, which are necessary to facilitate to core functions.

The scheme drawn before contains all the supporting functions.

The core function of this product, an open modular façade, could also be:

Being an open modular and flexible/upgradeable system; the system forms a barrier between inside and outside.

Assignment 12

Define the primary function of the product, and as many possible secondary functions.

Primary functions:

Being an open modular and flexible/upgradeable system; the system forms a barrier between inside and outside.

Secondary functions are functions, which a product can perform besides the primary function.

In this case, secondary functions are considered opportunities; these functions could the system contain, while still fulfilling the primary task.

- gaining energy from wind energy
- gaining energy from solar energy
- media
- integration of public functions: street lights, street furniture, plants (green)
- vertical transport
- collecting rainwater for spooling toilets
- night cooling
- self-cleaning
- connections for electricity

Assignment 13

Define for several lifetime phases as many aspects/functions as possible

Production phase	Installation phase	Application phase	Recycle phase
Integration of functions	Easy assemblance	Upgradeable	Easy disassembly
Modular production	Plug-and-play	Flexible in functions	Parts re-usable
Designing, testing,		Staying up to date with	Materials re-usable

producing modular elements before using		latest technologies	
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Assignment 14

Define for several social contexts as many design aspects/functions as possible.

Environment	<ul style="list-style-type: none"> - Energy saving - Design for disassembly - Extend lifetime (upgradeable) - Energy generating - Good appearance
Emancipation	<ul style="list-style-type: none"> - Understandable / workable for all users
Ethics	<ul style="list-style-type: none"> - Privacy providing - Good appearance
Culture	<ul style="list-style-type: none"> - Good appearance - Reflecting building typology
Employment	<ul style="list-style-type: none"> - Tasks of maintenance/service engineer - Easy upgradeable
Globalization	<ul style="list-style-type: none"> - Regarding international regulations - Integration of international products possible

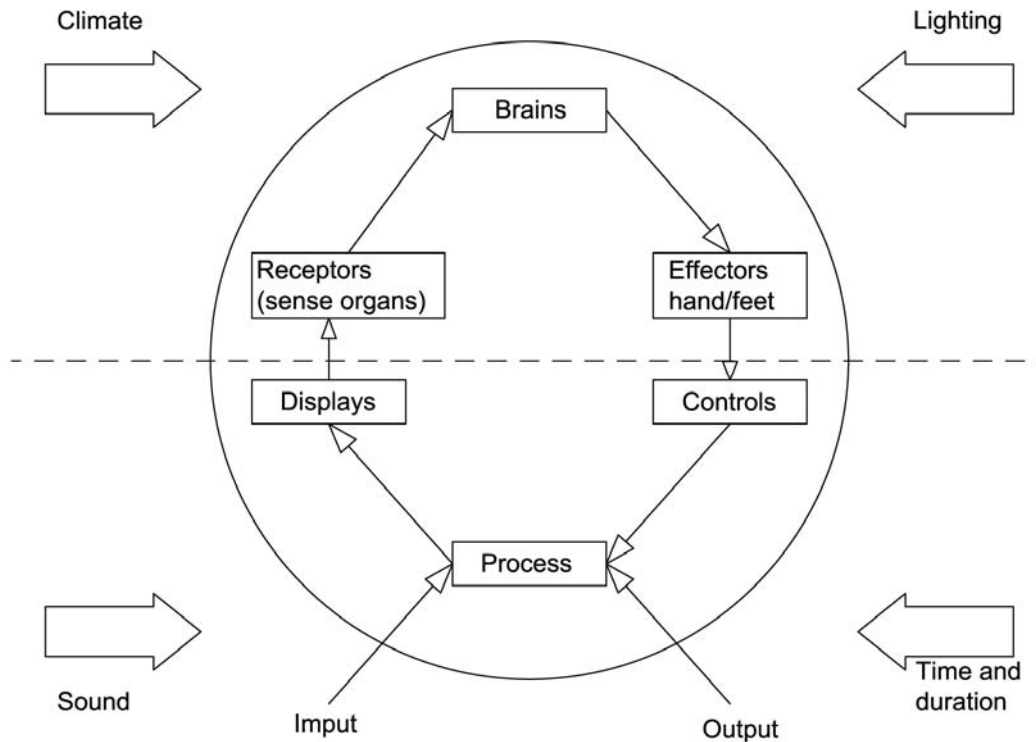
Assignment 15

Define as many application environments as possible.

Offices
 Hospitals
 Educational buildings
 Bank
 Library
 Police station
 Reception centre
 Shops
 Haircutter
 Dentist
 Restaurant
 Museum
 Community centre
 Urban environment
 Rural environment
 Workshop/studio
 Dwellings
 Eldery people-home

Assignment 16

Define functions and/or aspects to which attention should be paid for every phase in the man-machine cycle.



Man-machine cycle

Aspect/stage	Possible constraints	Points of attention
Input		
Output		
Time and duration		
Lighting		
Climate	Wet / dry, hold / cold, (acid) rain	
Sound		
Process		
Displays		
Receptors		
Brains	Understanding	
Effectors		
Controls		

Assignment 17

Mention as many constraints as possible, which can occur when using the product.

- Number each task
- Describe the situation in each task

- Think up possible constraints
- Consider the effect
- Mention the involved machine sub-system (controls, process of display)
- Mention the involved man sub-system (receptors, brain of effectors)
- Describe the desired functionality

To come to a number of tasks, it could be helpful to think of as many activities first, which can take place behind the façade. After that, the situations can be described.

In an earlier assignment, a number of application environments were brought up. For each environment, different activities will be undertaken.

Offices
Hospitals
Educational buildings
Banks
Libraries
Police station
Reception centre
Shops
Haircutter
Dentists
Restaurants
Museum
Community centre
Urban environment
Rural environment
Workshop / studio
Dwellings
Home for elderly people

The focus will be on office buildings, so probably it's the best to just describe those activities, but keep the other environments in mind.

For offices the activities could be:

- working behind a computer
- working behind a desk, writing or drawing
- making a telephone call
- having a meeting
- having a small break
- eating lunch
- cleaning the room

Also different situations could be thought about:

- different times during the day (morning, lunchtime, afternoon, evening, at night)
- different seasons (winter, spring, summer, autumn)
- different weather circumstances (a very broad scale of temperature ranges, different forms of precipitation, intensity of the sun, humidity, wind)
- different occupancy during time

Apart from that, different stages of the product must be considered. In every stage there can be different constraints and situations:

- Production phase
- Installation phase
- Application phase
- Recycle phase

There will be a number of tasks assigned to all different activities, combined with possible and relevant constraints. All tasks who start with an 1 are assigned to activity 'working behind a computer', the tasks who start with a 2 are assigned to activity 'working behind a desk', etc.

