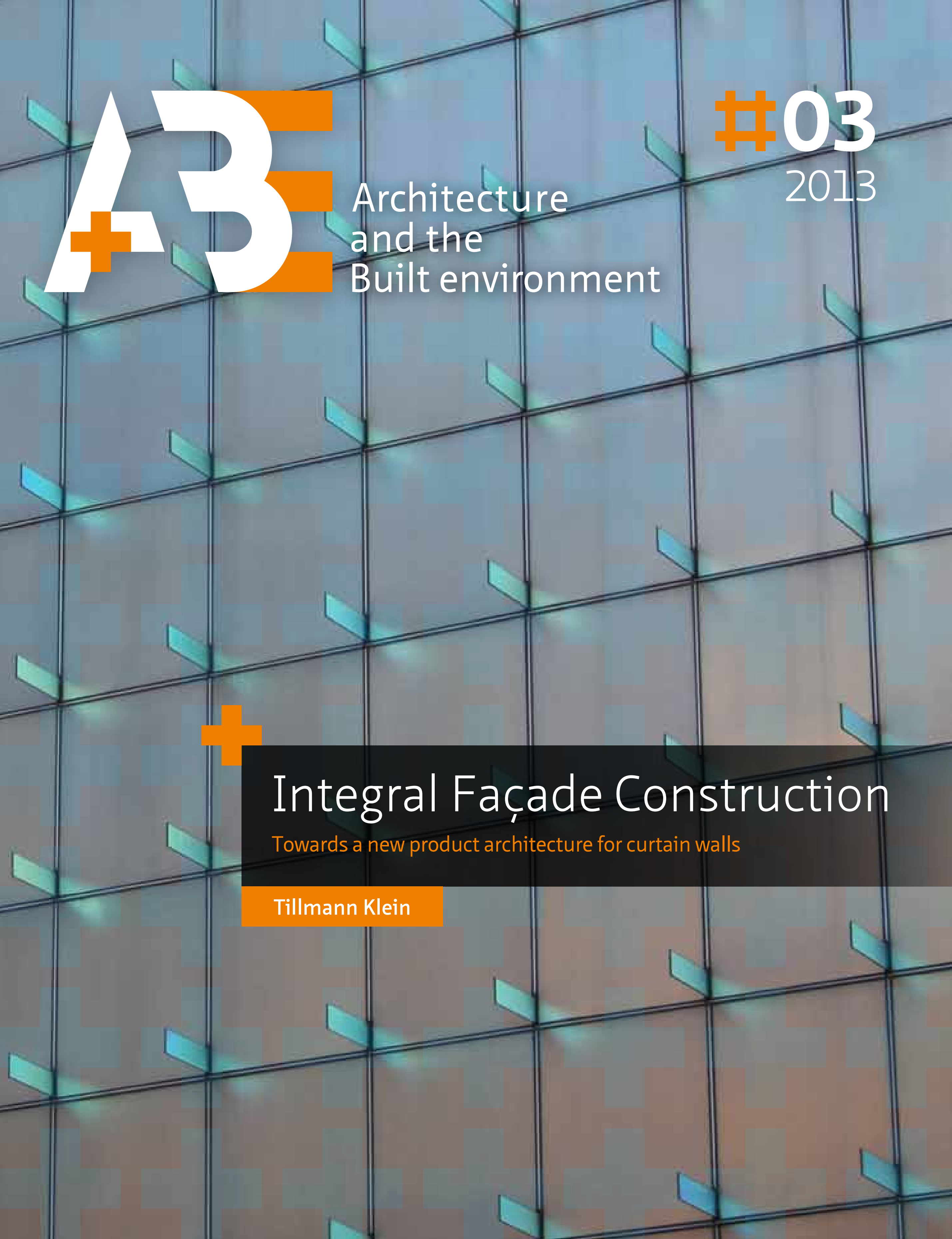

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Integral Façade Construction

Towards a new product architecture for curtain walls

Tillmann Klein

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Contents (concise)

Abstract

Curtain wall constructions are one of the most applied façade constructions today. Independently attached to the primary load bearing structure of the building they protect the building's interior from external climate conditions and allow great design freedom.

With continuously rising requirements in terms of energy savings the constructional principle has reached its limits and strategies for improvement are needed.

Incrementally evolved over time it is closely related to the architectural design and building processes. Based on literature research and stakeholder interviews the dissertation maps out the traditional and craftsmanship related façade design and construction process currently employed. In a next step, future challenges for façade constructions to cope with a changing market environment are identified.

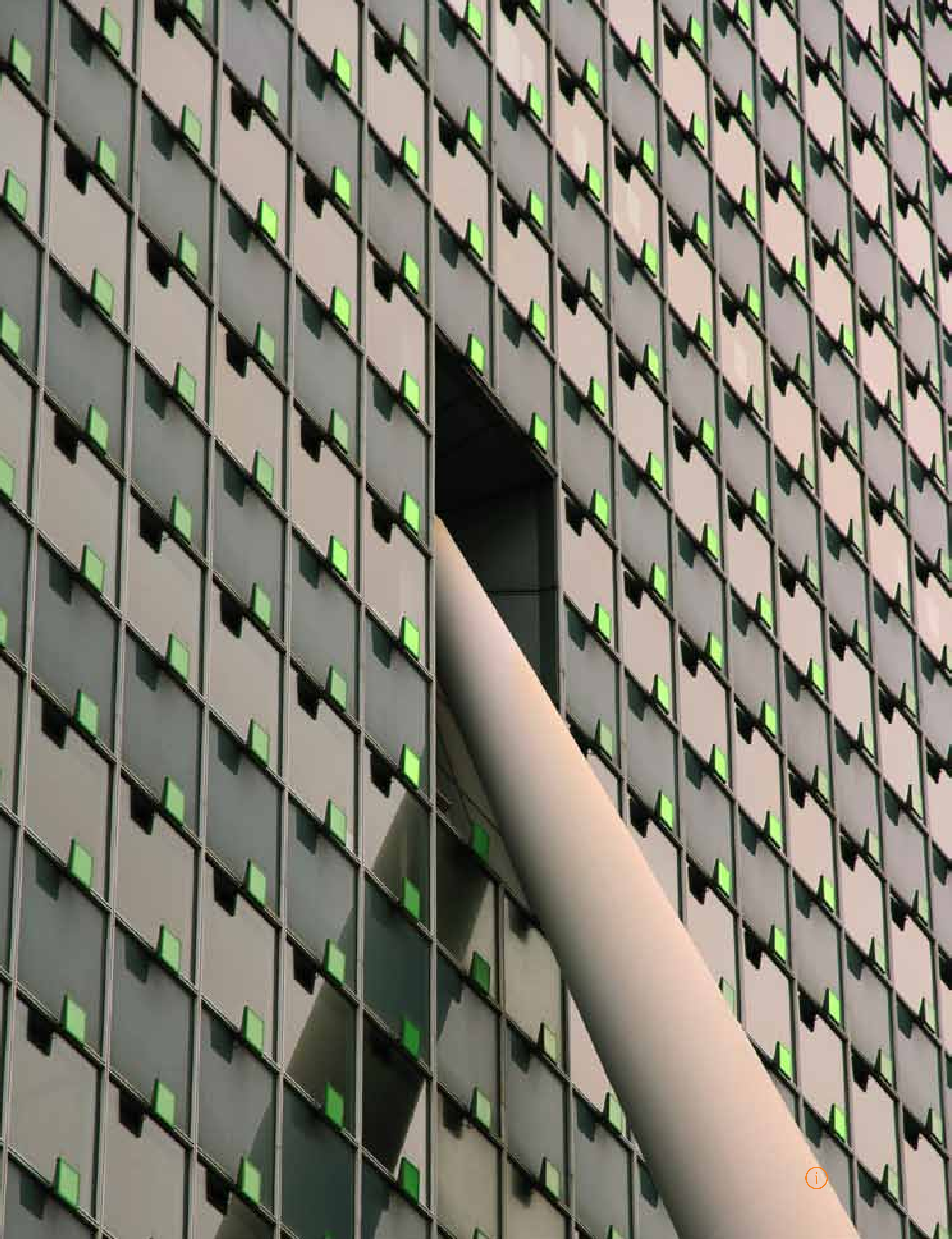
A façade function tree is developed and the theory of product architecture is applied to create a comparative basis for analysing different historical and contemporary façade products and systems. The function tree as well as the analysis clearly show how the fragmented market structures has influenced contemporary façade construction and leads to extremely modular product architectures.

Numerous case studies for a new approach are conducted and summarised in several matrices. The case studies show how different modular and integral constructional strategies can respond to the future challenges. The pros and cons of different façade solutions, their potential for innovation and robustness in terms of market conditions are investigated.

The dissertation concludes that a greater diversity of façade types with a more integral construction is needed to meet the sometimes conflicting future challenges. If this can be realised, a greater diversity of more integral design and construction processes will evolve simultaneously. The role of the different stakeholders will change and a new way of educating architects or façade specialists will be required in order to meet the needs of the future building market: Away from a purely application oriented towards a product architecture driven approach, which clearly includes the implications of façade product architecture on the structure of the design and construction process.

Contents (extensive)

Side notes



1 Introduction

§ 1.1 Background

The curtain wall is one of the most successful types of façade construction and widely accepted amongst architects. Its development at the end of the 19th century is a direct result of innovations in the field of structural building. The introduction of frame construction made it possible to eliminate massive exterior wall constructions and therefore allowed for a completely new definition of the building envelope.
As the name implies the curtain wall is a construction independent of the load-bearing structure of the building that protects the building's interior from weather and climate conditions. Its non-load-bearing property allows for expansive transparent areas. The result is a previously unknown freedom of architectural design possibilities for the façade with equally great new options for the interior space.
The construction type bears different names in different regions. The term curtain wall is used in English speaking countries; in the Netherlands it is translated with 'vliesgevel' – membrane façade – which highlights the permeable, textile-like character of the building part that separates the interior and exterior spaces. In Germany it is called 'Vorhangfassade'. The term 'Vorhang' is the equivalent of curtain, but the verb 'vorhängen' also means to literally suspend the façade in front of a structure. Today, the majority of façades, particularly those of utility buildings are constructed this way.
The dissertation focuses on the future development of the curtain wall. While the requirements on façades have slowly increased over the last decades, the curtain wall has evolved from craftsmanship oriented constructions to highly developed façade systems. But its constructional principle is still the same. Simplified, it can be described as a two-dimensional stick system with infill. With the latest requirements of almost energy neutral buildings, faster building processes and increasing technicalisation of the building envelope this constructional principle is reaching its limits. The curtain wall system has reached a state of maturity; and it needs a new approach to guaranty that this successful product will meet the challenges of the future.

§ 1.2 Historic development of curtain walls

From a technological viewpoint the curtain wall can be traced back to the botanical green houses of the mid 19th century. Here, the new developments of the Industrial Revolution with their extensive use of metal constructions found their way into architecture. Factually they were not viewed as architecture but rather as functional buildings. This might be the reason why a predominantly rational and structurally innovative construction could stand in the foreground (Kohlmaier and Sartory 1991) although it did not meet the architectural design ideas of the time. A large boost was given by the introduction of green houses, provoked by the growing interest in foreign plants from discovery journeys. Because plants need as much daylight as possible, façades were built with a maximum of transparent area. Structurally, they cannot truly be separated from the primary, cast-iron load-bearing structure; yet they do already show the division into linear profiles made of rolled steel as well as plane-filling elements that were typical for later curtain wall constructions. At the end of the 19th century the green house structures led to the metal frame construction method in architecture.

Figure 1
Palm House, Kew Gardens London, 1841-1849. Cast-iron columns and joists form the primary structure. The envelope consists of formed rolled steel profiles with bracing glass panes..

In 1853, Elisha Otis invented the crash-safe elevator. That and a high readiness for investment and high land prices caused Chicago, after the great fire of 1871, to experience a building boom of ever higher buildings. The architects of the Chicago School, in particular, drove this development. The frame construction method allowed for large unobstructed spaces, and a high degree of pre-manufacturing enabled fast construction. A new building type evolved as an alternative to the massive construction method with load-bearing exterior walls. These developments did not occur in a continuous manner, and a detailed description of the process would exceed the scope of this work. However, starting with the Reliance Building by Burnham and Root,1895 (fig.2), it is useful to give a brief inside into the development of the curtain wall.

Figure 2
Reliance Building, Burnham and Root, 1895

The façade features the typical Chicago Window – one large fixed window and flanking elements with operable leaves. The riveted steel structure on the interior made it possible to include a, for those times, very large proportion of glazed areas. The rhythm of the light terracotta cladding with its gothic inspired ornaments matches the steel columns embedded in the façade. In its time, the building must have made a deep impression with its lightness in colour and structure against the background of a city predominant built with dark brick. However, its architectural performance would only become appreciated in later times. The building marks a transition into the modern age. It is only in the 20st century that the structure of the façade was completely separated from the load-bearing structure of buildings.

Figure 3
The Bauhaus in Dessau by Walter Gropius und Adolf Meyer, 1926

The Bauhaus in Dessau by Walter Gropius and Adolf Meyer heralded Modernity (fig.3). Built in 1926, it is another milestone in curtain wall architecture. The three to five storey high building includes studios, class rooms and a dormitory, and features white plastered façades with windows as well as multi-storey steel glass façades spanning several storeys. The construction is suspended and therefore particularly lean. The concrete floor slabs are visible. Any sort of ornament is purposefully avoided. Lacking insulation and sun protection, this façade was definitely questionable in today's building physical terms; however, from an architectural standpoint it clearly shows the concept of a curtain wall structure in its purest form.

Scott Murray (Murray 2009) writes the following about the façade of the Bauhaus: "If the frame structure can be considered a feat of engineering´, then the curtain wall was architecture's response, exploiting the frame's potential to reconceive the building envelope."

After the Second World War a number of outstanding curtain wall clad buildings were erected; amongst them the Lever House by Skidmore Owings and Merril, 1952 (fig.4), and the Seagram Building in New York by Mies van der Rohe in collaboration with Phillip Johnson and Kahn and Jakobs, 1958 (fig.5). The curtain walls form an uninterrupted envelope around the buildings. Both consist of steel constructions. The Seagram Building's interior and exterior was clad with stainless steel metal. It is fully glazed with coloured spandrels to camouflage the underlying parapets. The Seagram Building shows the typical Miesian I-shaped mullions for structural purposes. Both buildings do not feature operable windows and rely fully on HVAC systems. The glazed curtain wall façades with their gridded structure in combination with a departure from the typical urban building block have made these buildings into icons of Post War modern architecture. They were soon widely observed by architects all over the world.

Figure 4
Street view and detail of the renovated Lever House, Skidmore Owings and Merril, New York, 1952

After the war, the aluminium extrusion process found its way into the building industry. Extruded aluminium sections were more economically and allowed more detailed profile patterns and were a perfect material for curtain walls. Another technological development thrust resulted from the float glass method, with which Pilkington industrialized flat glass manufacturing in 1959. It provided large quantities of high-quality glass panes which contributed to the worldwide adaptation of this building method. This in turn led to public criticism of the gridded and glazed, scale-less architecture of the time.

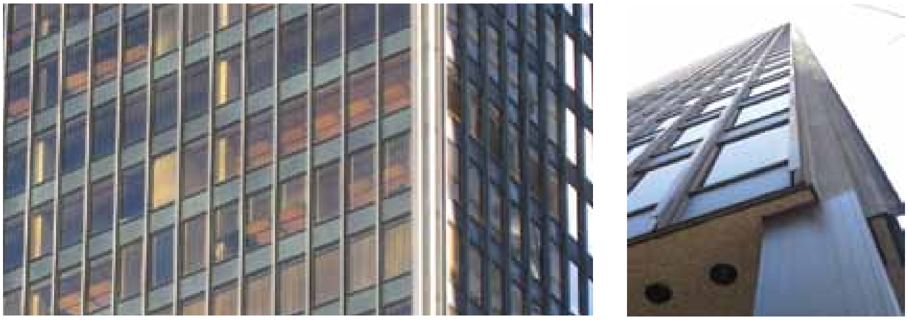


Figure 5
Detailed view and corner solution, Seagram Building, Mies van der Rohe, New York, 1958

The first oil crisis during the Seventies of the last century created a new development. Energy consumption now became a decisive parameter in the design of curtain walls. Additional layers of glass were added to the façade structure to improve thermal insulation. And the material glass itself was further developed. During the Seventies single pane glazing was completely replaced by multi-layer insulating glass panes. Reflective coatings as well as so-called Low E-coatings (low emissivity) provided the glass panes with additional functions to reflect heat rays. "Dallas Architecture" took centre stage, as Just Renckens aptly describes this style (Kohlmaier and Sartory 1991; Renckens 1997). Highly reflective glazed buildings popped up throughout the entire world. The basic reason here for was to reflect the sunrays on the exterior skin in order to avoid overheating of the interior space. Effective exterior sun protection was not possible at great building heights, because of wind loads and maintenance costs. The visual connection between interior and exterior space disappeared.

But this development was also driven by architecture. Postmodernism as a countermovement against the hitherto predominant modernity bethought classic formal vocabulary which is often stylised by the entire building volume. One example is the AT&T Building (now Sony Building) by Philip Johnson and John Burgee (fig.6). Stone panels, although feigning a massive structure, are mounted on steel frames, which are spanning from floor to floor and are in fact a curtain wall.

Another example is the State of Illinois Center by Murphy/Jahn, 1985 (fig.7). The dramatic shape is clad by a scale-less curtain wall. Whereas the curtain wall in the designs of modernity was still a symbol for a "glass box", in postmodernism it evolved into an appropriate means to realise any architectural shape.
It was only in the Nineties that the curtain wall was redefined. The awareness had risen that it is not only important to save scarce resources but to also save the environment itself.

Figure 6
AT&T Building, Philip Johnson and Richard Burgees, 1984

Figure 7
State of Illinois Center by Murphy/Jahn, 1985

Therefore, to further reduce the need for energy consumption additional structural glass layers were supposed to enhance the façade's functionality. The gap includes sun protection that in high buildings is thus protected from the wind, and the multi-layered structure provides improved insulation in winter. Natural ventilation is at least partially possible again with the help of protected windows in the inner structural layer. Designs with energy-saving double façades win high-rise competitions. Buildings such as the RWE Tower by Christoph Ingenhofen in Essen and the Commerzbank in Frankfurt by Norman Foster are created (fig. 8,9). Innumerable variants of the double façade are being developed. Today we better understand the advantages and disadvantages of this strategy, and the design of such a construction can be better predicted due to new computer-controlled simulation tools. Double façades inhabit also disadvantages in comparison to single layered constructions, such as the potential overheating of the cavity or condensation problems. Not least due to extremely high cost, today double facades are usually only employed for tall buildings.

Figure 8
Commerzbank Tower, Norman Foster, Frankfurt 1997.

Figure 9
RWE Tower Essen, Ingenhoven Overdiek, Kahlen & Partner, Essen 1996

§ 1.3 State of the art

The requirements posed on façade constructions have increased steadily over the past decades. After the oil crisis the first regulations concerning the energy consumption of buildings were drawn up. Furthermore, an increasing number of codes and directives were created that deal with environmental pollution, product and user safety.
The building industry was forced to set and enforce new standards, particularly in terms of building physical aspects. Certification reports had to prove that certain thermal insulation properties, air and water tightness of the curtain wall were maintained.
The increased complexity of curtain wall constructions caused a development from craftsmen structures in the Fifties to today's sophisticated building systems which, however, still include all steps from manual to industrial production. Fully industrially manufactured subcomponents such as insulating glass units are sometimes integrated into the construction during pre-manufacturing processes. But these then still need to be manually mounted to the building. Fully industrialised façade construction is still

far off. The principle of construction has never changed. Curtain walls still consist of a structure separated from the load-bearing structure of the building with linear, load-carrying elements and fillings made of glass or other materials.

§ 1.4 Curtain wall, building industry and architecture

The development of the curtain wall must be understood in interrelation with the building world. In contrast to all other structural disciplines, architecture is the decisive factor; a fact that impacts the building and decision-making processes as well as the construction itself. Architecture is always related to a specific location. Through properties such as material specification and proportion it creates a statement and an understanding of the surroundings. It interprets the surrounding context and tells us how we should live. This presupposes one of architecture's particularities: if we want to take responsibility for the location and the specific building task, architecture must primarily be project-oriented. This differs, for example, from the automotive industry which works product-oriented. An automobile is characterised by technical as well as formative features that are separate from the location it might be used at.

The fundamental character of architectural creation can therefore be viewed as an open-minded scanning of possibilities, iterative striving for the optimum project-specific solution. On this basis, architecture has evolved incrementally over millennia as one of the oldest construction disciplines.

In order to transform architectural designs to built constructions, crafts have developed; specific disciplines with a predefined task spectrum such as masonry, carpentry, metal working, plumbing, and others. The advantage of such a craftsmanship-oriented division is quality assurance due to a limited work spectrum as well as the possibility to define interfaces between them. An example: installing a window in a brick wall is based on traditionally defined variants and interfaces. If these are used, dimensioning and work outlines are clear. The craftsmen know what to do if planning remains within the given canon.

This has also been the basis for the development of tender procedures. Basically, the entire building process is divided into separate crafts which are planned by different planners such as structural engineers or buildings services engineers, and are also executed by different companies. The underlying idea is that the architect guides the entire process much like a conductor. He/she ensures architectural integrity and merges the different planning and building tasks. He/she specifies standard services as well as components and interfaces deviating from these.

Façade construction plays yet another role within the building industry. From a technical viewpoint the facades is one of the most complex building parts. It must withstand environmental impact, while separating the interior and exterior climates creates numerous building physical issues. But the façade is also significant from an

architectural standpoint. Together with the overall shape of the building it defines the urban appearance. At the same time it determines the relationship of interior and exterior space and the user comfort level.
The increasing complexity of modern façade constructions requires that the conventional planning service of the architect needs to be complemented by additional, more in-depth planning phases of the executing company. This is one reason why, over the past ten years, the profession of façade engineer has gained in importance.
The allowed tolerances for façade systems lie in the millimetre range, and production and assembly have reached a high degree of prefabrication. In contrast to craftsmen-oriented crafts such as masonry, for example, building onsite does not follow the architects drawings; rather, logistic and craftsmen integration is primarily handled by the executing companies. Their originally linear organisational structure (production) has thus developed into a project structure (engineering, production, assembly) (Renckens 1997) that needs to be seamlessly integrated into the overall project flow.

Figure 10
Industrialized production of unitized façade elements on a conveyor belt

Figure 11
Manual assembly of windows on site

The particularity of the iterative architectural design process in conjunction with grown, linear craftsmen-oriented processes in the building industry has led to a modular construction method. To clarify: the design team needs reliable statements about the performance of products and their architectural quality and possibilities at an early stage. At the same time, product flexibility needs to be maintained in order to be able to react to changes in the design.
The brick is an example of a product that has undergone perfect development in the canon of the building industry. Its modular principle makes it possible that it can be pre-manufactured individually. Material properties and processability are known both to the planner as well as the mason (and other craftsmen on the building site). Within the scope of its geometric possibilities it can be adapted to every architectural building shape, and decisions can be made independently.

Façade systems feature a similar modularity to accommodate glass panes of various thickness, different post and mullion constructions or architectural design elements, for example. Thus, the system product achieves the greatest possible variability to fulfil the requirements of existing building processes with separated structures.
It becomes clear that a curtain wall construction must be understood as the physical realisation of a function requirement – such as building physical separation, visual contact or room comfort level - and also needs to meet the particularities of the building market it is embedded in.

§ 1.5 Why is a new approach needed?

First of all the growing demand for low energy consumption and a raised sense of comfort have given the façade a new important role in the overall building concept. It must not only be extremely well insulated but also adaptive in order to positively modulate the interior climate. This ultimately has a positive effect on the use of energy. The facade becomes an integral part of the climate concept. Ideally, a façade should be able to temporarily adapt its properties such as insulation and heat and daylight transmittance.

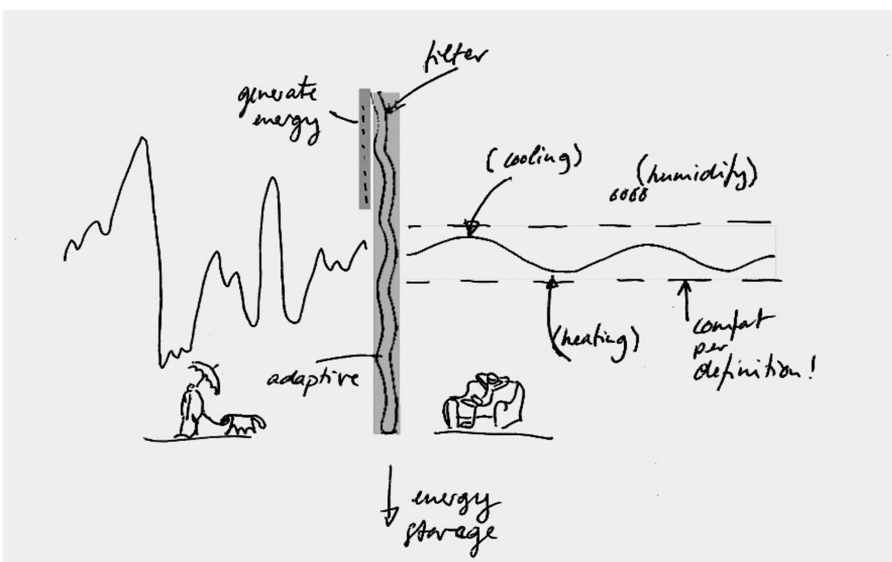


Figure 12
The new role of the curtain wall, actively modulating the exterior climate according to the interior needs, as well as generating and storing energy.

Some functions need to be adapted from minute to minute such as sun protection or transparency to provide an optimal amount of daylight or to prevent overheating. Some functions need to undergo seasonal changes, such as the amount of insulation, and yet others need to change over several years, reacting to changing users. More and more, façades are tuned according to the building's use, its location, orientation and building services.

§ 1.5.1 Increasing technicalisation of façades

The result is an increasing technicalisation of the façade. More building services components are being integrated into the façade. Today, electric sun protection devices have already replaced their manual predecessors because they function accurately and without user intervention. New developments include encompassing sensor technology for incident sunlight, rain, temperature, as well as CO2 content of the internal air. New tendencies also show an integration of ventilation devices with supply and exhaust air as well as heat recovery in the façade construction.

The development can be compared to that in the automotive industry. In order to reduce fuel consumption we do not only need an economic engine but also improved aerodynamics, overall weight reduction, good tires and ergonomics that promote an economic driving style.

The façade becomes a part of the building services concept. This is not a new idea but the extent to which the façade will actively contribute to it is new. This calls for an integrated design and decision-making approach and a considerable amount of knowledge about both disciplines from the engineers involved. The effect of this development on the architectural design of the façade can be great and is rather unexplored.

A recently published study (Mahler, Himmler et al. 2008) proves that the physical combination of façades and decentralized building components can prove beneficial in terms of reduced energy demands and raised comfort. There are several buildings that have already been executed this way.

However, problems in combining the traditionally separated crafts of façade building and services are far from being solved. It will need new building processes and physical interface structures to address these issues. And we need to answer the question who will take the lead in engineering the details and how the responsibilities will be distributed. These are problems that are rather new and challenge the traditionally separated building disciplines.

§ 1.5.2 Constructive limitations

But it also becomes clear that structural changes are necessary. If we look at the insulating properties of a curtain wall, the system limitations become apparent. Structurally we are talking about linear systems with fillings of glass or panels (sticks and fillings). The following illustration (fig.13) shows the U-value development of glass and frame. Even if the U-value (the heat transmission coefficient) is not the only parameter to measure the performance of façade constructions, it is still apparent that the development has stagnated over the past few years. The graph shows values that correspond to the customary market standard of the given time period. The data for glazing was contributed by Rainer Walk, Interpane. It shows the U-value that was available on the market at that time. The data for curtain walls was contributed by Klaus Hees, Kawneer. The values are a rough indication only, but in both cases the stagnating development is clearly visible.
The performance of glass panes was improved yet another time by adding an additional pane to create triple glazing. Triple glazing was already available in the 1990s, but is only widely applied since recent years. It seems to be the limit of the feasible. Some glass manufacturers consider quadruple glazing; however, these products will not be made available anytime soon due to the performance-cost ratio, thickness and weight. The curtain wall cannot be further improved by adding additional constructive layers. Architecturally, they must be as lean as possible, while forming the backbone of the construction. The improvements over the past years were related to adapting the sealing system with additional profiles, adding reflective coatings, or thermally improved cover strips. The systems have not been fundamentally modified but rather existing constructions underwent continuous optimisation. The current prognosis is that contemporary curtain wall systems will not be able to fulfil the requirements of the European norms for energy consumption reduction (Directive on Energy Performance of Buildings - EPBD) which is supposed to be published in 2015. The façade profile will thus become the weak spot of the entire system.

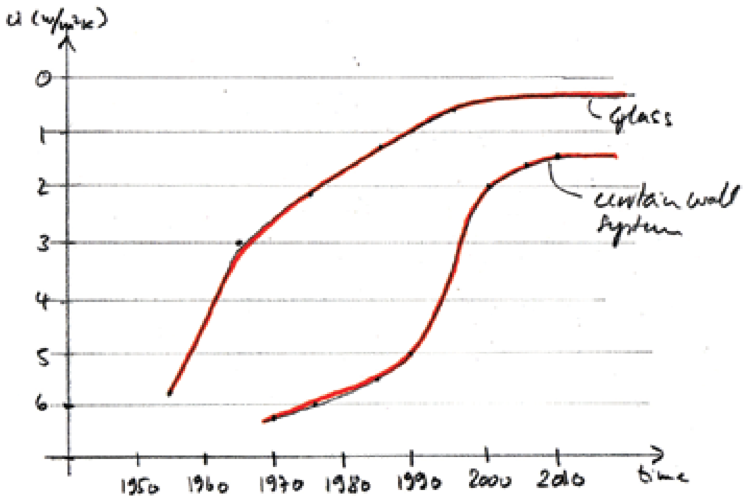


Figure 13

Development of thermal performance of façade systems and glazing. The information was contributed by Rainer Walk, Interpane and Klaus Hees, Kawneer.

§ 1.5.3 New materials and technologies

Developments in the field of materials and technology could ask for radical changes as well. New materials, foil technology for example, evolve from customized solutions to established systems. And the rather new development of 'Smart Materials', which are able to adapt their properties, needs to be mentioned here. Energy-generating materials, such as PV cells are widely applied. Others, such as self-cleaning surfaces or electrochromic glass panes that can change their properties from transparent to opaque are applied sporadically; often on an experimental basis. They are on the verge of a broader acceptance in the market. New production methods such as 'rapid manufacturing' generate questions about the future of façade manufacturing as well. Another aspect is that the sustainability debate includes the used materials themselves as well as the construction type. In the future, we need to consider the ecological footprint they create, and how they can be separated and recycled at the end of their useful life.

The above described development toward a façade as an integrated building component and the new and sometimes still unknown technologies and materials are a great challenge for current façade construction which has reached the limits of its performance capabilities. The developments meet a building market with strong and incrementally developed dependencies and execution and tendering procedures. The ramifications relate to all areas and stages of façade construction.

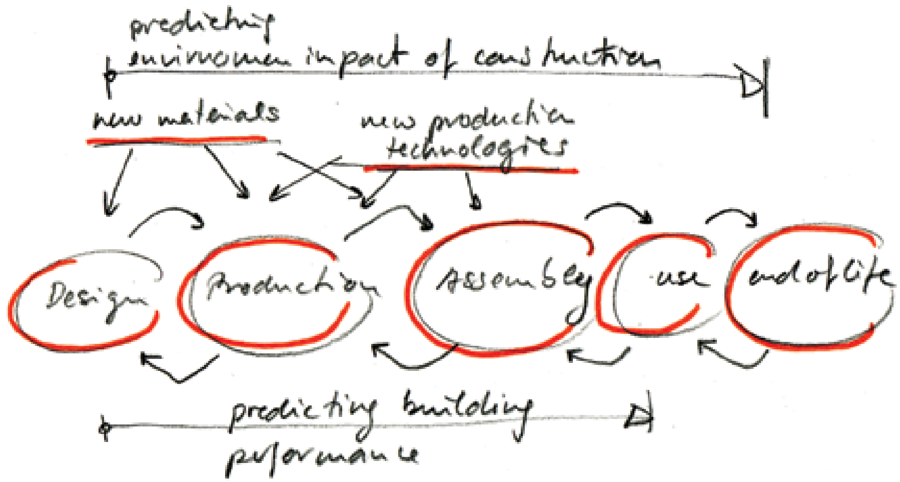


Figure 14

Construction phases and new developments. Basically, these developments have an influence on all phases. A linear process with one way dependencies is no longer possible.

On the one hand existing methods and technologies are being optimised, and on the other hand new ones find their way into the market. All of these materials and technologies exert considerable pressure on the façade industry; partly driven by architectural design requests, party by the chance to enhance the functionality of façades. At the same time there seems to be no common and strategic approach to integrate the new developments into the existing market structure.