More situations could be invented, like two people working in a room, and one of them is too cold.

Task	Situation	Possible constraints	Effect	Sub-system	User-system	Required functionality
1.1	Working behind a computer / direct daylight in the room	Too much light on the screen	Unpleasant working situation	process	receptor	Sunscreen / some sun blocker for the computer
1.2	Working behind a computer / direct daylight in the room	It get's too warm	Unpleasant working situation	process	receptor	Sunscreen / cooling machine / ventilation
1.3	Working behind a computer / open window	Draught	Unpleasant working situation	process	receptor	Closed window, still ventilation
1.4	Working behind a computer / open window	It get's too cold	Unpleasant working situation	process	receptor	Closed window, still ventilation / warming device
1.5	Working behind a computer / cold outside	Cold downdraught	Cold hands: unpleasant working sit.	process	receptor	Warming device / interrupt draught / better insulation
1.6	Working behind a computer / high humidity	Possible condensation inside	Computer doesn't work properly	process	receptor	Moist eater / better ventilation / no cold places
2.1	Working behind a desk / open window	Draught	Papers blow away	process	receptor	Closed window, still ventilation
2.2	Working behind a desk /					

To find all the possible situations and constraints for facades in common, would cost a lot of time and energy, while a lot of functionalities are trivial and not worthwhile looking at. For this brainstorm typical situations and constraints concerning a modular façade have been discussed.

The brainstorm had the following results:

Situation	Constraint	Functionalities
Load on the facade	Units fall down	<ul style="list-style-type: none"> - Self-carrying - Extra structure - Connected to existing
Transport	Damage of the edges	<ul style="list-style-type: none"> - Click on the visible parts later on - Click on the vulnerable parts later - Good packaging - Cassettes, frame - Strong edges
Transport	Efficient storage	-
Transport	Handling (carrying)	
Transport	Unit > 19 kg	<ul style="list-style-type: none"> - Smaller elements - Lighter elements - Use tools
Infrared radiation	Too much heat in room	<ul style="list-style-type: none"> - Sunshading - Polaroid glazing - Polachroom glazing - Electrochroom glazing - Louvers
Heat conduction	Energy loses	<ul style="list-style-type: none"> - Nanogel in translucent parts - Thicker walls (more insulation) - Hollow viber (translucent)
Daytime, little light	Too dark inside	<ul style="list-style-type: none"> - Daylight lamp - Use mirrors to reflect light far in the room - Glass viber
Façade exists, change of performance later	Labor intensive, doesn't fit	<ul style="list-style-type: none"> - Design interface - Use standardized sizes - Design empty space, panels who fit them
More energy on the façade than used (sun)	Energy waste (when using other sources)	<ul style="list-style-type: none"> - Solar energy - Water convectors - PCM's - Store energy somewhere else
More energy on the façade than used (wind)		<ul style="list-style-type: none"> - Turbines - Pressure - Venturi-effect (jet)
Existing system, architect wants design opportunities	System doesn't give possibility, expensive	<ul style="list-style-type: none"> - Difference between technical functions and visio-spacial functionaties - Adding design cladding, independent of the system - Separate technical elements and visual elements - Use free-form elements
Design opportunities	How to make free form elements?	<ul style="list-style-type: none"> - grid differs: industrialized system for more grids - lego, based on several standardized sizes - grid is flexible, same connections - size depending elements and not size depending elements

		- Spacial louvers, performance
Radiation	Some radiation wish able, others not	- nano technology coatings: reflect certain kinds of radiation. Not suitable for massive use
Working situation	Persons have different demands of daylight	- controlled daylight for the spot - create blind spots on the façade - elements which follow the sun - elements which follow the person - combine with person identification systems - dynamic mirrors - louvers reflecting light
Building is changed, modules are left	Waste	- Re-use modules - Re-use parts - Re-use materials - Dump modules - Upgrade modules - Re-manufactory, use them in new design (supply based design)
Idea	Idea	- Design a smart element, which can be shown: smartbox. Make the system standardized, special for that box, but it can also be used in other systems. All the added values are in the box
Integrate all kinds of components	Who is responsible when one breaks?	- Make a clear interface, car radio - Tell the façade company to buy the climate company
	Fire protection	- Attachment of the façade parts is most vulnerable

For the three different types of heat loose or win, the constraints and functionalities must be found:

- convection
- radiation
- conduction

Two different functionalities:

- Finished in the factory: the system can have everything in it, like electro wiring.
- Just partly pre-fabricated: reacts more flexible to changes, but more elaborated on site.

This system might be too elaborate; for more simple products it is more suitable, but for a façade with a lot of possible different scenarios it will be very extensive.

The goal of the brainstorm is to find (sub-) problems of facades, based on different situations; *not* based on current façade systems. Each sub-problem requires a new functionality, which will be generated. In order to make the new system unique, a sum of functionalities will be chosen to elaborate on more.

It could be an option to find (sub-) problems in current systems. On the other side could that mean that the new functionalities which are generated for the problems are already used in façade systems, or are somehow

In Wim's scheme the constraints do not directly occur due to the primary functions of the product; at least not because of failure of the door itself. External influences cause the problem, through which the constraint occurs. In the man-machine cycle can be found where to look for a solution.

For this function analysis the modular façade is considered a system for which the primary functions have been solved. Outer influence can cause problems on all different fields. That way both new functions for the façade can be found, as the old functions can be improved.

The division is made on base of the different phases of the product as mentioned in [20] by W. Poelman. Instead of these phase division coming from industrial design, it could have been possible to choose a division that is more common in the building industry. However, since it concerns the development of a

product (system) the phases in the building process are not taken into account. Whether the product is eventually possibly used by architects is not yet of importance; so it is not useful to contribute a certain phase of the building process to the façade system.

Task	Situation	Possible constraints	Effect	Sub-system	User-system	Required functionality
1.1	Production phase; design flexibility					
1.1.1	Production phase; architect wants design flexibility	System doesn't give possibility, or is expensive	System is not used by architects	Process	brains	<ul style="list-style-type: none"> - rapid prototyping - difference between technical functions and visio-spatial functionalities - adding design cladding, independent of the system - Separate technical elements and visual elements - use free-form elements - design a smart element, which can be shown: smart box. Make the system standardized, special for that box, but it can also be used in other systems. All the added values are in the box.
1.1.2	Production phase; how to make freeform elements	Is expensive	No freeform elements are made	process	-	<ul style="list-style-type: none"> - grid differs: industrialized system for more grids - Lego, based on several standardized sizes - grid is flexible, same connections - size depending elements and not size depending elements - spatial louvers, performance - rapid prototyping of special elements - use frame with flexible connections in three directions - use hinged connections -
1.1.3	Production phase; climate engineer wants freedom in different elements	Parts from different suppliers have different sizes	Parts don't fit	Process	-	<ul style="list-style-type: none"> - use enough space to adjust the parts; fill gaps up with flexible material - use adjustable frames; fill out the openings of different sizes with other material - reserve a space on a certain zone for climate units; this zone is filled up flexible - use standardized elements -
1.1.4	Production phase; Structural engineer wants modules for all kinds of structures	One system is designed	System just fits for few structures	Process	-	<ul style="list-style-type: none"> - use different types of frames - use a flexible connection to structure -
1.2	Production phase; Transport					
1.3	Production phase; Integration of components					
1.4	Production phase; Handling of elements					
1.5	Production phase; Storage					
1.5.1	Production phase; produced elements need to be stored	Storage cost space and money; elements out of date	Not too many elements can be prefabricated	process	-	<ul style="list-style-type: none"> - use efficient storable volumes - use only elements that are produced by other companies (order them) - just produce elements on order (rapid prototyping) -
1.6	Production phase; Flexibility in use (different buildings)					
1.6.1	Production phase; Flexibility for different buildings	System is made generally for buildings	Can't be used for all buildings; building typology	process	-	<ul style="list-style-type: none"> - make modules especially for certain building types - make different systems for certain building types (dwellings, utility buildings, etc.)

						-
2.1	Installation phase; Transport					
2.1.1	Installation phase; Transport	Damage of edges	Bad connections; bad appearance; safety problem; leaks	process	-	<ul style="list-style-type: none"> - Click on the visible parts later on - Click on the vulnerable parts later - Good packaging - Cassettes, frame Strong edges
2.2	Installation phase; Building physics					
2.2.1	Installation phase; Building physics	Bad weather circumstances	Building delay	process	-	<ul style="list-style-type: none"> - easy connections (clickable) - mounting from inside -
2.3	Installation phase; Handling of elements					
2.3.1	Installation phase; construction worker carries unit	Unit too heavy (>19kg)	Not allowed to carry by one person	process	effectors	<ul style="list-style-type: none"> - lighter elements - use tools - smaller elements - use two construction workers
2.4	Installation phase; flexibility (different components)					
2.4.1	Installation phase; Flexibility (different components)	On the building site a change of units is made	Units and frame no longer correspond	process	-	<ul style="list-style-type: none"> - use sliding parts in frame(e.g. the post or rails so the frame is adjustable - use springs in the openings to let a broad scale of sizes fit and be fixed - use only standardized modules -
2.5	Installation phase; Integration of components					
3.1	Application phase; building physics					
3.1.1	Application phase; infrared radiation	Too much heat energy in room	Room gets too warm	process	receptor	<ul style="list-style-type: none"> - Sun shading - Polaroid glazing - Polachroom glazing - Electrochrom glazing - Louvres
3.1.2	Application phase; UV radiation					
3.1.3	Application phase; little direct sunlight	Too little light inside	People working in the dark	process	receptor	<ul style="list-style-type: none"> - Use mirrors to bring light far in the room - Daylight lamp - Glass fiber
3.1.4	Application phase; heat conduction	Translucent/ transparent parts	Energy loses	process	receptor	<ul style="list-style-type: none"> - Nanogel in translucent parts - Hollow fiber (translucent)
3.1.5	Application phase; Heat conduction	(Metal) frame	Energy loses; inside condensation	process	receptor	<ul style="list-style-type: none"> - Use carbon-fiber instead of metal - Improve thermal bridge - Fill profiles with nano-gel - Let no part of the frame be outside -
3.1.6	Application phase; sunlight on the facade	Not all the radiation is wish able	Unwanted radiation in the façade	process	receptor	<ul style="list-style-type: none"> - nano technology coatings: reflect certain kinds of radiation -
3.2	Application phase; Working situation					
3.2.1	Application phase; users have different wishes of inner climate	Just one temperature and climate	People unsatisfied with climate	process	receptor	<ul style="list-style-type: none"> - climate influence add-ons per working place (like in car dashboard) - using computerized steering systems -
3.2.2	Application phase; Users have different wishes of daylight	Amount of daylight controlled over whole facade	People unsatisfied with daylight	process	receptor	<ul style="list-style-type: none"> - controlled daylight for the spot - create blind spots on the façade - elements which follow the sun - elements which follow the person - combine with person identification system

						- dynamic mirrors - louvers reflecting light
3.2.3	Application phase; change of users with different wishes	Changing façade parts labor intensive	User dependent on previous user's wishes	process	receptor	- easy changeable units - changeable units from inside - units with wider range in ventilation capacity - multifunctional units - Big basis; small amount of high-tech units changeable - Use dynamic layers -
3.2.4	Application phase; Change of modules from inside	Opening in the façade; safety problem	Too high risk situation	process	controls	- screen for the opening - small units → small opening - a slide for the opening when removing unit -
3.2.5	Application phase; working situation	Façade blocks outside view	No view to outside, unhappy working atmosphere	process	-	- enlarge use of transparent materials - reflect outside view to the inside with mirrors - project outside view on the façade on the inside -
3.3	Application phase; Building change					
3.3.1	Application phase; Building change	Labor intensive, doesn't fit	Façade stays unchanged	process	brains	- Design interface - Use standardized sizes - Design empty spaces and panels who fit them
3.3.2	Application phase; new techniques or new regulations	Some parts need to be changed, some don't	All parts are changed, or no parts are changed	process	-	- Define functions and their need of flexibility - Use different types of connections - Modules must be totally independent -
3.3.3	Application phase; New techniques	U-value can be improved by new material; hard to reach part	Frame cannot be improved	process	-	- define
3.3.3	Application phase; building change	Rain during building change	Water gets in the gaps	Process	-	- a slide for the opening when removing unit - temporary screen for the opening - let water run to outside again -
3.4	Application phase; integration of components					
3.4.1	Application phase; integration of components	Breaking of a component: who is responsible	Not clear responsibility: lawsuits	process	-	- Use a clear interface: car radio (evident separation between elements) - Tell the façade company to buy the climate company
3.5	Application phase; Fire protection					
3.5.1	Application phase; fire protection after change of modules	Modules have different sizes	No closed connection between floors	process	-	- no modules on floor height - only modules with certain height on floors - let modules always slide in direction of floor -
3.6	Application phase; energy					
3.6.1	Application phase; Energy on the façade (wind)	More energy on the façade than used	Energy waste	process	-	- Use wind turbines - Use pressure differences - Use venturi-effect (jet)
3.6.2	Application phase; Energy on the façade (sun)	More energy on the façade than used	Energy waste	process	-	- Use solar panels (PV) - Use water convectors - Use PCM's - Store energy somewhere else -
3.7	Application phase; usability					