§ 1.6 Objectives

As mentioned above, there is a multitude of developments and requirements that demand new strategies for the future of the curtain wall. These can be found in the market structure as well as in curtain wall construction, which both have incrementally developed over a long period. The objective of this dissertation is threefold. First, it sets out to chart the particular structure of the façade market. Secondly, the state of the art of curtain wall construction is assessed. Both tasks are necessary to scout for and evaluate new approaches to façade construction, which is the third objective of this research.

§ 1.7 Research questions and methodology

The dissertation is based on the following hypotheses:
Without a new constructional approach to curtain wall construction, the challenges that lie ahead cannot be met. And secondly, the current structure of the supply chain blocks the development of new constructional solutions.
A three-step approach is used to corroborate the hypotheses. Firstly, the structure of the façade design and construction process needs to be analysed. Based on that, the construction of curtain walls can be assessed. Both need to be clearly linked. In a third step new, alternative approaches can show how the problem can be overcome.
Accordingly, the main research question of the dissertation is:

- *How can a new approach to curtain wall construction be developed, in order to deal with the rising performance demands, growing complexity and the new role that the building envelope plays for the building as a whole?*

Methodology for the analysis of the façade design and construction process (Chapter 2)

The first question to be answered is how the façade design and construction process should be analysed.

- *How can the façade design and construction process be analysed?*

There is a certain procedure with which the process of building is conducted. A market analysis must to relate to this procedure. The process is reflected in architects' services. The author's experience as a façade planner shows that façade design and building includes specialised steps. Due to the complexity of façades, special façade designers are often involved and the façade builder creates a special execution design before the façade goes into production.
An explanatory literature study is conducted, including the services description of the Dutch and German market. In addition, the fee structure of façade planners (UBF 2008) is analysed. Based here upon, the structure for the design and construction process is defined. But this structure only addresses the sequence of actions and not the actual behaviour of the actors in the process and what influence the process has on façade construction itself and on innovation. An interview methodology is developed addressing experts from different stakeholder categories. The interview includes different question groups, addressing the experience of the interviewees with real projects. Thus, a link is created between the market structure and real project solutions.

Analysis of the design and construction process (Chapter 3)

Chapter 3 focuses on the analysis and the interpretation of the interviews. The chapter aims a answering the following research questions:

- *How does the façade construction process work and what are the driving factors and bottlenecks for innovation in façade construction?*
- *In order to answer these questions the following secondary questions need to be answered:*
- *What are the process steps, what are the dependencies?*
- *How is the aspect of architectural design geared into the façade construction process?*
- *What is the role of the different stakeholders in this process and how does the decision-making process take place?*
- *What is the impact of the façade construction process on innovation?*

Finally, chapter 3 maps out which challenges curtain wall construction will meet in the future:

- *What are the future challenges for curtain wall construction?*

Systematic for a constructional façade analysis (Chapter 4)

First of all a method must be defined to analyse façade constructions.

- *How can a systematic for a constructional façade analysis be defined?*

The systematic should relate to the dependency between the material and immaterial side of the process, and it requires a basic vocabulary to analyse construction in a comparable way. It must be more than a simple description of parts and components; meaning it needs to include the role that all parts play in terms of the structure of the market, decision making, architectural design and innovation.
The assumption is that this is reflected in current construction theories. The chapter starts with an exploratory literature research, aiming at answering the following research questions:

- *How are façade construction and its dependency on the façade design and construction process described in literature?*
- *What vocabulary can be derived that is suitable for the analysis of façade construction?*

This study first focuses on architecture related literature and, in a second step, on literature from the field of product design. It leads to a series of graphical tools, such as a façade function tree, functions structures and the schematic of product levels as well as to a vocabulary describing the relationship of constructive parts and components, their interfaces and the link to the building market.

Analysis of curtain wall product architecture (Chapter 5)

In chapter 5, the systematic is used to analyse historic and contemporary curtain wall constructions.

- *What is the state of the art of curtain wall constructions and how is it linked to the façade design and construction process?*

Different types of curtain wall constructions, whole systems as well as single components are mapped using the graphic schematics developed in chapter 4. In a second step this allows to answer the following research question:

- *How can contemporary curtain wall construction tackle the challenges formulated in chapter 3?*

It shows how tightly contemporary curtain wall construction is bound to the structure of the building market. The modular nature of its product architecture is the reason why it will be difficult to fulfil some of the future requirements.

Case studies for a new approach (Chapter 6)

Chapter 6 is based on the proposition that potentially better constructional strategies for the curtain wall can be found that will help to tackle future challenges. These new approaches will need a different market approach, decision making process, and role of stakeholders.
What strategies can be found to overcome the existing design and construction procedures and the mature construction concepts?
Different types of projects based on more integral product architectures are analysed. They are exploratory (new technologies), experimental (student design) and explanatory (real projects). They address different product levels from systems product to complete façades and market approaches.
Again, function structures and product level schematics are useful to describe the product architecture of a project. Additionally, individual product profiles, based on the schematic of the design and production process, are developed to show the market behaviour of each case.

Case study evaluation (Chapter 7)

Chapter 7 compares the results of the case study analysis with the analysis of contemporary curtain wall constructions. Product profiles are sketched, and the potential of integral as well as modular product architectures as they relate to future challenges is discussed. This allows determining the impact a particular construction type has on design and construction process.

Conclusion (Chapter 8)

Chapter 8 draws a conclusion by formulating generalised propositions on how to establish a new approach to the curtain wall.

Side notes

The reader will find a number of ´side notes´ inserted in the text. These do not directly contribute to the scientific content of the dissertation but help the underline the meaning of certain issues.
The following notes are included:

- The USB Story
- Sony Walkman – Design variety through modular components
- The joint – from meaningful architectural tool to jointless desires
- The bread clip – multifunctional integral device
- A Wall for All Seasons – Vision for the future facade

§ 1.8 1.8 Structure of the dissertation

The dissertation is made up of three building blocks.

The first block focuses on analysing the façade as it relates to the building market. In chapter 2, background and methodology for stakeholder interviews are developed. Chapter 3 evaluates the results of a literature study and interviews, and sketches a picture of the façade market.

The second building block is dedicated to physical/material aspects. A systematic to analyse curtain wall product architecture is developed in chapter 4. The results show the tight relationship between contemporary façade construction and the market situation (Chapter 5).

Finally, a new approach is discussed in the third building block. The systematic in chapter 4 is used to analyse different cases, ranging from existing façade constructions to experimental designs. The evaluation is done in chapter 7, by comparing the results with the analysed curtain wall construction from chapter 5.

Chapter 8 concludes the research.

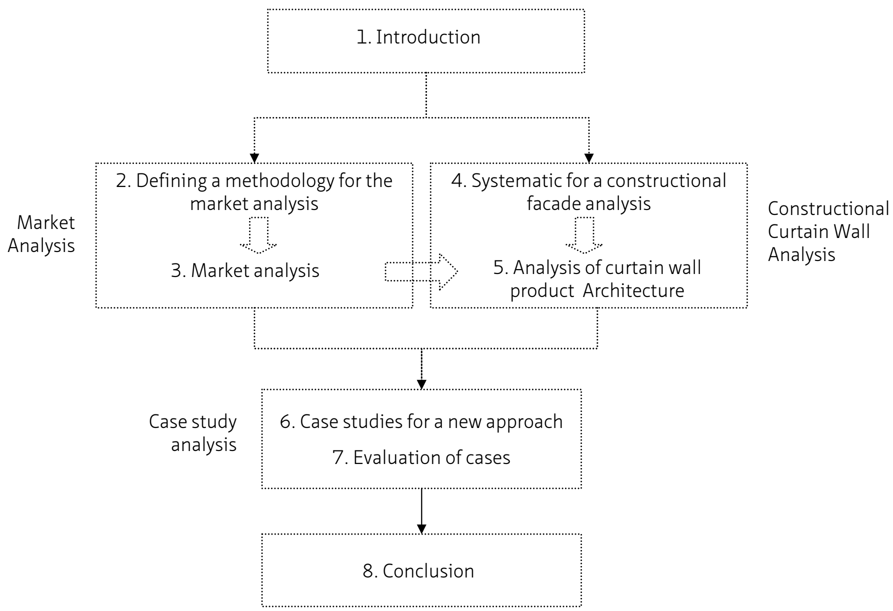


Figure 15
Schematic of the dissertation

§ 1.9 1.9 Definitions

Curtain wall
A curtain wall can be described as a non load-bearing building envelope. It is suspended from or stands on the primary structure of the building. Traditionally, curtain walls consist of a structural frame of metal mullions and rails with infill elements. But other frame materials such as wood or fibre reinforced plastics are possible as well. The definition of curtain walls also includes panellised façades in contrast to linear frames.

Design and construction process

The process describes in which way different stakeholders interact in order to create a façade (or curtain wall). The stakeholders include investors, designers, consultants as well as system providers, general contractors, façade builders and users. The process begins with the design of systems prior to the actual building project and ends with the end of life phase of a façade construction.

Product architecture

Karl Ulrich (Ulrich 1993) describes product architecture as a "scheme by which the function of a product is allocated to physical components". Product architecture includes the description of physical components as well as the interface between them. Ulrich argues that the way in which components are arranged and connected is of great importance to the behaviour of a product on the market, and therefore is important for the decision making process of manufacturing firms. Product architecture is not widely used in the field of building construction but it is the author's opinion that it offers a valuable vocabulary to analyse façade construction as it relates to the implication on the structure of the building market.

Integral construction and modular construction

Product architecture classifies different types of construction as either integral or modular with regards to physical components and their interfaces. The distinctive features of integral constructions are many-to-one mapping of functions and components (the components is multifunctional) as well coupled interfaces. A coupled interface of two components means that when a change is made to one of the components, a change to the other component is required in order for the overall product to work correctly. In contrast, a modular construction has a one-to-one mapping of functions and components, and these are connected by modular interfaces so they can be changed separately. A more detailed description is given in chapter 4.

Unitised façade systems

Whereas the majority of curtain wall systems are constructed on site as ´stick systems´ with linear framing components and planar infills, unitised systems entail factory fabrication and assembly to large panels and may include glazing. These completed units are mounted to the primary structure of the building. The benefits are fabrication in controlled interior environments and faster on-site installation times. A disadvantage can be greater use of materials and greater logistical effort. Today, large buildings or areas with high labour costs benefit the most economically.

Structural glazing

Structural -Glazing (SG) or Structural-Sealant-Glazing (SSG) describes a curtain wall system in which the glass panes are fixed to the frame by a glue or sealant. Pressure plates and screwed connections that press the glass panes onto the rebate gaskets are needed. The self-weight of the glass panes is typically transferred to the frame by hidden mechanical devices. Glass panes can even be used to stiffen the façade structure.

Double façade
A double façade or double-skin facade is a façade system that consists of two skins placed in such a way that air flows in the intermediate cavity. Typically, insulated glass units form the inner skin and the outer skin are made of single glass layers but other constellations are possible. The ventilation of the cavity can be natural, fan supported or mechanical. Apart from the type of ventilation inside the cavity, the origin and destination of the air can differ depending mostly on climatic conditions, the use, the location, the occupational hours of the building and the HVAC strategy.

Frameless façade
A frameless façade consists mainly of single glass panes or insulated glass units without framing elements. Instead, the necessary joints between the glass panes are closed by backfill elements and silicone sealants. The glass panes are directly connected to structural load bearing components on the inside or the outside.

´Polyvalent Wall´
The ´Polyvalent Wall´ is a vision for a new façade type, published by Mike Davies in his paper ´A Wall for all Seasons´ (Davies, 1981). It was intended to be built up from different layers on top of a glass layer to act as absorber, radiator, reflector, filter and transfer device at the same time, and needed to operate at a molecular level rather than at a mechanical level. It also includes sensing nodes and a local micro brain, connected to a central processor, to assure that the façade reacts to permanently changing external and internal conditions.
The idea was far reaching at the time, and has yet to be realised, but continues to inspire architects and engineers.

2 Methodology for the analysis of the façade design and construction process

§ 2.1 Introduction

One keystone of this dissertation is to analyse and exploit the impact of the design and construction process on façade construction itself, and to corroborate the hypothesis that the structure of this process is blocking the development of new constructional solutions.
In this context, design and construction process is defined as the entire process from the initial idea to the end of life of a façade. It includes the interaction of stakeholders and its impact on the physical construction of curtain walls.

The problem is multi-fold: First of all, the façade design and construction process in general needs to be examined. Obviously there are many ways how it is executed in practise. The process differs between cultural areas, but it also reacts on different project goals. If the overall goal is to achieve high quality, the strategy will be different than if cost is the primary concern.
As mentioned in the introduction, many stakeholders are involved in the realisation of highly individualised projects. All of them have their own agenda which will likely conflict at some point. They all play a different role in innovation, and it is necessary to understand their interaction.
On top of that, the domain of architecture involves certain characteristics in terms of design that differ from other disciplines. As will be shown later, façade construction plays a special role in this regard due to the complexity of the product.

§ 2.2 The design and construction process

This paragraph discusses the design and construction process related aspects necessary to answer the research sub-question:

- *How can the design and construction process be analysed?*

First, an appropriate sequence for the design and construction process needs to be defined. The different steps of the cladding supply chain are extensively discussed by Ledbetter, for example (Ledbetter, 2003). Here, the term cladding includes non load-bearing façades. A flowchart for rain screen cladding design and procurement from design to installation was drawn by Kalian (Kalian, 2001). Whereas these papers provide a lot of detailed information, they focus on managing the supply chain and not primarily on construction itself. It also does not include the phases after the installation of the façade.
Based on this and on the experience of the author as a facade designer in Germany and The Netherlands a general sequence of eight steps has been identified. The façade design and construction phases run parallel to those of the rest of the building. Even though these steps can differ slightly, the process is basically the same in most countries.
These steps are forming the structure on which the interview is conducted and the sequence was accepted by all interviewed parties.

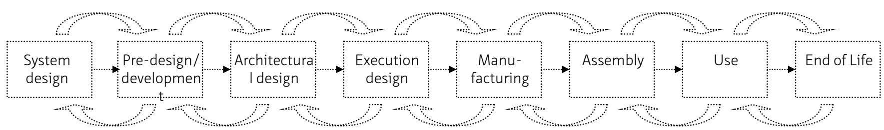


Figure 16
Design and construction phases of curtain walls

Theoretically, the process is linear, but in practice there is a back-coupling between the phases. During the design process, for example, it might become apparent that the list of desired functionalities has to be adjusted. Results from the execution design (e.g. Final material choices or detail geometries) often require a rethinking of architectural design implications a.o.
As the 8 phases form the backbone of the interview it is important to provide a brief explanation of each.

§ 2.2.1 System design

Façade system design is done prior to the actual design process. Systems are developed by system providers, anticipating market needs. Systems need to meet legal requirements as well as the requirements from architectural design.

§ 2.2.2 Pre-design/development

In the pre-design phase the basic requirements for the building are being defined. It begins with a market survey and feasibility study. The location, size of the building, the type of use as well as legal requirements lead to a first definition of functional requirements for the façade.

§ 2.2.3 Architectural design

The architectural design phase is further subdivided. It usually begins with a design sketch which is then worked out further. At some point, drawings are made for the building permit; and based on these, the architect's working drawings are developed. This process requires continuous calibration with the development of the other crafts. It must be mutually agreed upon with the client; costs have to be calculated. Depending on the project, structural or façade engineers are involved as well as climate designers. These phases are reflected in the specifications that describe the architect's/engineer's work. Depending on regional procedures or the type of tender, the façade builder might or might not be involved in different stages of this process.

§ 2.2.4 Execution design

To a large extent, façades are standardised products; partly due to their responsibility for the building performance Water/wind tightness and thermal performance of the construction have to be guaranteed, which can only be achieved by tested systems. In contrast, a concrete wall is composed of cement aggregate and steel reinforcement and is designed according to the particular needs of the application. Architect and structural engineer create the plan after which the builder will directly execute the structure.
During the execution design phase, the builder has to execute a number of internal design steps to be able to conduct the job. These are based on the working drawings of the architect; however, the level of detailing exceeds the planning ability of the architect. Very often, the decision about which system is ultimately used is made at this stage.
Later on, the design phases with their complex embroilment will described be in more detail in chapter 3.