3.7.1	Application phase; usability of the facade	Users don't understand working	No efficient use of facade's possibilities	display	brains	- use very simple and clear interface (e.g. to change module) -
3.7.2	Application phase; usability of facade	Modules aren't changed for long time	Knowledge of updating the facade is lost	display	brains	- use very simple and clear interface - deliver with manual - Force to change module every 5 years: use exhausting materials -
3.8	Application phase; flexibility					
3.8.1	Application phase; different components	Modules need to be changed; new supplier	Parts don't fit	process	-	- Use enough space to adjust the parts - Use a dynamic frame: changeable sizes of the openings -
3.9	Application phase; Movement					
3.9.1	Application phase; big temperature difference outside	Movement of the parts	Connections tighten up	process	-	- use flexible material between units - use enough space between modules
3.9.2	Application phase; Big temperature difference outside	Movement of the parts	Gaps between the modules	process	-	- use elastic material between modules - use elastic material to cover the gaps from the outside - use springs to push material to fill the gaps -
3.9.3	Application phase; Wind load on the facade	Movement of the parts (layered structure)	Noise, bad appearance, safety	process	receptors	- use springs to keep elements in place - pre- stressed fixings of elements - wind breaker as first layer - use wind energy (turbines, pressure, jet-effect)
3.10	Application phase; appearance					
3.10.1	Application phase; appearance	Modular facade; no building typology recognizable	Not popular system	display	receptor	- make a distinction between modules and free elements - add a design cladding - design different modules for different modules -
3.10.2	Application phase; appearance	Modular system; building looks almost the same after changes	Not popular system	display	receptor	- don't show the permanent parts; - don't show the grid of the permanent parts - make modules with significant different looks -
3.10.3	Application phase; appearance	Modular facade; building doesn't reflect company's philosophy	Not rentable	Display	receptor	- use flexible parts to change the looks - make design cladding optional - use different layers to change the looks -
3.11.1	Application phase; upgrading modules by service engineer	Upgradeable part not reachable	Not possible to upgrade; modules have shorter lifetime	Controls	effectors	- use modules only on floor height - design modules in a way, that upgradeable parts can be changed from inside -
3.12.1	Application phase; sustainability	Just one person in room, all climate units switched on	Energy waste	process	-	- automatic detection of ventilation needs by person identification system - units only switched on by person; switched off by no movement -
4.1	Recycle phase; Transport					
4.2	Recycle phase; building physics					
4.2.1	Recycle phase; Building physics	Rain during change of module	Water reaches inside of modules	process	-	- take the modules out on the inside of the building - use a screen on the outside of the modules -
4.3	Recycle phase;					

	Building change					
4.3.1	Recycle phase; building change	Building needs to be stable when changed	Parts that belong to structure can hardly be upgraded or changed	process	-	<ul style="list-style-type: none"> - don't make any parts part of structure - take care that parts that are part of structure don't need to be changed during lifetime building - don't solve stability in the façade - design a temporary structure when structure is changed - change parts one by one: surrounding elements can take over the supporting function
4.3.2	Recycle phase; building change	Building changed, modules are left	waste	process	-	<ul style="list-style-type: none"> - re-use modules - re-use parts - re-use materials - dump modules - upgrade modules (find out the reason for upgrading) - re-manufacture, use them in new design (supply based design)
4.4	Recycle phase; Integration of components					
4.4.1	Recycle phase; different components used	Building changed, to whom belong modules?	Not clear responsibility	process	-	<ul style="list-style-type: none"> - use clear interface - keep modules apart from each other (one-to-one mapping)
4.5	Recycle phase; Handling of elements					
4.6	Recycle phase; Design opportunities					
4.7	Recycle phase; Storage					

The function analysis was also helpful to find a number of boundary conditions and requirements of the design. These boundary conditions are not strict requirements, but must be considered as advices and recommendations.

- Make a difference between technical functions and visio-spatial functionalities. This helps to give the architect design flexibility using this system.
- Use enough space between the parts to adjust them. Parts of different suppliers and parts of different times can have (slight) differences in size.
- Just produce elements on order: pre-fabrication. This prevents the storage of elements (costs and modules will be out of date).
- Make modules especially for certain building types. Otherwise the building typology can't be reflected.
- Design elements that can be handled on the building site and in an upgrading phase: elements must be small, carry-able and not heavier than 19 kg.
- Define the functions of the (parts of) the modules and their need of flexibility.
- Modules with different functions must be totally independent. This is in fact inherent to product modularity.
- Use a very clear interface, so that the responsibility of the different parts stays clear.
- In order to let the upgradeable system succeed, the modules need to be changed every once in a while. Use for some parts exhausting materials.
- Make modules with significant different looks. When the building is changed, it may be wish-able to see that actual changes have taken place.
- Use standardized climate units and elements for other functions. This prevents that units won't fit in the reserved area in the frame.
- Use a flexible connection to the structure. This prevents the system for being suitable for only one type of construction.
- To minimize the amount of waste material in the recycle phase, make sure that the modules are re-useable; if that is not possible, make sure the parts are re-useable; next, try to make the

materials re-useable (easy re-useable and environmental unfriendly materials must be separated in specific parts or modules). Also good be tried to upgrade the modules so they can be re-used, or use them in a new design (supply based design).

The third category with results of the brainstorm is opportunities. These are possible functionalities and technologies which can be applied in the product in a later stage. The opportunities are listed below:

- Based on the idea of adding a design cladding: design a modular façade based on different layers, where a layer forms a module.
- A possible production method for the elements is rapid prototyping. Unique elements can be produced quickly and economically in order to provide architectural freedom to the architect.
- The use of freeform elements can also be a way to offer the architect design freedom.
- The frame of the system is able to vary in grid size. The system is still industrialized, but is applicable on more than one grid: so it gives the architect more design freedom.
- Comparable to the one above: the grid is flexible, but has the same connections everywhere. This could mean connections in the x- and y-direction, but also in other directions.
- Use hinged connections, so the frame can be 'bowed' in the right shape.
- Reserve a space in a certain zone (for example in front of the floors) where climate units can be placed. The space between the zones is filled up flexibly.
- Design modules so, that they can be stored efficiently.
- Only use modules that are produced by other companies by ordering them. This prevents storage costs and letting the modules be out of date.
- In order to reflect the building type by this industrialized system, design different systems for different building types (dwellings, utility buildings, etc.)
- In the installation phase, the visible or vulnerable parts can be mounted on the system in a later stage. This prevents the parts from damaging during transport or installation of the heavier parts.
- During transport, use good packaging (cassettes) or strong edges of the parts to prevent the modules and parts to damage.
- The connections between the parts and the frame must be easy, like a clickable system, in order to be able to install the system easily and making upgrading more easily.
- The modules could be mounted in the frame from the inside. This way there is no need of a crane or scaffolding during the installation phase.
- Use sliding parts in the frame to make the frame adjustable for different module sizes.
- Use springs in the openings to let a broad scale of sizes fit and be fixed.
- To prevent an abundance of infrared radiation to enter the room different types of sunscreens can be used, like louvers and screens. Also can different kinds of dynamic glazing can be used: polaroid glazing, electrochrom glazing, polachroom glazing.
- To save on artificial lighting, daylight can be brought further into the room with mirrors, daylight lamps and glass fiber.
- To make possibly translucent parts better insulating, use nanogel inside those elements. Hollow fiber plates are also translucent and very well insulating.
- Not all radiation on the façade is desirable inside. Use nanotechnology coatings on the glass to reflect certain kinds of radiation.
- To give the people inside influence on the climate of their own working spot, use climate influence add-ons per working place (like in a car dashboard).
- Use computerized steering systems with person identification to optimize the climate for all users.
- To control the daylight per working spot, use blind spots on the façade, or elements that follow the sun or follow the person, use dynamic mirrors or light reflecting louvers.
- In order to be able to keep the façade up to date with the wishes of the possible different users, use easy changeable units. Before, we have already seen that in the installation phase easy connections between the frame and units are desirable.
- The climate units should be of wide range or multifunctional to keep the possible different users satisfied with the climate.
- Use a number of climate units to meet the 'basic requirements' of all users, and use small changeable high-tech units to meet the personal requirements.
- A set of dynamic layers can help to create an inner climate after the wishes of all users.
- To prevent the façade from being hazardous during the change of a module (an opening exists) a sliding element can be placed in front of the opening.

- When the unit that is changed is small, the opening will be small. That means less danger.
- The façade blocks the outside view. Use more transparent materials. Or project the outside view on the inside of the façade, or use mirrors to reflect the view to the inside.
- After the change of modules, the rate of fire protection may have changed. To prevent this, just use modules of the same size and the same fire protection on floor height, or don't use modules on floor height. Another option is to let modules after installation slide towards the floor, so the gap between modules and floor is minimal.
- To generate energy from natural resources (sun and wind) use solar panels, water convectors, PCM's, wind turbines, use pressure differences or use the venturi effect (create higher wind speeds by using different opening sizes).
- In order to let the modules move a little because of temperature differences and extension, use flexible material between the modules. Or use gaps and cover the gaps with elastic material from outside. Springs can help to push or pull elastic material in the gaps.
- To deal with the movements because of the wind load, the same solutions can be brought up. Besides that an extra layer can act as wind breaker.
- To be able to reflect the company's philosophy the system can be changed by adding, removing or changing visual parts.
- When all the parts of the system must be able to be changed or upgraded, don't make any parts part of the structure.
Let the parts that surround the parts that are changed be able to take over the structural function of the removed part as long as there is no replacement.

Results of the Alcoa brainstorm

During the meeting with Alcoa on the 30th of November, the same preparation was used as before: the assignments of W. Poelman in [20]. The brainstorm was organized based on six different topics based on the different stages of the product. For each topic a number of constraints were brought up to discuss and find functionalities for. The participants were also given the chance to come up with new constraints themselves.

The list with topics and results:

Manufacturing

The brought up constraints for this topic were:

- Designers want different modules for different buildings. This makes pre-manufacturing more difficult.
- Buildings need to reflect a certain building typology. This makes pre-manufacturing more difficult.

The results:

- 'Customsizing'; cut it on site, or weave it on site.

A discussion follows on different ways to connect the modules. Suggested are:

- Glue the modules. A certain glue loses its binding properties when a high electrical tension is applied between the two parts and the glue is given a temperature of 53 C.
- Inflatable or vacuum connection between the parts. By letting air in or out upgradeabilities can be realized.

Storage

The brought up constraints for this topic were:

- Pre-manufactured modules need to be stored, because a quick reaction is required for a building change. Storage cost money and modules may be out of date.

The results:

- E-bay based network with the modules that are offered by different suppliers.
- Rent modules of a company.
- Upgrade modules when they get out of date.
- Standardization of the slot (for foolproof exchange), not only for ventilation, but for every point.

- Design adapters, which can be produced by different companies.
- What about current systems? Is it a solution to just make them simpler and more modular?
- Why do we need post-rail systems? Do we need glass in the first place? We could also use LCD-windows and just projecting the desired outside view.
- Global possibility: transport the system to all over the world, also to developing countries. Than the façade could also be like a consumer good.

A discussion follows about consumer goods:

- What do you do with your old mobile phone?
- Phones have a lot of functions, but most of it is a brand. Why isn't there something like that in the building industry? For example, the fashion façade: a system that mostly concerns about the image.
- The Smart car. They claimed it was possible to change parts to change the look. In the end, nobody uses that feature.

Transport

The brought up constraints for this topic were:

- During transport modules face the risk of damage (especially at the edges).
- Different elements don't lead to efficient storage and transport.

The results:

- Use round elements; at the building site they can just be rolled to the right spot.
- The instant façade. This is like towels or sponges, which sometimes can be found in hotels. Those products are packed together really tight; putting them in water brings the desired volume and size.
- Shelves where façade parts can be put in. (this could be a part of the construction.)
- Place certain parts (the vulnerable ones) on site (sunscreen for example)
- Put the modules on site together (like an IKEA piece of furniture). When the modules are foolproof, everybody can build them. So people could even build their own façade.
- Design a folding module. The transport is efficient, and it will be quickly unfolded on site.

Installation

The brought up constraints for this topic were:

- Modules need to be installed in different circumstances, environments and structures, while a quick reaction is required.
- Elements of different suppliers have different sizes; they may not fit in the reserved space. They may not fit when they are too big, or cause gaps when they are too small.

The results:

- The above described problem can be endorsed by Klaus Hees. The performance of a cladding system depends on the weather during the installation of the façade. During cold weather, rain, etc. it is hard to install the elements, because the gaps are difficultly tight. The solution for this problem could be a foolproof and weather proof system.
- The system could be installed by robots.
- Another constraint is that glue won't harden during the rain. (if we would choose for glue: glue is not allowed to be the only fixing)

Application

The brought up constraints for this topic were:

- What functions can be added to the standard range of functions?
- A component used in the façade fails, or the building is changed; who is responsible for that component?