§ 2.2.5 Production

The production of façades is a process with high logistical effort. The façade builder receives profiles and fittings from the system provider. These are cut and milled and then sent out to be coated. It is interesting to know that coating is a delicate matter. Typically, all elements of one colour are coated in one charge, because the next batch might show slight differences in colour and surface quality. Such aspects show that at this stage of the process changes in design are virtually impossible, and if done cause tremendous logistical effort. Therefore, this is the point when the design gets "frozen". Numerous subcomponents such as sun shading devices or glass panes will have to be designed, ordered and integrated in the production process. Depending on the production facilities, the builder will try to manufacture and pre-assemble as much of the construction as possible. The factory offers dry and clean conditions. The quality is easier to monitor than on the site, and mistakes can be compensated with all tools and spare parts at hand.

§ 2.2.6 Assembly

One can say that the more complex a system is or the more complex systems become in the future, the more inevitable pre-manufacturing and pre-assembly becomes. Today, more and more unitized systems are preferred to curtain walling systems, especially for large buildings with a great number of repetitions, although the material and production costs are considerably higher.
Finishing the façade is an important step in the overall construction process of a building. At this moment, all interior work can be executed independently of the weather; an important factor concerning the time schedule. Weather conditions pose a potential threat for the assembly of the façade. This risk can only be reduced by minimising construction time onsite. This does not only require skilled personnel, but also a products aiming at fool-proof assembly, which is difficult with increasingly complex constructions. At the same time, the façade has a lot of complex interfaces to other disciplines. The construction times for buildings become increasingly shorter; and very often production has to begin before measurements of the primary structure (concrete, steel) have been taken. The primary structure has to be finished in time for the façade to be installed. The tolerances are often in the range of centimetres, whereas façades allow no more than a couple of millimetres. Interior finishing touches the façade area, and there is a constant risk that the façade gets damaged by follow-up disciplines. In spite of these uncertainties the façade quality has to be according to plan; for example, because the sound absorption between rooms depends exclusively on the connection between dividing wall and façade, and the same is true for fire

protection. The façade as part of a networked climate concept creates another difficult interface to building services components.
Of course all of these parameters need to be considered in the preceding phases.



Figure 17
Unitised façade elements as delivered to the site

Figure 18
Assembly of unitized façade system from the inside

Figure 19
Assembly of a curtain walling system with scaffolding

§ 2.2.7 Use

This phase shows whether the façade matches all desired functionalities. A failure in comfort performance is directly observed by the user. The energy performance will be reflected on the energy bill. Monitoring is an important issue that grows with increasing complexity and the combination with building services installations. The responsibilities in case of failure have to be clearly stated. Maintenance and cleaning are considerable costs issues that must be accounted for in the early design phases. They depend on material and detail choices as well as on accessibility of the façade. Cleaning machinery such as cranes, lifts or ladders have a considerable effect on the architectural design. They are expensive and the question is what investment should be done beforehand to prevent high cleaning costs.

§ 2.2.8 End of Life

In former times, not much thought was spent on the end of life scenario of buildings, and façades in particular. In order to create energy neutral buildings recycling or reusing components is becoming a crucial issue A sustainable approach requires a concept for the end of life phase which needs to be developed in the phases from architectural design to assembly. Ideally, the components can be completely reused. But practice shows that this is hardly possible, because façades that where built 30 years ago do not fulfil today's requirements in terms of thermal insulation. In most cases this results in the need to exchange the entire system.
It becomes apparent that building a façade that lasts a very long time is the right strategy. Thereby it is important that the construction matches the type of use and the functionality of the building. Long lasting qualities can also be obtained by designing the façade in such a way that it can adapt to different uses. This way it can promote a second life of a building that is transformed from office building to dwelling, for example.

§ 2.3 Interview methodology

The first task was to identify and compare the standard processes and correlations for façade construction. An interview form was developed, slightly different for each stakeholder group (see 2.4). The interviews were conducted face to face and the answers were written down and then summarised in individual reports. Because of the different format of the answers (some with concrete numbers, others as subjective opinions), they needed to be reformatted in order to achieve comparable results. It is inevitable that this step includes an interpretation by the author. The report is part of the appendix to this dissertation.
In a next step the most important results of the interview are summarized. These findings are validated by sending them back to the interviewees with a request for confirmation or further commentary. This achieved two goals: Firstly, the summary aids the interviewees in contemplating their own individual viewpoint, and secondly, it ensures that the result correctly mirrors the interviewees' opinions.
The results of the process analysis are used as the basis for the development of case studies in chapter 6 of the dissertation.

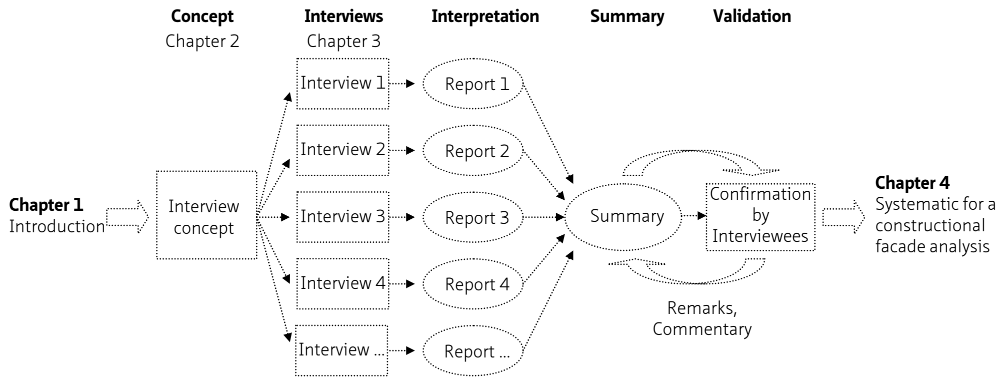


Figure 20
Schematic of the interview methodology

§ 2.4 The choice of interview partners

It was important to talk to those stakeholders that are directly involved in the topic, meaning who deal with office buildings and façade design and construction in particular. Another important factor was to interview experts in this field; people that have a certain impact on the market.

The following stakeholder groups were interviewed:

Architects/Consultants	5
Façade builders	5
System suppliers	2
Branch organisation	1
Project developers	1
Total expert interviews	**14**

The appendix includes a list of interview partners as well as the original interview forms. Chapter 3 focuses on the analysis and the interpretation of the interviews.

§ 2.5 Interview form

An interview form was developed to gather information about real design and construction circumstances. The interview itself was divided into three parts. The first part consists of questions about the company and the position of the interviewee. This section serves to compare the companies with their competitors and to understand their position about building and façades.

The second part includes questions about various building and awarding processes, and the relationship between the interviewee and other stakeholders. A two-dimensional schematic was created to accompany the questions, assuming eight main constructional phases on the one side and the involvement of different stakeholders on the other. The interviewees were asked to describe their relationships, interests, conflicts and decision-making criteria, which can differ from phase to phase, from their point of view. They had to fill in three schemata asking about their interests and opportunities, risks and bottlenecks and finally their opinion about innovation within in the process. The intention was to later combine the subjective viewpoints to a more objective picture of the situation.

The third part of the interview consists of questions about the current state of industrialisation, decision-making concerning façade products, innovation and finally the interviewees' opinion about future developments.

§ 2.6 Questions and quality of information

The questions have different quality levels. Some can be answered concretely, such as questions about revenue of a certain construction phase. Naturally, questions asking the interviewee's opinion about development trends or possibilities for innovation provide less concrete answers. The interview was conducted face to face. Thus the interviewees were accompanied while filling in the schemata with the goal to stimulate them and to elicit their particular views. The potential risk of unintended manipulation was mitigated by not only explaining the question itself but also the purpose of the question. With this method, reading between the lines is an important component for understanding the interrelationships. The information such gathered flowed indirectly into the analysis.

3 Analysis of the design and construction process

§ 3.1 Introduction

Chapter 3 focuses on the analysis and the interpretation of the interviews. The intention of the design and process analysis is to sketch the stakes of the different parties, their interests, conflicts, actions from system design to the end of life scenario and what impact it has on façade construction itself.

The chapter aims a answering the following research question:

- *How does the façade construction process work and what are the driving factors and bottlenecks for innovation in façade construction?*

In order to answer this question the following secondary questions needed to be answered:

- *What are the process steps, what are the dependencies?*
- *How is the aspect of architectural design geared into the façade construction process?*
- *What is the role of the different stakeholders in this process and how does the decision-making process take place?*
- *What is the impact of the façade construction process on innovation?*

Finally, chapter 3 maps out what challenges the curtain wall construction will have to meet in the future:

- *What are the future challenges for curtain wall construction?*

As mentioned earlier, the interview covers a very large field; and it was therefore not possible to work out all aspects in detail within the scope of this research. The focus lies on the principle workings of the process with more detailed information only where it seems to be useful. For that purpose, qualitative rather than quantitative research was conducted by interviewing the market players.

The research is mainly focused on the Dutch market. Internationally, there are differences on a detail level, which will be explained later.
This chapter is divided in four parts. It is based on the description of the typical façade construction sequence as described in chapter 2. This sequence serves as a backbone to organise the interview results which will be summarised in paragraph 3.2. A separate part is dedicated to the role of the stakeholders. Paragraph 3.4 provides the answers to the research questions.

The interview forms as well as the list of interviewed experts can be found in the appendix. The interview results are anonymised and the following abbreviations are used:
A – Architect,
C – Consultant,
D - Developer
F - Façade builder,
S – System supplier,
FM – Facility manager,
B – Branch organisation
I – Industry (Builder and supplier)

§ 3.2 Summary of the interview results

§ 3.2.1 Involvement of the stakeholders

Scheme 3.1 is a summary of question A1/I1 relating to the involvement of the different stakeholders in the façade construction phases.
Architects and engineers are regularly involved in consulting the client during the project development phase. Façade builder and system provider are not actively involved in project related work at this point, but try to establish long term relations with clients and architects or consultants. A particularity of the system supplier's work is that he develops his products in advance of the process described here.
The involvement of the building user and the facility manager is more or less reduced to phase six. In some cases, the facility manager is involved in consulting the architectural design phase.
Society, meaning all of us, has a passive role, but actually a great interest in all phases. Society wants good architecture to enhance its cultural development. Amongst other interests, it desires sustainable product methods, minimised transport, minimal waist, low energy consumption of the building and a sustainable end of life scenario.

It is an interesting fact, that the stakeholders that are actively developing, designing or building a façade are only sporadically involved in the time of use or the end of life phase of a building/façade.

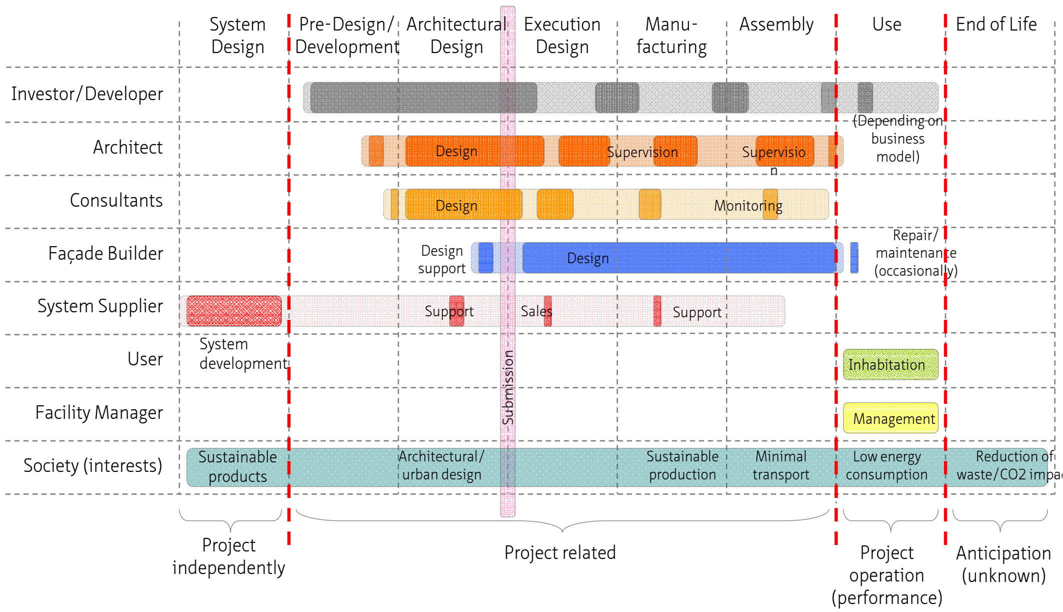


Figure 21
Involvement of stakeholders in the different phases of the façade design and construction process (Summary of questions A1 and I1).

§ 3.2.2 Contracting strategies

The way how a façade project is contracted is crucial for the way in which the different stakeholders interact with each other. Contracting out is the moment in which a project is handed over from the designers to the executing parties. The following questions aim at identifying different contracting strategies as well as their effect on the process.

In question I7/A9, four different tendering strategies were explained to the interview partners:

1 Open tender: The façade is tendered on the basis of extensive specifications. (Basically, the façade builder has no influence on the design.)

2 Builder involvement: The builder gets involved in the architectural design (he/she might even get paid for this).
After that he/she competes with other companies that are also asked to submit a quotation.

3 Direct contract ('building team'): The façade builder is involved from the beginning, and then negotiates a price and gets the job.

4 Functional specifications: The tender document specifies functions only. (Can you make a façade that can do this and that, and how much will it cost?)
The answers showed how often the interviewees were involved in these strategies:

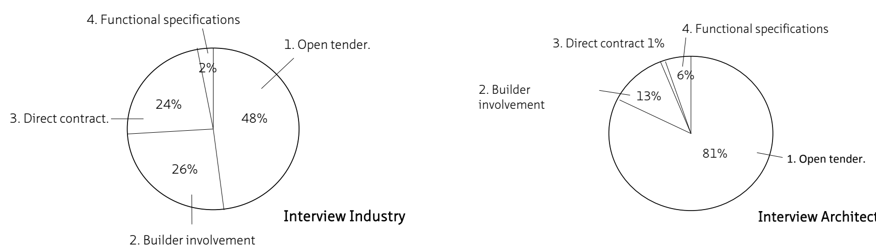


Figure 22
Percentage of different tender procedures as seen by the façade builders (I7) and architects (A9)

According to the façade builders, most projects (45%) were contracted in an open tender process. The façade is tendered on the basis of extensive specifications, meaning that the façade builder does not have a great influence on the design. In only about 26% of the projects the façade builder was involved ahead of the tendering procedure and in 24% of the projects where executed with building teams. Interestingly, the branch organisation has a different opinion about this, although it cannot provide concrete figures. They estimate that 80% of all the façade jobs are tender open (procedure 1); 5% with builder involvement and 15% (2) in building teams (3). The difference could result from the choice of façade builders that were interviewed. However, it proves the dominance of the open tender procedure. Architects also show their involvement of 81% in the open tender procedure.

The following table shows the opinion of the stakeholders concerning the effect of the different procedures on the following aspects:

Procedure	Open tender	Builder involvement	Direct contract	Function specif.
Best quality and architectural design	A2 (2)	F2 A1 C1 (4)	F2 S2 B1 A2 C2 (9)	B1 (1)
Best innovative potential	A1 C1 (2)	F1 S1 A2 C1 (5)	F2 S2 A1 (5)	B1 (1)
Lowest price of façade	F3 S1 B1 A1 (6)	A2 (2)	F1 A1 (2)	F1 S1 A2 C1 (5)
Most economic way of working	F2 A1 (3)	F1 S2 A2 (5)	F1 S2 B1 A1 (5)	B1 C1 (2)

Explanation
A=Architect, F=Façade Builder, S=System Provider, C=Consultant, B=Branch organisation, A2 = Two architects have voted, (X)= total number of votes

Table 1
Summary of questions I9 and A11. The table shows the number of scores per stakeholder group

- The best architectural quality is reached if the façade builder is involved from the beginning (procedure 3) (9/16 votes).
- Procedures 2 and 3 (also with involvement of façade builder) seem to provide the best opportunities for innovation (together 10/13 votes).
- The lowest price of a façade can be achieved by an open tender procedure (1) (6/15 scores) or with a functional specifications (5/16 scores). However, the latter scores very bad in terms of architectural quality and innovation potential. This is probably the reason why this procedure is mostly chosen by clients and general contractors, whose interests are dominated by financial concerns.
- The industry stakeholders can work most economically with procedures 3 or 2, when they have an influence on the process (together 7/10 scores)

The table also shows that the façade industry clearly sees the biggest potential in an early involvement of their discipline, or even better, a direct contract situation.

§ 3.2.3 The involvement of general contractors (questions A13, I32)

According to the façade builders, 70-80% of all jobs are commissioned by general contractors, which resembles the statements of the interviewed architects. A large part of their honorarium is usually paid by the general contractor (not only for façades). A tendency towards more GC involvement could not be observed here.

§ 3.2.4 Façade Design

As mentioned above façade design happens in two phases. The architectural design is followed by an execution design phase conducted by the façade builder. We need to take a closer look in order to understand how the curtain wall is created on a project by project basis.

Architectural Design

Although differing in detail, in most countries there is a basic sequence in which architectural design is conducted. At first, there is a definition of functions followed by a preliminary design. This design is further developed. At some point the design has to be negotiated with the authorities and becomes fixed. All technical details of the construction are specified and the tender documents are created. More phases follow: After awarding of the contract, the builder's drawings are analysed and approved, followed later by supervision on the construction site.
All the products of a phase have to be agreed on by the client. This forces the architect to work in predefined steps. At the same time, the iterative nature of the process forces him to feedback the results to previous phases. Naturally, the architect tries to make decisions as late as possible in order to be able to incorporate possible design adjustments. A lot of experience is needed to conduct a façade design effectively.
Architects services in the Netherlands and German are defined in the Standaardtaakbeschrijving[1] (BNA, 2008) and the Honorarordnung für Architekten und Ingenieure[2] (HOAI, 2010). A comparison shows an interesting difference.

1 Standard job description (free translation by author)

2 Fee Structure for Architects and Engineers (free translation by author)

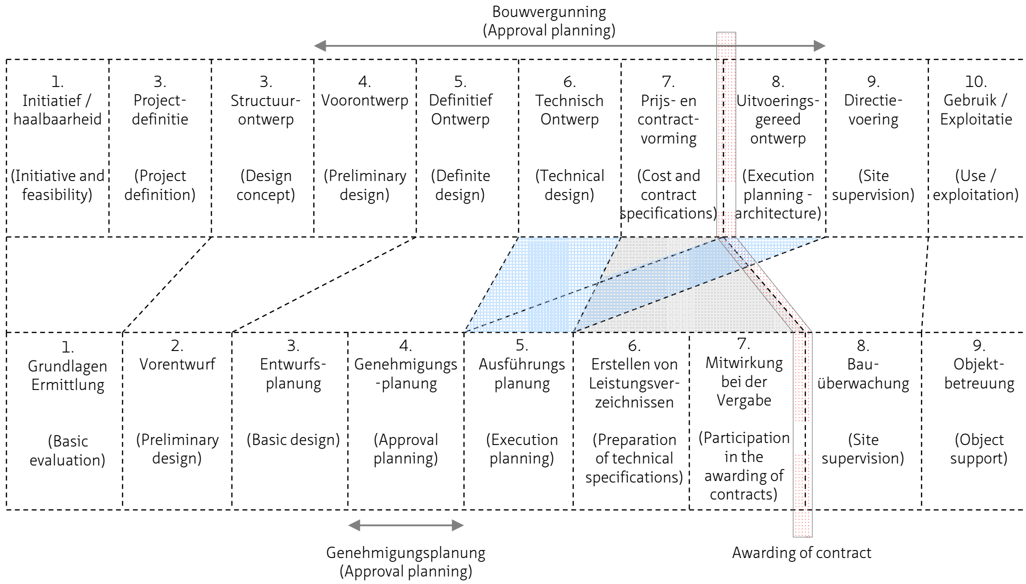


Figure 23

Comparison of architectural design phases in the Netherlands and Germany

In Germany, the architectural executing planning is usually finished before the technical specifications are created. In the Netherlands, the working drawings are created after the awarding of the contract in collaboration with the façade builder, potentially providing him with greater influence. That could be one of the reasons why, in Germany, an 'engineering approach' can be observed more often. This means architect and engineer work out building plans to a deeper level, rendering them with more power, but also with a higher responsibility and liability, which results in much higher insurance levels.[3]

Concepts for end of life scenarios

It is interesting that end of live scenarios are not a part of the architects services. The involvement ends at the last phase - object accompanying. In Germany, this phase makes up for only 3% of the entire contract, if it is part of the contract at all. Object accompanying includes maintenance concepts, but neither in the Netherlands nor in Germany is

3 Normally the liability of Dutch architects is limited to the volume of their honorarium, whereas in Germany it is basically unlimited.

monitoring of the energetic performance a dedicated item in the service descriptions. This shows why the architect's involvement basically stops once the building is erected.
The interview showed that there does not seem to be a clear picture of what an end of life scenario for façades actually means (questions A2, I1). Only one system supplier mentioned that he is developing cradle to cradle certificates. Most parties are not involved with the subject at all. Some of the architects encountered the problem, when refurbishing buildings, but without being able to draw real conclusions. One of the interview parties was member of the Green Dutch Green Building Council, showing his potential interest in the topic. On the other hand all interviewed parties agree that sustainability is becoming an issue of the future, although.

Execution design

Façade builders conduct a number of different design phases. Every company has its own strategy, but generally the process looks like following:
The first phase before the tendering procedure is an advice and sales phase where they are involved depending on the tendering procedure. Generally, every façade builder conducts two or three design phases.. In a first phase, the basic project design is developed on the basis of the architectural design. Possible missing elements in the tender documents are discovered. This means that first decisions have to be made right at the beginning together with the architect e.g. about profiles that require certain delivery times. In a second phase, the design is elaborated and completed. Usually, the results of each design phase are sent to the architect/consultant for approval - which takes up extra time that needs to be considered. Finally, the production and assembly design phase starts. Although the design is often based on existing systems, the façade builder draws every profile, every gasket, and every slot he has to drill. He needs to order the complex systems products with all necessary components, which often requires support from the system supplier. He needs to know the glass properties, glass sizes and weights. Structural calculations have to be done. He also needs to adhere to order and delivery times. Coatings are done in separate processes. He draws up all metal panels as fold outs, and much more. It is a very complex and time consuming procedure that requires a lot of knowledge and experience. It can take 10 – 15 or more details done by the façade builder to realise just one architectural detail. The façade builder needs a linear procedure. He starts his design from the bottom up. The time schedule defines all the decisions that have to be made at a certain time to keep the process from coming to a grinding halt.

System design

A large part of current curtain walls is based on façade systems. These have been developed prior to the whole design process. The goal of the system supplier is that his products are explicitly inquired in the tender document (which is not always possible), and his interest is to assist the design team. After the submission he sells his products to the façade builder, provides support and adapts his systems to the project needs, if necessary. He will use the acquired knowledge to upgrade his system portfolio.

Scheme of the façade design process

Figure 24 shows the complex combination of architectural design, execution design and product design.
The architect works iteratively, whereas the façade builder prefers a linear process. He needs early and definite decisions. Time pressure is high, and he has to adhere to complex logistic procedures concerning the work of the suppliers of subsystems as well. As the analysis of contracting strategies has shown, most projects are executed in an open tender process. Hereby the builder's work actually starts after the awarding of the contract. Very often though, the builder gets involved beforehand, providing input to the design team. The early involvement of companies is twofold. On one hand, it offers valuable technical input, making sure that the façade design is technically and financially solid, but on the other hand the builder naturally has an own agenda that might not comply with the one of the client or architect. Thus, there is a mutual interest but also a potential conflict.
The natural tension between architectural design and industrial production has been questioned in the interview (questions I13 and I14). All the industry stakeholders stated that they are concerned with architectural design to a certain extent. It is seen as very important factor, not least because delivering a project of high architectural value (even though they often do not know what that specifically means) is a sales argument. At the same time they say that architectural design often conflicts with their work. The main reason here for is a lack of knowledge of the architect while formulating his desires.
If a general contractor is involved he will pay the façade builder and often the architect as well. It depends on his contract with the client how much influence he has on decisions in the execution of the façade. He has the overall responsibility for the project, takes on risks, and wants to meet personal financial goals and limitations. Cutting cost always works to his benefit.
This means more potential conflicts between the three parties.

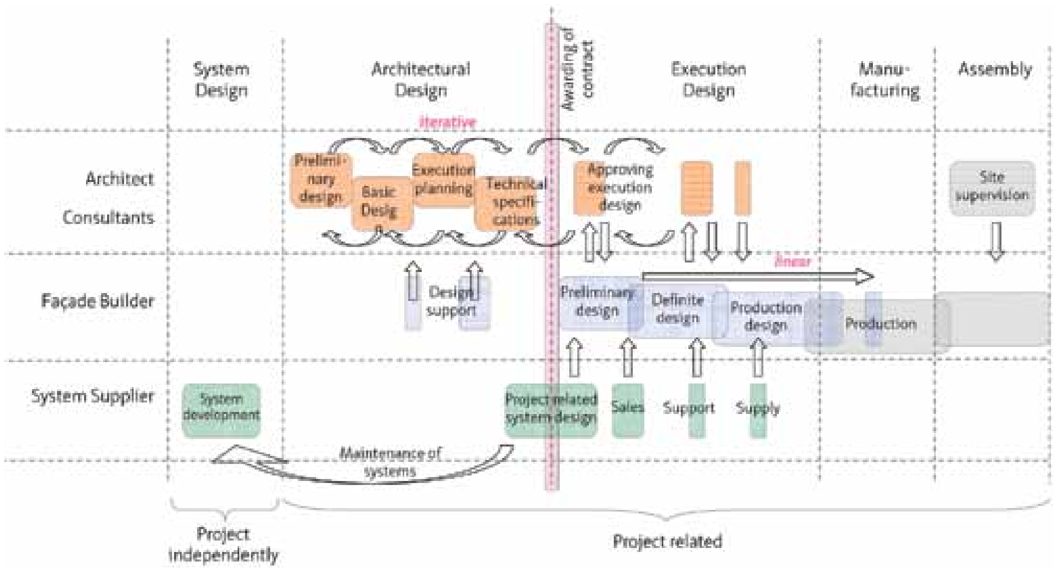


Figure 24
A scheme of the façade design process. Architectural design, execution design and product design overlap.

§ 3.2.5 Profit potential and risks in the façade construction process

Architects

In questions A5, A6 and A7 architects where asked about their turnover, their profit situation and their risks in the construction process. Since the number of the interviewed parties had to be limited, the figures can only been seen as rough indications of the situation.

The results of the interview show that German architects make 66% of their turnover before submission (accordingly to HOAI). In the Netherlands, this percentage is even higher at 86% with a tendency to give more responsibility in the working drawings to the companies.

Three of the four interviewed offices did in fact only conduct a small fraction of their work after the submission. This would often be artistic supervision, partly paid by the client and partly paid by the general contractor

Netherlands phase	IH	PD	SO	VO	DO	TO	P&C/ Subm.	UO	UD	GE
A1				16	46	46	8	12	2	
A3**				65%*			35%			
Germany phase	**1**	**2**	**3**	**4**	**5**	**6**	**7/ Subm.**	**8**	**9**	
A2***	3	7	11	6	25	10	4	31		
A4***	3	7	11	6	25	10	4	31		
E1	20	20	20	20	20					

*A3: Phase SO to DO = ~65% and TO to UD =~35%, SO = least money but very time consuming
**A3: Works with the DNR standard. The development goes more toward a limited involvement ending at DO+. More design and build contracts. This means that the technical detailing is left to the executing parties.
***A2 and A4: Both roughly according to the legal phases HOAI.

Table 2
Summary of question A5, the turnover in % according to the different architectural design phases.

Table 3.6: Summary of question A5, the turnover in % according to the different architectural design phases.
Four of the five offices gain the biggest earnings in the early design phases. The execution drawings (TO or phase 5) seem to be relatively labour intensive and therefore not very profitable. Good quality is in direct relation to planning effort.

No definite answer can be given on the question about involved risks for architects (A7). Every phase has its own risks, but they all depend on each other. The early stages seem more risky for internal processes, because mistake here will lead to a higher effort for making good in the following phases. Generally, the communication with the client is very important. Design changes can mean a lot of extra work. The final design phase is risky because the costs become fixed, and because building laws must be adhered to. Creating the working drawings and running the construction site potentially bears a lot of external risks. It can have a direct negative effect on the work flow of other parties and cause constructional failures.

Façade builder

A very small portion of the façade builder's turnover relates to the use of the building (maintenance contracts). Design and assembly make up for a rather large part, but the biggest turnover is generated during production and material supply.

Facade Builder	Develop-ment	Design	Material/ supply	Produc-tion	Trans-port	Assembly on site	During use of building	End of life
F1		15-20	20	35		15-20	5	
F2	no information							
F3	1	18	50*	25	1	10		
F4	2	5	41	25	2	25	1	
Result	1	ca.16	ca.35	ca.28	ca.2	ca.18	2	
	*F2 builds highly engineered and steel and glass structures and therefore is not working a lot in the standard market. This results in relatively high turnover in the design and material phase							

Table 3
Summary of question 13, the facade builders´turnover in % according during the different phases..

The question about the profit potential (question I4) seems difficult to answer. Two companies do not really make a distinction between the phases, but calculate the project as a whole. Three companies name the design phase as essential, because it includes many decisions concerning the efficiency of subsequent phases. Only one company sees a big profit potential in the assembly phase whereas two others (one of which is the branch organisation) clearly do not. Two companies see a big margin with material supply whereas one does not.
The result is an inhomogeneous picture which might have to do with the different internal workings of the companies and if, for example, the façade assembly is subcontracted or not. No direct connection between turn over and profit can be identified.
The answers to question I5and I5b about the involved risks for the industry show that material failures and the quality of subcomponents only seem to pose a small risk. Failure and claims do not occur often. Façade builders seem to rather fear the problems that result from external communication and physical dependencies or such that relate to other parties on the construction site than internal planning mistakes, wrong cost calculations or evaluation of the task. This leaves a rather self confident picture.

§ 3.2.6 Project duration

The project time from assignment to finishing has become shorter over the last years (see questions A16/I11). Almost all interviewed parties confirmed this trend, but it was not possible to quantify this. One company has recently made a step to shorten delivery times for unitised systems by about 20%, reacting on a market request from Great Britain. Reasons for the reduction can be seen in the market pressure, and it was made possible by a higher degree of prefabrication (unitised systems).

Only one façade builder does not observe this tendency due to its involvement in 'bouwteams' (building teams) from the beginning of a project, according to procedure 3 as mentioned above.
Most of the interviewed parties (except one) could potentially work faster (see A17/I12). Different estimations range between 10 and 15%, which actually means that the internal process is already rather optimised .The external dependencies seem to be the bottleneck for a quicker process, but also the traditional craftsmanship oriented building process was mentioned ("Drying of concrete"). At this moment, a reduction would mean higher risks and higher costs.
A higher degree of prefabrication, earlier orders of supplies, earlier definitive decision making by client and architects would be needed. The double planning effort of architectural design and execution design (see also Figure 24) was also mentioned as very time consuming.

§ 3.2.7 Façade system products

Decisions about façade concepts, systems and products are primarily made by the architect or architects' consultants (80-90%) (see questions A18/I17).

	low	middle	high	comments
Architectural quality	B (1)	S2 - F4 - S1 - E1 (4)	S1 - A3 - A4 (3)	
Design openness/ flexibility	F4 (1)	B - A3 -E1 (3)	F4 - S2 - A4 (3)	A: Not off the book but adaptable to architects desires
Costs	S1 (1)	B - S2 - S1 - A3 - E1 (5)	F4 - A4 (2)	
Performance	A3 (1)	F4 - E1 (2)	B - S2 - S1 - A4 (4)	
	(a) = total number of votes A3: "This is different from project to project. Everything is adjusted to the norms and regulations. This defines the lowest quality. Everything tends toward the lowest quality and that is a problem."			

Table 4
Summary of question (A19, I17) , arguments for façade products.

There does not seem to be a common idea about decisive arguments for façade products (question A19). All arguments are considered of middle or high importance. The answer of A3 that these decisions could differ from project to project is interesting. Three of the four architects state that their knowledge about technical aspects of façade products is limited and that they have to rely on consultants (question A20). They are responsible for the definition of performance specification anyhow. The reason for the limited knowledge would be a lack of time due to the rising complexity.

§ 3.2.8 Façade costs

Façade costs in relationship with the whole building (question A22/I28)
When evaluating façade costs, one must distinguish between curtain walls and windows (which is the working field of the interviewed parties) and claddings. And it strongly depends on the building itself. The estimation is 25% for cladding and façades, and 10% only for curtain walls and windows. Unitised systems account for 20-30% of the costs of a building, because they basically cover the whole building envelope.
Most of the industry stakeholders expect the façades to become more expensive in relationship to the bulidng as a whole (question I29). One reason might be the integration of more functions such as an active contribution to the building services.