The results of the first question:

- Communication (media) façade
- Energy gaining
- Through-away façade

- A façade that is built for a planned upgradeability: the parts need to be upgraded have a lifetime of the planned time.
- Cleaning air: the air, which enters the building, but also the air that is around the building, is cleaned.
- Outside device that regulates the radiation, which enters the room.
- Problem and deterioration seeking device.

The results of the second question:

- The builder of the module. For a piece of furniture this would be IKEA, so for a façade this is the module producer.
- The party that has been paid; if something breaks, you just have one address to go to: and that is the party you paid for to build the façade.
- When the problem is not the module, but the interface. The problem now does not lie with the manufacturer, but with the party who installed the element. He is responsible.

Recycle

The brought up constraints for this topic were:

- The building is changed, and some modules are not used any more.
- Elements of the modules in the façade have different lifetimes

The results of the first question:

- The previously mentioned glue can be used to disassemble the modules with the help of a high electrical tension and a temperature of 53 C.

The results of the second question:

- What is meant with the lifetime? Is it the technical lifetime or the cultural lifetime?
- Make all the elements of the same material.
- Make the modules itself modular as well. An advantage of that is that used materials that appeared to be toxic can be taken out more easily.

Appendix II: Modular hardware

Trox/FSL Type FSL-B-100: decentralized window and façade ventilators with high acoustic performance

This unit is a ventilation unit produced by Trox/FSL with an incorporated noise control. The air from this unit is not heated or cooled, just filtered. The way the unit is put together and the way the unit can be placed makes this type of unit interesting to study.

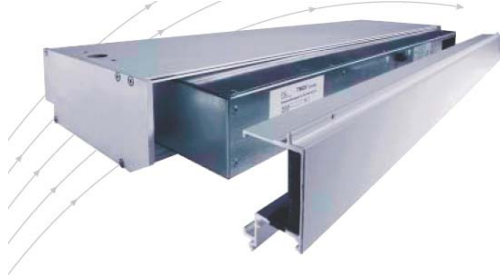
The type FSL-B-100 consists of an external casing with inspection flap and modular insert. The external casing is an aluminum box with reserved space and clickable connections for the inserts. The box can be connected to the façade structure and with that provides enough stability for the modular inserts while providing a thermal break in the construction between rear and front detail.

The units can be installed both vertically, at the site of a window for example, or horizontally, as the sill or under the sill.

The modular approach enables the installation of the external casing at an early stage of the construction process. After the installation of the external casing modular inserts of supply or extract air elements with acoustic and thermal insulation can be installed to meet the requirements of the façade units. Other advantages of this approach which are mentioned by Trox/FSL are the prevention of contamination and damage to the vulnerable modular inserts and the possibility to change functional configurations after the completion of the building.

This type of units has an overall height of 100 mm and is variable in depth and width between 231 to 600 mm and 1000 to 3000 mm respectively. This way they can be ideally matched with the constructional and structural situation. For the units with electrical components a 230 V voltage supply is necessary. The two stage fan inside provides a choice of flow rates as follows: 30/40/50/60/80 m³/h.

The parts that need to be changed regularly are the filters. To change them the inspection flap which covers the external casing must be opened. The filters can subsequently be changed without removal of the modular inserts.



To get more specific information from Trox, especially on the design of the units, the representative offices of both Trox the Netherlands as Trox Germany have been contacted. Reports of the whole conversations can be found in Appendix II. Here, the most important findings are given.

What information is needed of the decentralized ventilation units:

- How many units are needed in an office?
- How big are the units? How small can they get?
- Can they be designed project depending (like is done Stadttor in Düsseldorf)? And when?
- What are the positive aspects of decentralized ventilation units? And what are the negative?
- How big are the 'standard' units?
- How are standard units usually connected to the building or façade?
- How flexible do they need to be; what is their functional and technical lifetime?
- What do the units need to let them work: electricity, water, air, etc? And how much?
- How big do the ducts need to be which lead to the units?
- How does the future of the development of the units look like?

From consulting Merford (Representative office Trox/FSL the Netherlands):

- The number of the ordered units must be in the order of a few hundred to make specially designed units cost-effective. The Capricorn building is an example of a project with specially designed units.
- The units need to be connected with the electricity grid (230 V) and with four water circuits (2 warm, 2 cold; both have one supply circuit and one return circuit). The pipes are comparable with pipes used for regular radiators (Ø15 mm).
- The connection of the pipes to the units is located mostly at the heat exchanger; the connection itself can be flexible.
- The technical lifetime of the units is comparable with the lifetime of the façade itself. Vulnerable parts are the moveable parts, like ventilators and valves. These elements are placed so (they often are slid into the unit as a module) that they can be maintained or changed. The filters need to be changed twice a year, so they also have been placed in a way that they can be easily changed.
- The future development of the units will mainly lie in the energy supply; perhaps another way of supplying them with cold or warm water can be found. The four pipes could for example be exchanged with one pipe supplying water, and the heating or cooling of the water happens at the location of the unit itself. The Smartbox is already experimenting with this (the adiabatic cooling). The units of the future will not be significantly different from the ones today, so both technical and functional lifetimes are considerably long. The future development is limited because of the comfort, which at least has to stay at the same level. That limits the developing of units with bigger capacity: the ventilation air can't be blown inside with bigger speed and lower or higher temperature, because that would lead to an uncomfortable situation.
- The units are suitable for buildings with limited depth, because the influence and reach of the units is only possible until about 7 m from the façade. Because the limited capacity of the units, they must be used in combination with active thermal mass. The decentralized climate units just provide the desired ventilation and could steer the inner temperature slightly towards the right direction.
- The main advantage of using decentralized units is the saving on space for shafts and floor height because of the redundancies of lowered ceilings. Also the individually controllable comfort and inner climate are important.
- The major disadvantage of the units itself is the maintenance. The filters need to be changed every half year and this needs to be done on the working place. On the other hand, this also means that the malfunctioning sensitivity of the system is reduced compared to a centralized system; malfunctioning of a unit doesn't lead to a bad inner climate in the whole building. Limited sound insulation is another disadvantage of the system: complete closure of the façade is not possible when using these units.
- According to the representative of Merford the advantages won't lie in the saving on the energy use of the building installations, unless fundamentally different sources are used like river water instead of drinking water. This would however be the same for centralized systems. The comfort level determines the energy use, not the system.
- In the Netherlands there is not a trend noticeable to use more decentralized units. The building process in the Netherlands doesn't have an integrated approach, which is absolutely necessary for the integration of building services in the façade. In a very early stadium should already be decided to use decentralized ventilation units and even the integration of a supplier of these systems is necessary. The disadvantage of this process is that early choices cannot be changed during the process, which is not the case for the current process: every part of the process (façade planning, building services, structure, etc.) can be done by an individual party and not until a late stage during the process they get in touch with each other. In Germany the use of decentralized systems is more common; perhaps the building industry is prepared to spend more money on the façades.