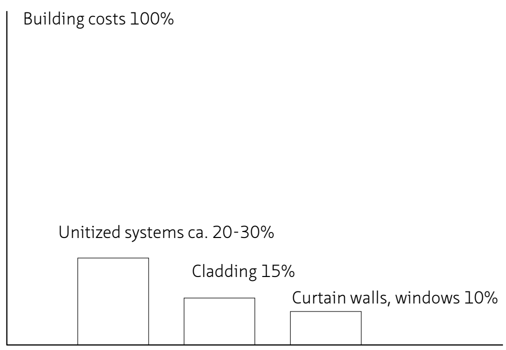


Figure 25
Façade costs in relationship with the building as a whole (questions A22/I28)

Façade costs by category (question I26)

Table 5 shows the façade costs by category. This is only a rough estimation, because no hard figures were available to the interviewees, but it gives a good indication about the distribution of costs. One interesting aspect is the high material costs. With the tendency toward unitised systems, more effort gets shifted to design and production. Also material costs will be rising, simply because of more complex systems (question I27).

Facade Builder/ System supplier	Design	Material	Production	Transport	Assembly
F1	20-25	20	35-40	1	20-25
F2	15-20	50	20	1	10
F3	5	43	25	2	25
S2	5	35	40	2	18
Average	12	37	31	2	18

Table 5
Summary of question I26, façade costs by category.

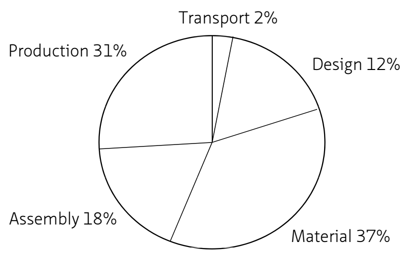


Figure 26
Façade costs by categories (I26)

The following scheme shows a comparison of different costs between a curtain wall and a brick wall with insulation and ventilated brick facing. One can see that the brick builder earns his money with skilled labour. He largely depends on the situation/ condition of the construction site. The potential for cost saving is limited, but he can increase efficiency by improving the work processes such as using larger bricks and lifting equipment.

Until the 1950, the situation in the curtain walling business remained about the same. With the introduction of complex façade systems, however, the focus completely has shifted. The core business is design and logistics and the façade production (assembly of subcomponents). Hereby the largest investments are made on processing equipment. Obviously material procurement becomes an essential part of the business with roughly 40% of the turnover. Façade builders today are system integrators with an industrial production and a relatively low degree of craftsmanship on the construction site.

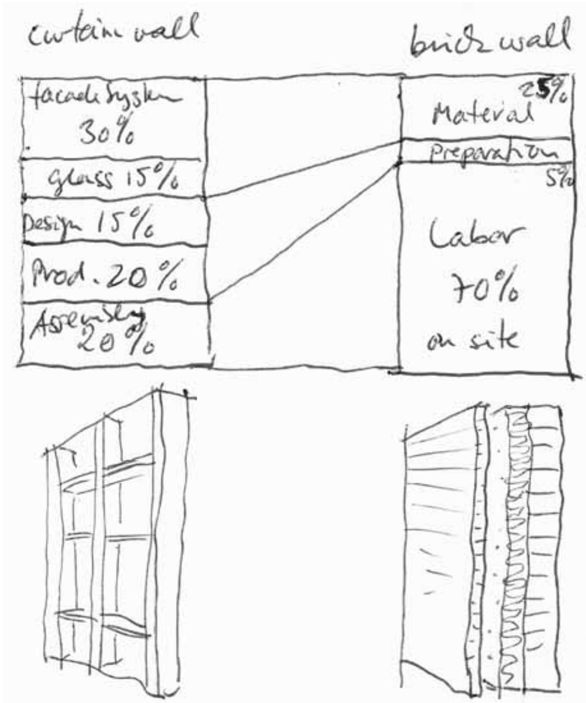


Figure 27

Comparison of costs for curtain walls and brick walls

§ 3.2.9 Building services integration in façade construction

Building services installations in façades are all devices that actively contribute to the climatic performance of the building. At least on a standard level, all interviewed parties have some experience with this topic (question A24/I20); meaning the integration of electrical sun-shading devices or night cooling openings. One architectural office and one façade builder have actually built decentralised climate installations with the façade.
Two of the four architectural firms say that they know about the potential of this approach (question A25), whereas two only have rudimentary insight. The system providers both have experience with decentralised components. Amongst the façade builders (question I21) there is a rough understanding about the potential of the integration of building service components.
Being asked about their opinion on this approach (question A26), three of the four architects see it positive as an architect's task that potentially contributes to good

comfort and energy savings. One architect principally does not consider the approach for ´normal ´buildings.
All façade builders are open to the idea of integrating building services into façade construction (question I22 and I23). Their opinion is that this is a chance for their discipline. It is questioned if the façade builder should become the builder of installation or the integrator of such subcomponents. They are used to integrate subcomponents such as glass panes, sun-shades, and to specify and design the interfaces between those and the façade construction. But they are rather critical about leaving the own field of expertise, when also building installation.

§ 3.2.10 New requirements and challenges for the discipline of building envelopes

All industry stakeholders expect rising complexity in form of higher requirements (U-values, fire protection) or integration of components in form of solar appliances or building services (see question I36). One party expects more legal issues and claims, which might have to do with the complexity or a shift toward a more competitive market.
The same is true for the architects. They believe the challenges are better U-values and the integration of building services (question A31). Three of the four offices see the need to expand their scope by gaining more technical knowledge (A32).

§ 3.3 Stakeholders in façade construction

After a summary of the façade construction process it is now necessary to sketch the role of the different stakeholders.

§ 3.3.1 Owner/ Investor

The owner/investor (not the same as the user) of a building seeks a high value/ investment ratio. This is achieved by good architectural quality, durable construction, low maintenance cost in combination with low investment. For the investor, the success of a façade is measured in its profit potential.
On one hand he is seeking control about all aspects of the building/façade, on the other hand he will try to minimise his organisational effort. He needs the architect to design the building and give it the optimal functionality. He will try to hand over the risks to the general contractor or the façade builder. With the increasing importance of the

energetic performance of a building (fulfilling legal requirements and environmental goals as well as minimising costs during use) he will demand a clear definition of the performance goals as well as guarantees at the beginning of the project.
The owner/investor himself is not actively involved in innovation, but his attitude largely determines the chance for it. For him, innovation always bears uncertainties; thus he will have a strong opinion about it.

§ 3.3.2 Architect

The architect is the one to integrate the input of the different stakeholders in order to create the building/façade. That means he has to bridge the gap between functionality, technical realisation and artistic expression. Designing means dealing with a lot of unknown factors. Therefore his work is of an incremental nature. To continuously optimise the design, the results have to be looped back, and earlier design decisions are questioned. The architect is a central figure in the process and has influence on most decisions, but at the same time his work conflicts with all other stakeholders. He is the only one educated in terms of architecture, and it seems to him that he constantly has to defend architectural qualities so that he does not need to compromise in favour of the interest of others. The architect faces the problem, however, that complexity continuously increases, and that he has to rely on the expertise of consultants, façade builder and also system supplier. He is in constant danger of losing control of the process.
The architect is the one predominantly responsible for innovation on many levels. At the project basis, he can promote the use of innovative technologies, materials or systems. He is the one able to create an overview of the needs of the market and technical possibilities, and in principle could stimulate fundamental innovation. However, architects are mostly generalists with limited knowledge of individual technical aspects, and typically do not have the financial capacity to realise innovations by themselves.

§ 3.3.3 General Contractor

The central resource of the general contractor is his ability to organise and to take on risks for the client. His responsibility for the building is high, which means that he will always try to pass it on to his subcontractors. His profit potential lies in the difference between the agreed upon price and the real costs. Naturally, he will try to translate the specifications in the most economic manner, which can lead to conflicts with the other stakeholders.

He is only interested in innovation if a financial benefit is involved. Departing from his traditional methods usually means a risk. He therefore plays a rather conservative role in the process.

§ 3.3.4 Façade builder

The façade builder translates the architectural design into a realisable construction and has to guarantee the performance of the façade as a whole. The integration of numerous subcomponents requires a considerable amount of planning and logistic effort.
He has trained the employees and invested in his production facilities. Naturally, he will try to use these resources as much as possible. Time and financial pressure is very high and departing from the methods he is used to or experimenting poses the risk of being inefficient.
He tries to establish a relationship with the architect and the general contractor, but to a large extent decisions are made by price. He needs support from the system supplier.
He knows two types of innovations: First of all, innovations that concern his own way of working, design, production and assembly. The success will be measured in financial benefit for the company. Secondly, he knows innovation that concerns façade construction itself, which he does on a project by project basis. He does not have the capacity for strategic and fundamental innovation (with the exception of a few large façade builders who do have this capacity).

§ 3.3.5 System supplier

The systems supplier's role is ambivalent. His main focus is towards the architect, who decides about the application of his products, but it is the façade builder who buys them. The products must be highly flexible in terms of architectural design and, at the same time, they need to be kept simple and understandable for the façade builder. The system supplier desires a long term relationship with the façade builder who needs to be kept up to date with the latest developments, but with the architect and façade consultant as well.
Delivery times are short and he needs to keep a large inventory of all parts, which is expensive. The system catalogues need to be maintained continuously for external communication and orders from the façade builder.
The products are highly developed and require constant upgrade to keep up with legal requirements - a difficult task. Façade systems are tested for wind, water and air tightness as well as sound insulation and U-values, blast and burglar resistance and structural integrity. If necessary, the system products can be adapted to the needs of a particular project, but fundamental innovation such as the development of a new

system is expensive and takes time. The system supplier scans the market for possible new developments and strategically invests in new developments, which he adds to his system portfolio.

§ 3.3.6 Facility management

Low maintenance effort and clear responsibilities in terms of failure or damage are central interests of the facility manager. With façades becoming more active and hooked up to the central building management system, facility management becomes increasingly complex and important. Constant monitoring of the functionality as well as the energetic performance will become a task of future facility managers. Apart from that, the future facility management will also have to develop a long term vision of the façade, including end of life scenarios. This also means that facility management will be involved even in the early design stages.

§ 3.3.7 User

In addition to representative and appealing architecture the user wants high comfort, low energy consumption and little maintenance effort. And a certain amount of flexibility is needed in order to adapt the building according to changing needs. User interests are focussed on the time of use of the façade.

§ 3.3.8 Society

Society has a passive and perhaps rather unconscious role in the process of façade construction, but the interests are actually rather strong. First of all, society demands good architectural design, which is a reflection of our cultural mind set. Secondly, it is interested in sustainable manufacturing and assembly methods and a low use of energy of a building, which is reflected in energy regulations. And although we do not have according regulations yet, our growing environmental consciousness also demands low embodied energy and a potential for reuse or recycling of used materials and components.

§ 3.3.9 3.3.9 Project partnerships

The interviews showed (question A15 and I30) that most often the involved stakeholders change from project to project. All interviewees stated that they have preferred partners to work with, but that price pressure determines the actual project partners. In the same way as architects sometimes have the possibility to work with their preferred consultants or partner companies, the façade builder works with a fixed number of different preferred suppliers. It is necessary to establish long term relationships and trust in order to be able to function in a market with great time pressure.

§ 3.3.10 A critical view on the on the results of the interview

Before the market analysis is interpreted and finally concluded, it is necessary to step back and take a critical view of the interview itself, which served as the basic tool to collect the data.

As mentioned in the introduction, this inquiry covers a large field. Many stakeholders are involved and the process is multi-facetted. Conducting the interview made it clearer than ever that there is more than one way to build façades. Every interviewed party had a different experience, a different focus, different preferences, which sometimes made it hard to compare the results. Also, not every curtain wall is the same with different levels of standardisation. But still, there is a common understanding of e.g. the sequence of process steps, how an architect works or how a project is tendered. This is the basis on which all the different views can be tied together.

The consequence of choosing an interview format (and not a multiple choice method) leads to answers of different qualities. In the interview reports, the results have been collected by partly citing the interviewees and partly by reformulating their answers to get comparable results. Thus a certain amount of interpretation is inevitably included. To overcome potential misinterpretations, the conclusion of this interview was returned to the interviewees for confirmation and additional comments. The answers of the interviewees are included in the following summary. The number of interviewed architects and façade builders was higher than that of the other categories because of their involvement in the design process where we wanted to make sure to achieve a certain level of detail.

A total of 14 experts have agreed on the content; all with a different point of view but still one can postulate that all of them have a deep insight into the topic.

Some of the questions did not deliver a clear result; for example the question about the risk and failure potential for certain aspect in the process (question I5). A risk analysis for the different stakeholders would be worth a complete separate research. The result does thus not deliver the desired detailed information but the basic finding that, for example, façade builders believe their internal processes pose low risks and are under control. The same can be said about the question of decisive arguments for façade products (questions A19, I17). There was no clear-cut opinion. In this case, we cannot draw the conclusion that there are no clear arguments, but it can be said that the interviewed parties do not have a clear picture of these products, and obviously have never done an analysis themselves (which is astonishing in case of the system providers at least!). In return, this insight proves the hypothesis that the façade industry (the same as the entire building industry) really has developed incrementally and in an empiric way. The slow and continuous adaption and improvement of façade systems has never raised fundamental questions and thus prevented revolutionary changes.

§ 3.4 Summary of the process analysis

This part aims at answering the research questions that have been formulated in the first chapter. The second goal is to identify challenges for the discipline of façade construction. This summary is validated by sending it back to the interviewees with a request for confirmation or further commentary.

§ 3.4.1 Process steps and dependencies in façade construction

- *What are the process steps, what are the dependencies?*

The analysis has revealed some interesting points about the process of façade construction. First of all it shows the embroilment of the stakeholder actions. It can be described as an utterly complex process, happening again and again with different stakeholders for different projects.

This entire process has developed incrementally and in parallel to the other crafts. It is based on a craftsmanship driven building concept. But unlike the other crafts, façade construction has long incorporated industrial processes.

This is also the reason why a complex combination of architectural design, execution design and system design is needed to create a curtain wall that, on one hand, needs to match craftsmanship driven procedures and, on the other, needs to cope with the needs of industrialised products (see Figure 24 Façade design process).

In the centre of the façade construction process is the awarding of the contract. This phase is the moment when design and engineering intensions are handed over to the executing parties (see 4.2.2 Contracting strategies). Four different methods have been defined, all with different impact on costs, innovation or architectural design. The main difference is to what degree the engineering team predefines the project, and to what extent the builders are allowed to influence the process. This decision becomes especially important when a project is making a step into unknown terrain e.g. introducing innovative design methods or constructions. The integration of building services into the façade construction is another such case. It becomes clear that careful decisions about the contracting strategy are essential to bring this kind of concept to a success.

The hypothesis that processes become shorter can be confirmed without being able to extract clear figures about the trend. (See 4.2.6 Project duration). Most parties say that principally they could work faster. Figures of around 10-15% have been mentioned on different occasions. This actually means that their internal processes are rather optimised. Most interviewed party's state that their internal risks are rather manageable and limited; giving the impression of a rather self confident and highly developed industry. But the general opinion is that faster projects would lead to considerably higher risks, mostly because of the dependencies with other parties. It is thus the not the ability/inability of the individual stakeholders but the process itself that is the bottleneck for a shorter project duration.

It is most interesting that the entire façade construction process ends with the assembly phase for all designing and building parties. Façade builders are only sporadically involved with maintenance during the time of use of a building; however, they see a market potential. Though all interviewed parties agreed that sustainable design and construction will be the task of the future, they do not seem to be clear on what terms such as ´embodied energy´ and ´end of life scenarios´ practically mean for their discipline. This also shows in the fact that sustainability and end of life scenarios are not explicitly mentioned in the legal descriptions of architects' services in The Netherlands and Germany. It is therefore no wonder that the holistic view on all aspects of sustainability is missing.

The future demands buildings with optimal energetic performance. This concerns operational energy as well as embodied energy in constructions. Here, the façade will play an important role. This energetic performance has to be predicted by the designing and building parties. It has to be planned and executed on a project to project basis, and for phases when these parties are usually no longer involved in the project.

§ 3.4.2 How architectural design is geared into façade construction

- *How is architectural design geared into the façade construction process?*

The interview showed that façade design actually happens on different levels. First, there is architectural design. A particularity of façade construction is that its complexity exceeds the depth of other crafts and with it the knowledge of the architect. This is why, secondly, an execution design phase by the façade builder is needed (see Figure 24: Scheme of the façade design process). The iterative architectural design procedure has to be linked to the linear procedure of the builder. Not only is this very time consuming, but also prone to conflicts. Symbolically, this is when the baton of architectural intentions gets handed over to the executing party.

Finally, the façade design gets influenced by the system design, which is done ahead of the project. Systems, on one hand, help the architect to fulfil his design goals. They are tested in terms of their thermal or structural performance. They come with knowledge about costs, etc. On the other, they limit the design possibilities. He can only choose from what is available. The products can be adapted to some extent, but typically there is no time and money to create fundamentally new products.

It is interesting to see that the architect can achieve the highest turnover in the phases before the contract is awarded, and only a fraction of the work is conducted while working with the façade builder. Also, most architects state that the biggest profit potential lies in the early design stages (See 4.2.5 Profit potential and risks in façade construction). At the same time, creating the working drawings for the executing parties, involves high external risks (see question A7). Furthermore, three of the four architects stated that their knowledge about façade systems is limited and that they need to rely on consultants and the support of system supplier and façade builder (question A20). Architects generally find that façade systems offer limited design possibilities.

All industry stakeholders state that architectural quality is of great importance for their work (a definition of what architectural quality exactly means is not given), but that, at the same time, it often conflicts with it (questions I13/14). This is an inherent problem, which can lead to the architect becoming more and more excluded from the materialisation of the façade. With the use of more and more complex façade products, there is the inhered danger that his design will be compromised in the execution phase.

§ 3.4.3 The role of the different stakeholders

What is the role of the different stakeholders in this process and how does the decision-making process take place?

The following scheme characterises the relationship of the stakeholders in the façade construction process.

On top is the client/investor, who has made the decision to build. He has the architect to help him translating his ideas into a built product who in turn needs the support of several consultants. Together with the client, they define the architecture, but also the performance goals of the building. Those will be translated into performance goals of the façade/curtain wall. The general contractor takes over the project, and guarantees to build it according to the given specifications. He subcontracts the façade job but will maintain the responsibility for the overall process in terms of costs and time.

The system suppliers develop their products beforehand and try to get into the process by convincing architect/consultant and façade builder that they have the right solution for the job. Façade system products themselves are mature, which shows in the answers to the question of involved risks for façade builders (I5). Material and system failures do not occur often, which is a sign that they have reached a highly developed standard and that the correct manner of application is known.

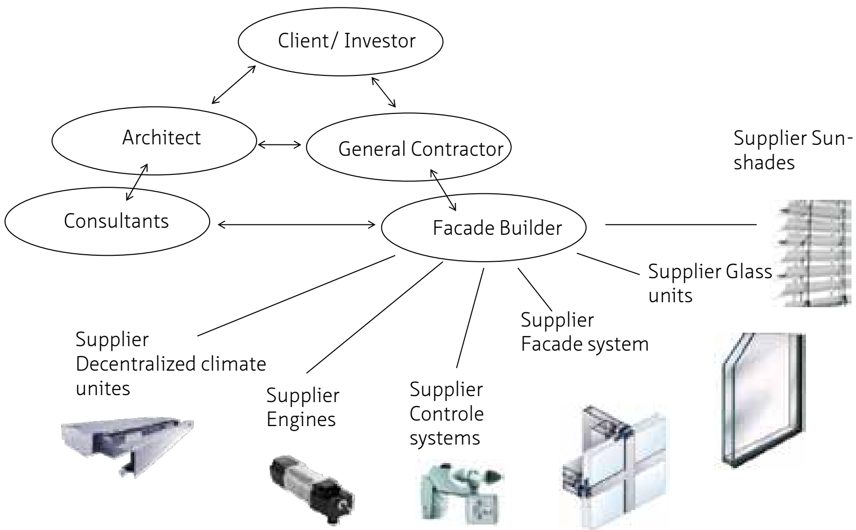


Figure 28
Scheme of the relationship between the stakeholders

The scheme makes it clear that façades are composed of highly developed system products. And the number of system products will further increase with the trend to integrate adaptive and building services related components. It is interesting to note that the architect typically is the one who decides about those components, but at the same time, does not have full detailed knowledge of them.
Another interesting aspect is to see what will need to happen to this stakeholder relationship if one anticipates a more sustainable approach. This could mean lower energy consumption of the building as well as lesser embodied energy in the façade construction or disassembly strategies. Whereas the latter will mostly concern the systems themselves and the way the façade builder assembles them, the use of energy and the comfort level must be seen in close relation to the building as a whole, its construction typology, the type of use and the building services concept.
Unlike cars, a building cannot be tested before put on the racetrack, and the results must be estimated beforehand. It requires a more integrated design team and simulation tools. But the relationship with the façade builder and system supplier will also become very important right from the beginning of a project. The performance of façade system products (guaranteed by testing certificates) is essential for the

performance of the façade. The knowledge about those as well as the effect of services components, if installed decentralised with the façade or centralised somewhere else in the building, are necessary to make the correct decisions in the early design stages. And all of this will need to happen under an increasing time pressure.
The architect needs to reinforce his role. Together with his consultants he is the only one in this process that is in control of the building as whole and can judge the effect of façade functionality and performance. Frankly said, he also is the lonely defender of his architectural intentions and needs to know what the technical development will mean for his design. Most decisions will be made at the beginning of the project. To efficiently work in such an environment he will need to build up experience and gather the knowledge about all parts. Whether he will do it by teaming up more closely with the other stakeholders or by expanding his own core team is the question.

§ 3.4.4 The impact of the façade construction process on innovation

- *What is the impact of the façade construction process on Innovation?*

Architecture is a project oriented and competitive discipline. Constantly differing parties work together, trying to create the best possible result for a specific task. Their success is measured on the project basis. They have all accumulated their own experience and knowledge, which they will are try to introduce into the process. Thus, innovation in the process of façade construction has a decentralised and accidental nature.
Innovation in façade construction takes place on different levels and the stakeholders all have a different idea what innovation means. New design tools can improve the design process. Climate simulation, for example, can help to predict a certain energetic performance. And tools for information exchange can improve the design process. Architects can stimulate innovate concerning a new architectural design style. The desire to create free form architecture, for example, has led to many inventions in 3D shaped claddings.
Façade builders focus on innovation of their processes, to improve building speed, lower costs and risks. System suppliers try to improve their products anticipating market needs and the desires of architects. Clients and general contractors need to agree on these because it might mean higher risks for them or higher cost for solutions that exceed the standard.
All developed solution concepts need to be measured concerning their impact on the architectural design on different levels: urban, building and detail scales. Here it is important to understand that this is the fundamental nature of architecture as a discipline. Contrary to e.g. product design or the automotive industries it is not about creating optimum products that anticipate a market, but about finding answers for a specific task. The particularity of façade construction is that within its architectural

context, it strongly relies on products (Estimated 38% of all façade costs are spent on system products; question I26).
Ever decreasing project duration in combination with higher requirements on the façade performance (energetic performance of buildings) forces the team to a solution oriented approach using available products.
On can say that the whole façade construction discipline innovates slowly and evolutionary. Radical innovation cannot be introduced for standard buildings. This can only happen in exceptional projects where all involved parties mutually agree to take an experimental leap forward. It seems logical and is confirmed by the answers to question I9 and A11, that innovation has its best chances, when a) the financial pressure is relieved and b) all stakeholders are involved to some extent. The competitive tendering procedures generally break down innovative speed. In a competitive environment, innovative ideas are only granted if they verifiably save time and money.
The analysis does not show that the structure of the building market actually blocks innovation, but innovation definitely happens de-centrally and peripherally, driven by the different stakeholders. This generally leads to an incremental improvement of façade construction. Since it happens project-wise and with differing teams, it has a highly accidental nature. The market structure with its inherited procedures works like a guiding structure but, at the same time, it is a straitjacket for fundamental innovation.

§ 3.4.5 Future challenges for façade constructions

The situation of the design and construction process is described in the previous paragraphs. However, another question needs to be answered in order to be able to evaluate façade constructions on how they will be fit for the future:

- *What are the future challenges for curtain wall construction?*

Defining future challenges is also important when developing an approach for future constructions. The chapter is summarised by formulating a number of challenges, resulting from the process analysis. These challenges have a general nature and, in order to establish a connection to façade construction, they are translated into façade functions. For example: For the future challenge ´Minimise embodied energy´ three functions can be defined that have an impact on façade construction. We can minimise embodied energy by a) choosing materials with a low impact, b) reducing material quantities or c) offer the possibility to recycle materials. The following chapters of this dissertation explain the role of façade functions and how they are translated into physical façade components.
It has to be noted that the challenges are of a general nature and the list might not be complete. However, the interview experts all agreed on the following list:

- **Minimise embodied energy**
  The embodied energy of a construction can be reduced by the choice of materials and their quantity and the way these materials will be treated at the end of their life or at the end of life of the façade construction.
  Functions:
  - *Choose materials with low impact*
  - *Reduce material quantities*
  - *Offer recyclability*

- **Minimise operational energy**
  Operational energy can be influenced by a high insulation value and adaptation to the exterior climate. One example is an adaptable sun shading system that blocks radiation in summer but lets the energy permeate when outside temperatures are low. Finally, user behaviour has an impact. This of course is difficult to guide with curtain wall construction.
  Functions:
  - *Provide high level of insulation*
  - *Adapt to climate*

- **Predict façade performance:**
  It will be increasingly important to predict the façade performance not only in terms of operational energy and comfort, but also embodied energy.
  Functions:
  - *Predict use of operational energy*
  - *Predict embodied energy*
  - *Predict comfort*

- **Create a faster process**
  The process durations will get shorter and, at the same time, the façade construction will grow more complex. The design and building process itself is the bottleneck.
  Functions:
  - *Shorten design process*
  - *Shorten production and assembly process*
  - *Reduce external risks resulting from a faster process*

- **Enable architectural possibilities**
  Architects, as decision makers, have limited knowledge of increasingly complex constructions. Façade systems offer limited design possibilities. Architectural design often conflicts with the interests of different stakeholders.
  Functions:
  - *Bridge knowledge gap between system design, architectural design and execution design*
  - *Allow a maximum of architectural variety*
  - *Support architectural design intentions throughout the process*

- **Stimulate innovation**
  Innovation should be embedded as a goal in the way we are building. As mentioned above, innovation happens de-centrally in the design and construction process. This is not a bad thing, but the problem is that it is of an incremental and accidentally nature and does not happen systematically. Innovation should be centrally stimulated to guarantee that completely new concepts can emerge. But innovation should not only be embedded in the creation of new façades and products but also in existing constructions.
  Functions:
  - *Control level of innovation centrally and systematically*
  - *Incorporate de-central innovation*
  - *Upgrade existing constructions*

Figure 29 gives a summary of the results.

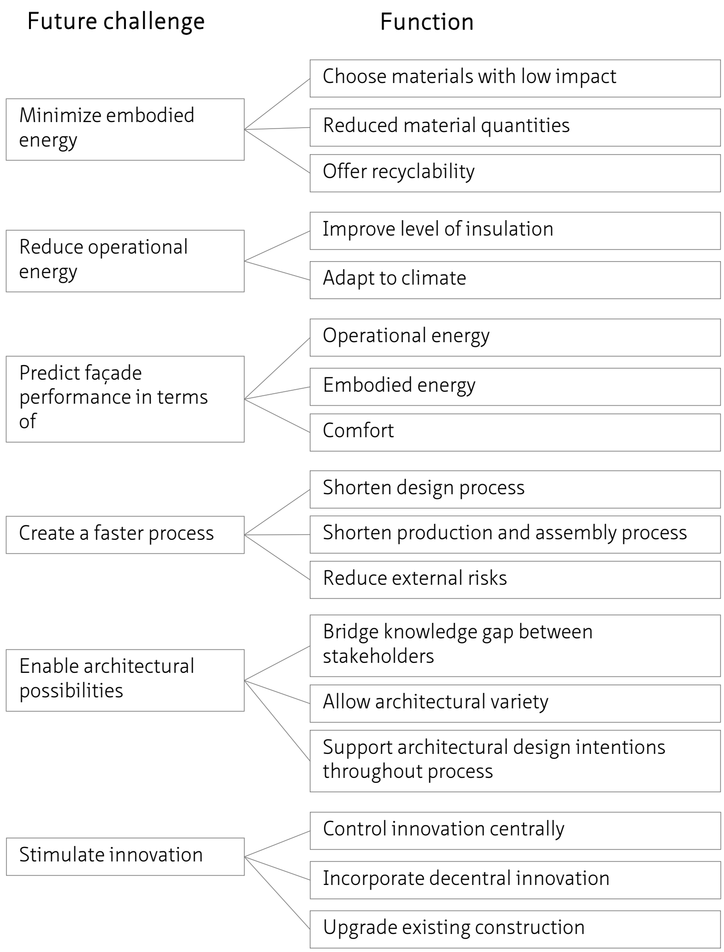


Figure 29
Future challenges can be translated into functions for façade construction.

Some of these functions relate to façade construction and some to the façade design and construction process. In a next step, the later category of challenges can be allocated to certain areas on the process. Figure 30 shows what impact the future challenges have on the different construction phases and stakeholders.

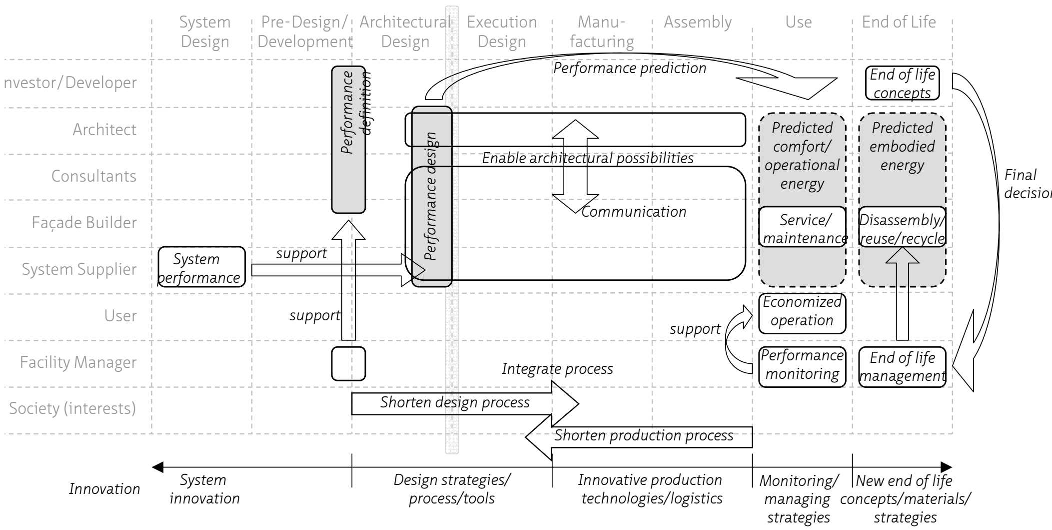


Figure 30

The impact of future challenges on the different construction phases and stakeholders

Chapter 6 shows the research about the way façade construction can respond to these challenges and the according façade functions in the future.

4 Systematic for a constructional façade analysis

§ 4.1 Introduction

The previous chapter gave insight into a fragmented market structure and the role of the different stakeholders. Compared to other disciplines in the building industry, façades involve a high level of industrialisation, resulting in a complex and unique planning and decision making process.
Now we need to analyse the state of the art of façade construction. The constructional strategies in use today have developed simultaneously with the building processes and it is thus important to look at the connection of both the immaterial (market) and material (construction) properties, as Eekhout (Eekhout, 2008) calls them, to be able to successfully analyse façade construction.
For this purpose historic as well as contemporary curtain wall constructions need to be assessed. This chapter aims at providing the basis for the analysis in chapter 5 by defining a systematic. Accordingly the main research question of this part is:

- *How can a systematic for a constructional façade analysis be defined?*

The systematic should relate to the dependency between the material and immaterial side and it requires a basic vocabulary. The assumption is that this is reflected in current construction theories. The chapter starts with a literature research aiming at answering the following research questions:

- *How are façade construction and its dependency on the façade design and construction process described in literature?*
- *What vocabulary can be derived that is suitable for the analysis of façade construction?*

The study assesses professional literature from the field of building construction and façade construction that is used for education and information of architects, builders and system providers. Secondly, selected literature from other disciplines such as product development was included. Based on the author's experience, the above mentioned dependency is not typically mentioned in the first category.

The theory of product architecture in particular provides good insight as it provides a detailed description of the relationship between construction and the managerial side of a product. Therefore this work dedicates space to this topic.
The literature study also shows that functions are essential when developing or analysing products, or in this case curtain wall constructions. They can be described as the objective a construction is designed for. This chapter provides a detailed overview of functions in general and the role of façade functions in particular.
At the end of chapter 4, a systematic is developed for the analysis of façade constructions that follows in chapter 5.