From consulting Trox/FSL Isernhagen, Germany:

- The design process of the decentralized units is as follows:
Trox/FSL plays part in the building process already in an early stage. The choice for decentralized ventilation units has major consequences for the building planning (structure, façade, etc.). In this stadium the architect, the client and the façade planner determine what functions the decentralized unit should incorporate and where the decentralized units should be placed. This is mainly of conceptual nature.

In a later stage the units are designed specially for the project, if necessary. According to the Trox representative 90% of the big projects which are involved with Trox are being helped with a special solution. A special solution is always possible, depending on the price; at a high price even five special units can be made. As a rule the order of 100 units pays off to produce them specially.

- The sizes of the unit of the Capricorn building, especially the depth, are approximately the minimum sizes of the unit. Otherwise the fans and the heat recovery will not work properly. When the depth is kept 20 cm the other sizes can be various, but they depend on each other and on the desirable functions of the unit.
- The thermal break is most of the times not solved within the modules. The biggest part of the modules is situated on the inside of the façade and just a small ventilation tube breaks through the thermal line. If a thermal break is necessary it is placed in the casing of the unit. Two metal plates are then separated from each other by a polymer.
- The biggest advantage of decentralized ventilation is the individual control, which results in a high acceptance of the users; when the users can control their own climate they will sooner be satisfied with the climate than with a centralized and uncontrollable system. Besides that energy can be saved using decentralized units. Rooms which are not used are not ventilated, unlike in a situation with a centralized system. Another advantage is the saving on a lowered ceiling, which gives extra room height or saves in total building height; ventilation pipes and shafts are not necessary. The latter makes the use of decentralized systems also suitable for restoration and refurbishment. In old building the space for ventilation pipes and shafts is often limited, so solving this in the façade zone is a good opportunity.
- The main disadvantage is the difficulty to incorporate the moistening and the de-moistening of the air: it is hard to keep the air on a constant humidity. Moistening of the air is possible, but de-moistening is not. If the function of moistening is required, an extra water duct is necessary. Besides that it is not possible to ventilate a large office. The decentralized units have a reach till 6 to 7 meters from the façade. The cooling and heating function of the decentralized units only works in combination with an additional application, for example thermal active mass or floor heating. Just the peak loads in the inner climate can be taken by the decentralized units. Only in very well insulated buildings, which have very good additional applications to keep sunlight out in summer can be cooled and heated with decentralized units only.
- The units need a standard electricity connection of 230 V. To cool and heat the air the units need to be connected to four water ducts: 2 for cooling and 2 for heating. As said above the units need an extra water duct to enable moistening of the air. The connections with the water ducts are mostly flexible to be able to take the unit for heat recovery out and clean it for example. Flexibility is reached by making the connection with a flexible hose.
- The lifetime of the units is depending on the insensitivity and duration of the use. There are several parts which are more vulnerable than others, so they will have a shorter lifetime. The ventilator is probably the most vulnerable part. It has according to the producers a minimum lifetime of 60.000 h. With conventional office times of 2500 h per year this means the ventilator will survive 24 years. Hence, the lifetime of the unit is 24 years, or even more if the ventilators can be replaced.
- The units will probably not be exchanged by other, new developed units. This would be easy to do, but practice has shown that is not usual. It is however customary that certain parts of the unit are exchanged (if one is broken) or that certain parts are cleaned. Filters need to be changed a few times a year. The heat exchanger and the inside of the casing must be possible to be cleaned; these are the air transporting elements. The electrical parts like the ventilators, the valves and valve propulsions, the Printed Circuit Board (PCB) and the sensors must in case of errors and effects be exchanged.

The future development of the units will probably lie mainly in the field of energy efficiency. The current units embody almost all the necessary functions; the sizes of the units will probably not decrease because of the room needed to treat the air towards the desired quality.

Other development themes in the future could be the cleaning and filtering of the air; solutions for this could for example be found in the field of active oxygen or UV radiation. These new applications of air cleaning are in fact also contributions to a more energy efficient unit.

Solar PV-cells need to have the photo-voltaic panels themselves to produce energy, a battery to store energy and an electrical converter from a direct current to an alternating current. The photo-voltaic cells deliver a direct current, while an alternating current is necessary for the net.

The batteries and converters are offered by the company Mastervolt.

The Mastervolt MVSV (gel)battery 2/280 (smallest in this series)

Sizes: 125 x 207 x 401 mm

Weight: 23 kg

Lifetime: 20 years

The Mastervolt MVSV (gel)battery (biggest in this series)

Sizes: 214 x 488 x 819 mm

Weight: 196 kg

Lifetime: 20 years

Converter Mass 12/500

Sizes: 313 x 187 x 82 mm

Weight: 3.4 kg

Lifetime: -

Converter Mass 12/2000

Sizes: 420 x 318 x 130 mm

Weight: 9.4 kg

Lifetime: -

The actual solar panels are connected with a DC connection with the converter. The converter is connected with a system manager to be able to read the effectiveness of the panels and to look at the status. The system manager can also be used to influence the solar panels and its effect. The converter has also a connection with the net. This is an AC connection; through this connection the energy which is produced by the solar panels is given to the net. The energy needing devices and applications inside the building collect their energy from the net. The differences of the offered amount of energy and the used amount of energy are measured.

Another option could be to connect the inverter to a battery instead of to the net. This provides an energy storage possibility for the abundant produced energy, giving the building the chance to be self-providing. The other applications of the façade could for example be connected to this battery, or even the whole electrical system of the building, depending on the amount of solar panels and their ability to produce energy.

The best is to offer both possibilities: future development is hard to predict, so the connection to the net could now be desirable, but not at all in the future. To complete the concept of a flexible system, these possibilities must also be considered.

Appendix III: Question list architects

Question list architects on the service integrated façade.

At the TU Delft (Faculty of Architecture, chair Design of Construction) a research has started to find out more on the topic of service integrated facades. With this type of facades is meant the integration of decentralized building services, like ventilation, heating and cooling, in the façade or in the façade zone.

Advantages of this kind of systems are:

- The use of decentralized climate units makes a central climate system redundant: which could lead to:
 - o Individually controlled climate: higher comfort
 - o More freedom in the building planning, especially the floor plans
 - o Lower energy costs: only the installations of occupied and used rooms are switched on.
- Many functions can be integrated besides the already mentioned ones, for example:
 - o daylight provision
 - o artificial lighting
 - o energy gaining

The main disadvantage of this kind of systems is:

- The design limitations; the systems are mostly pre-designed and allow a limited variation in geometry.
- Higher effort compared to centrally controlled systems

To get a vision of the future of these concepts, we are asking for the opinion of several involved parties the building and design process. We formulated a questionnaire with the foreseen problems and opportunities, so we can get a notion of the thoughts on this type of facades. The last question comprehends the formulation of your personal specific demands, opportunities and problems of these facades.

We really appreciate your contribution to this research by filling in this questionnaire and giving your opinion on this topic.

We will treat your form confidentially and will not provide a third party with the confidential information.

For any questions or remarks please contact me by mail or by telephone:

Joep Hövels

e-mail: j.m.hovels@student.tudelft.nl

tel.: +31 6 – 248 91 334

General info

Your company's name (optional):

1. Studio-A1 Amsterdam
2. -
3. TU Delft

In what specific field(s) are you and your company active?

1. Offices, theaters, schools
2. Initiation, advise, development
3. Education, research, advise, design

*Are you familiar with service integrated façade systems, or do you even have design experience with it?
If yes, in what way?*

1. Not directly, I know how the system works
2. Theoretically
3. From 1993 till 2000 Prof. Jan Brouwer was researching these items in a study the 'intelligente gevel'. As a member of the research group I was involved in this. A lot of information can still be found by Ype Cuperus

The following façade systems are examples of existing service integrated façade systems. Both systems can be considered as element facades.

They integrate among other things natural and mechanical ventilation, heating and cooling. The goal of both systems is besides function integration the saving on energy and the production of energy.

E² by Schüco

The goal of the concept is creating a façade solution that combines on an esthetical way the façade functions ventilation and air-conditioning, operable elements, sun shading and solar cells. The higher goal of the façade is to build buildings that produce more energy than they use.

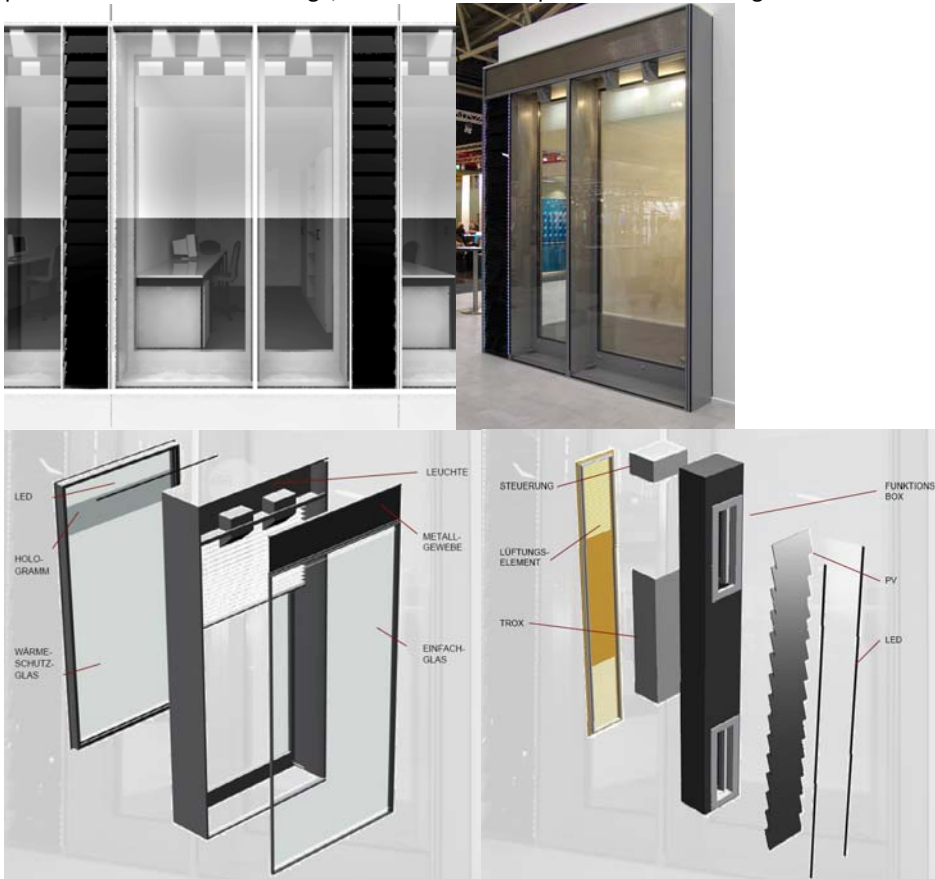
The offered variations are mainly in terms of functionality; different climate units, different profiles and variations based on the specific building properties (room height, grid, etc.) are possible.



TE-Motion by Hydro Building Systems

The building designer is free to choose the relation between the number of glass elements and functional, closed elements. Depending on the size of the room, each room needs at least one closed, functional

element. Because of the plug-and-play technology which is applied in this system, the user can decide to place other units in a later stage, even after the completion of the building.



Are you familiar with the existence of specifically these systems or with comparable systems?

1. I'm not fully familiar with this system, but I think I understand the use
2. No
3. Not yet. However, these kind of ideas will have been on the minds of a lot of designers who have been involved in building and façade design and research. So indeed familiar with the existence of ideas.

Would you consider applying one of these systems (possibly after a few minor changes) as a façade of your design? Please explain.

1. Yes, why not, particularly if thinking about making a glass façade, this could be a good idea, to think about the alternatives.
2. Provide as alternative to other solutions
3. I would consider to study the possibilities in relation to other properties of the building and maybe at the end of a study conclude to draw up a proposal in terms of a desired building or design.

In terms of architectural design, would you like to express the idea of integrating of building service components in the façade (for example by showing the actual functional units)?

1. This question involves too much the way a particular building could be conceived. In this respect I think it depends on the overall design.
2. In some cases ok, in some cases not.
3. No, I think a building is not about that. Just like a human being is not about breathing in or out.

What would be the biggest advantages to choose for one of these systems?

1. Energy saving
2. Less installations in the room
3. Higher comfort level

1. Energy saving.
2. Are the advantages proven?
3. Higher comfort level

What would be the biggest disadvantage for you?

1. Probably the costs
2. Appearance always the same? Design possibilities??
3. According to common knowledge building components with mechanical equipment may become problematic because related to a building they are more short term based. An advantage might be that every 10 or 15 years by replacing elements, comfort will stay in time with rules which are changing: adaptables and frames.

If this concept is new for you, what would you like to know before applying it?

1. All limitations in the application in a project
2. How it works, deals with extremes (climate/use), different appearances? Costs!
3. The thinking and thoughts about it related to implementation in an artificial environment. Form and design can be solved according to desires.

Do you have other remarks on the topic of façade design in this context (concerns or advices)?

1. Not really
2. -
3. Please: focus on strategies, and then develop products and solutions “based on strategies in context”.