The following schema shows the structure of this chapter:

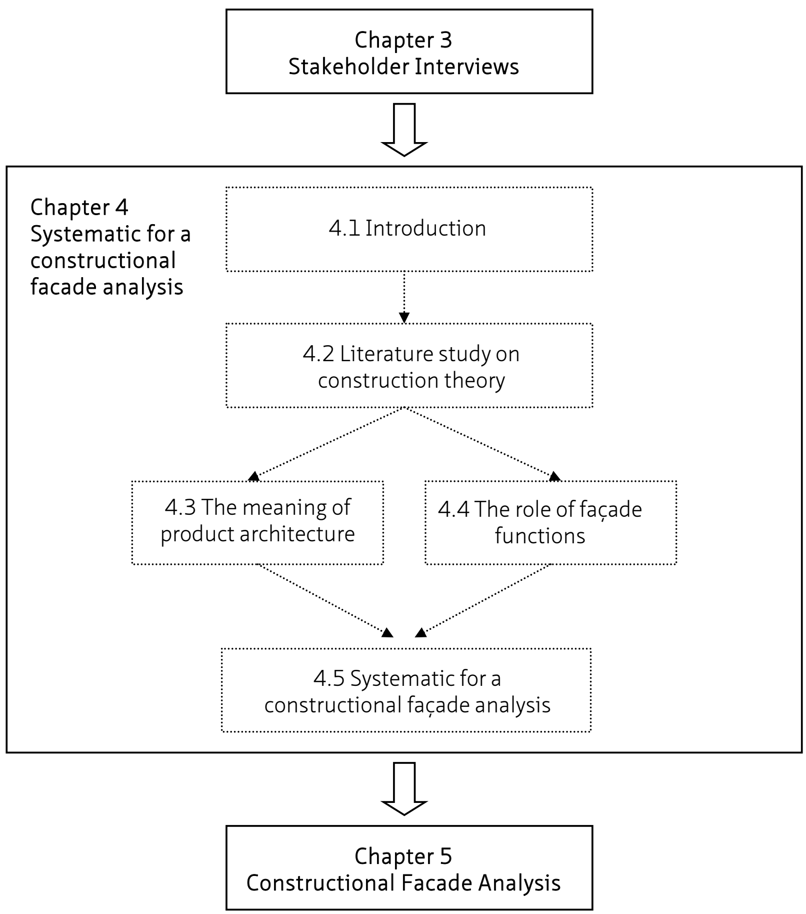


Figure 31
Structure of chapter 4

§ 4.2 Literature study on construction theory

Within the building process, architects are mainly responsible for deciding on the application of façades (see Part 2); thus, the selected literature shows a list of international books on the subject of building construction and façade design that are used to educate students and practitioners in architecture. Of course, the selection cannot be complete and refers to a certain cultural region, but it the author's belief that it reflects a general level of knowledge in the educational field. Furthermore, two guidelines have been examined which reflect the best practice as well as the current norms and regulations for façade construction in the European Community. The guidelines are directed at producers, system suppliers and façade builders.
The literature study also includes a number of books from the field of product development that provide a more detailed insight into construction.

§ 4.2.1 Construction theory in building construction

Building Construction Illustrated (Ching and Adams, 2001)
In their book, Ching and Adams describe building element, component, and system in terms of their end use. The content is presented with graphically appealing drawings and sketches in a very intuitive manner. They state that it is nearly impossible to cover all building materials and construction techniques available, since they continuously adjust to new developments.

The book describes typical conditions of glazed curtain wall systems, and interestingly states that there is no need for extensive detailing except when existing components are modified. Obviously the idea is that façade construction itself is not the core task of architects, but of specialized system designers. The aim of the book is to provide the architect with the fundamental principles of curtain walling construction.

Constructing Architecture: Materials, Processes, Structures; a Handbook (Deplazes, 2005)
Deplazes sees construction as a result of the artistic design process. The content of this handbook is divided into the chapters Materials (modules), Building elements (wall, roof, etc.), Structures (building typologies) and Buildings (examples), oriented on the building process. This structure is used to explain the meaning of construction for the metaphysical architectonic space.
Façade functions are generally explained, and façade construction is exemplarily shown with detail drawings. Curtain walls are not explicitly discussed, but sun-shading devices and their functionality.

Components and Connections (Meijs and Knaack, 2009)
In the first part of their book, Meijs and Knaack describe and explain building components according to their function. The second part focuses on connections between those components, and develops an entire explanatory vocabulary on jointing and fixing methods. Façades are discussed under the topic of tightness and permeable constructions, and standard joints within façade construction are explained in terms of their function. In principle, this gives good input to the research, but the starting point is the traditional building composition, seen as an assemblage of building components rather than the market structure as driving force.

The following books focus on façade construction itself.

Façade Construction Manual (Herzog et al., 2004)
This book is an extensive and rather complete collection of up to date façade technology. The focus lies on the architect and the architectural design process and historic development. It begins with an explanation of the functional requirements of façades, followed by diagrams and schematic graphics showing the façade morphology. This dissertation will relate to this information when façade functions are further defined. General planning advice for different façade performances is given for topics such as fire protection and thermal insulation. Material and production technologies and detailing are explained using numerous built examples. The extensive collection provides architects with an inspiring overview over possible façade solutions. Façade construction is explained in general terms. There is no link to the facade design and construction process.

Gevels en architectuur; facades in glas en aluminium (Renckens, 1996)
The book gives a rather comprehensive overview of curtain wall technology. It provides a detailed description of curtain wall history, contemporary constructions, aluminium and glass material production and properties and sun regulation mechanisms as well as building physics. It is written from the perspective of a façade builder and therefore provides more in depth knowledge as the typical teaching material for architects. Chapter 9 shows project examples with a trend from passive towards active regulated façade concepts. A small section is dedicated to the organisation of the façade design and construction process, based on the phases of the Dutch legal relationships between architects and clients (BNA, 2004) (See also chapter 3 of this dissertation). While the focus of this interesting book lies on the description of the state of the art, it does not question what influence the process organisation has on the way we construct façades today.

Jellema hogere bouwkunde 4B. Bouwtechniek omhulling gevels (Rentier et al., 2005)
The book is part of the ´Jellema Hogere Bouwkunde series´. Purpose of the series is to deliver basis knowledge for higher and scientific education in the fields technology,

building methods and building process. Architectural design and history is not a dedicated part of the book.
It gives a relatively detailed description of curtain walling typologies and construction, and explains general building physical issues as well as jointing and assembly methods. The book gives three typical examples of "active façades" where the curtain wall is part of the climate regulating installations. The integration of building services into the façade is not explicitly mentioned. The book delivers a good background on how façades are constructed and how different components are typically attached to each other. However, is does not mention aspects such as the reason why construction has developed the way it has, decision making procedures and the involvement of different stakeholders.

Modern Construction: Facades (Watts, 2005)
The beginning of the book provides a summary of the cooperation of system supplier, manufacturer and builder as well as the implication it has for architectural design. Façades are subdivided into the materials metal, glass, brick, plastics and wood. Curtain walls are explained in the chapter about glass. The strategy of the book is to explain façade construction by describing general details in combination with an analysis of selected realized projects. Watts states that he describes many common technologies, but that an extensive and complete evaluation is not possible because building construction is subjected to constant change and development.

Façades. Principles of Construction (Knaack et al., 2007)
The book demonstrates the principles of façade construction and provides guidelines for appropriate application and detailing. It systematically describes the most common types and lays a link to future developments such as building services integration. It also talks about the meaning of different materials for construction in detail.

Guideline for design and execution of window and door assembly[4] (RAL, 2006)
This guideline is issued by the RAL Gütegemeinschaft. The goal of this independent organisation of producers and service providers is customer protection on many levels. It issues the RAL seal of quality to builders and system suppliers that follow these quality standards. The organisation publishes best practice standards directed at planners and builders.
The guideline referred to here explains the basics of the execution of window and façade joints and connections to the building as well as applicable norms and regulations. It is widely acknowledged in Germany, and gives many practical detail

4 Original title: ´Leitfaden zur Planung und Ausführung der Montage von Fenstern und Haustüren´

examples. It reflects the German standard; thus, market compatibility is embedded. It critically discusses whether the explained regulations necessarily reflect best practice solutions but the effect of the details on the structure of the building market is not questioned.

Guidlelines for aluminum constructors[5] (ALCB, 2010)
The European Building Directive (CPD) regulates the safety and technical requirements of all products used in construction works in the EU. This directive is responsible for the definition of Eurocodes such as DIN EN 13830 for curtain walls and the clear terms for access to CE marking.
The book referred to here contains the Belgium national translation of the codes; it is updated annually.
It is coordinated by the Aluminium Center Belgie and distributed to extruders, system builders, façade builders, coating companies and glass producers. This book is exemplary for similar publications for different countries within Europe. It gives detailed information about all legal requirements that a façade construction has to meet; and therefore is a crucial tool for developing façade related products or façade applications. It does not provide answers on how exactly the requirements can be translated into constructions.

§ 4.2.2 Construction theory in other disciplines

The following books and papers are related to the field of product development. Even though not explicitly directed at building technology (except the first one by Mick Eekhout), they can be applied to this discipline, because particularly the field of façade construction with its high level of industrialisation belongs to both disciplines.

Methodology for product development in architecture (Eekhout, 2008)
The book is directed at product designers in the field of building technology as well as architects. In the first part of the book, Eekhout develops a terminology for building products concerning different aspects. Firstly, according to the product environment, meaning the level between on-site production and industrialisation. Secondly, according to product type such as standard product (brick) or system product (window frame) or building system. Finally, he introduces a hierarchical range of

5 Richtlijnen voor de aluminium constructeur (Free translation by the author)

industrial building products according to the level within the construction, starting with raw materials via components to the building level. In the second part of the book, methodologies for the design of building products are developed. The theory is useful for this research, and is partially applied in the next chapters to analyse the construction of curtain walls.

The role of product architecture in the manufacturing firm (Ulrich, 1993)
The paper collects knowledge from different research communities such as those dealing with design theory, software engineering, operations management and product development. Ulrich describes product architecture as a "scheme by which the function of a product is allocated to physical components". He argues that the way in which components are arranged and connected is of great importance to the behaviour of a product on the market, and therefore is important for the decision making of manufacturing firms. Ulrich illustrates this content with many practical examples. Product architecture is not widely use in the field of building construction but it is the author's opinion that it offers a valuable vocabulary to analyse façade construction as it relates to the implication on the structure of the building market. More detailed information about product architecture is provided later in this thesis.

Technology Diffusion in Product Design (Poelman, 2005)
Technology is a crucial part of industrial design engineering. This book aims at developing a conscious approach of systematically integrating new technologies in the design process.
"The study tries to uncover the mechanism in the relationship between industrial design engineering and technology issues. Besides that the study tries to present models, methods and tools to improve the diffusion of technology in industrial design engineering". Although from a historic point of view, curtain walls actually belong to the field of building construction, are applied by architects and developed by building specialists, there are a lot of similarities to the field of industrial design. Poelman gives a very interesting summary of types of product functions than can be utilised for this research. Although he aims at developing new products, his work is well suited for analysis purposes.

Produktontwerpen, structuur en methoden (Roozenburg and Eekels, 1991)
The design of new products is a very complex matter that has to be oriented toward the market, technical functioning, design, costs and the effect on the environment. The book focuses on the methodology of this process. It is very useful to understand the nature of product development; and for this research in particular, the explanatory context between design problems, developing product functions, requirements, and design criteria.

Engineering design methods: strategies for product design (Cross, 2008)
This educational book focuses on the design of products that have an engineering context, and is therefore of interest for the field of façade design. It introduces design theory in general and how the design process is executed. It also highlights the context of design management. The book encompasses an array of general objectives down to the detailed design.

§ 4.2.3 Conclusion of the literature study

The researched literature discusses various aspects of the construction of curtain walls. This relates to construction typologies, structural principles, building physical requirements, applied norms and regulations and, in some of the examples, the role of curtain walls as building services components. Several books also extensively discuss the architectural development and significance of curtain walls.
It is interesting that at no point a connection is made between the construction and the structure of the façade design and construction process. Only Watts generally explains the implications of the relationship between architect, system supplier/ manufacturer and builder. One can find explanations about the role of different components and how they are assembled, e.g. how glass panes are produced and how they are mounted, how often joints have to occur in mullions; but the question of how these constructional strategies correspond to the previously analysed process structure remains unanswered, for example which detail corresponds to the fragmented market and which one to different steps in curtain walling design: system design, architectural design or execution design.
There are several reasons for this. The book Jellema 10, bouwproces-ontwerpen puts it into one sentence: "A building is made in a complete different way than any other commodity. It is mostly designed for a specific use and investment is made at a moment when it is still unclear if the target within the given border conditions is reachable." [6]
A crucial point is touched by adverting to the inverted approach as it compares to other disciplines. If I buy a car, I know what I will get. When an individual building has to be realised in a rather short amount of time, the designers have to rely on proven methods

6 Free translation by the author. Original: ´Een gebouw komt op geheel andere wijze tot stand dan welk ander gebruiksvoorwerp dan ook. Het wordt meestal specifiek voor het gebruiksdoel ontwikkeld en er moet al in worden geïnvesteerd op een moment dat het nog volstrekt onzeker is of het einddoel, binnen de gestelde randvoorwaarden, haalbaar is.´

to a certain degree. Deplazes, for example, sees building constructional principles as tools that in combination with the design process can be arranged into a holistic architectonic body. And basically there are endless possibilities to create a building. Buildings (and façades) are individual constructions with an architectonic message. Cars are mass products.

At this point it should be allowed to cite Vitruvius (Vitruvius, 1960), who in the first century B.C. wrote the first book about architecture known to us. Vitruvius gives a rather comprehensive explanation about what it means if buildings are designed for a specific use: "Buildings must be built with due reference to durability, convenience, and beauty." He describes durability as "…material wisely and liberally selected". This could be liberally translated as a reference to building construction. Convenience can be interpreted as a faultless function with regards to the desired purpose of the building and with beauty he refers to the metaphysical or artistic aspects of architecture.

This means that building construction is only one of the aspects that have to be touched upon in architecture. Architecture is much more than construction alone and is important to understand the self-conception of architecture as a discipline and consequentially the nature of its educational material as analysed above.

Over the centuries, building technology has developed incrementally. Literature on building construction can be seen as an attempt to deliver an overview over the existing strategies, which obviously is a gigantic task in itself. The requirements, norms and regulations alone that have to be adhered to when designing a building (or a façade) are frightening. In this context, teaching material does not consider rethinking the inherited ways of building or even the creation of new technologies a task for architects. In contrast, other disciplines such as product development offer a deeper understanding of the relationship between construction and market. The theory of product architecture explicitly discusses this relation. In addition, the literature analysis shows that functions are essential in understanding construction. In fact, the purpose of construction is a way of fulfilling one or more functions. The following subsections discuss the meaning of product architecture and the role of façade functions at a deeper level, which will then help to define a vocabulary for the constructional façade analysis.

§ 4.3 The meaning of product architecture

Ulrich's paper - briefly introduced above - supplies a valuable vocabulary for the purpose of this research. In order to clarify the significance that product architecture can have; specifically for the construction of façades, the paper is discussed and rendered in more depth. This section was supported by the graduation work of Joep Hoevels (Hoevels, 2007).

§ 4.3.1 Introduction

One aspect that all constructions have in common is a functional structure that is represented by physical components. These components are connected by interfaces, which themselves can be physical elements or just a description of a certain way of interaction. Each construction has its own architecture. Ulrich (Ulrich, 1993) describes product architecture as the scheme by which the function of a product is allocated to physical components. More precisely he describes it as:

- The arrangement of functional elements
- The mapping from functional elements to physical components
- The specification of the interfaces among interacting physical components

Product architecture is closely linked to areas of managerial importance such as product change, product variety, component standardisation, product performance and product development management.
These are all issues we have to address when discussing façade products. The field of building technology does not explicitly consider product architecture as a strategic approach. It rather relies on steps of an incremental evolution as described above. Here lies the chance to create new insights into how façade construction is interlinked with the building market.

§ 4.3.2 Functional elements, modularity and integration

The functional structure of a product describes the functional elements and their relationships. These functional elements are represented by a physical component and these are interconnected by interfaces.
Basically, product architecture can be modular or integral. These two extreme types of product architecture have different interfaces: integral product architecture consists of complex mapping from functional elements to physical components. Modular product architecture consists of one-to-one mapping; meaning that there is a one-to-one relationship between functional elements[7] and physical components.

7 Ulrich uses the term ´functional element´. In other analysed literature, the term function is used instead.

The following examples illustrate these types of mappings. To simplify the issue, a computer is used as an exemplary product. It is reduced to four functional elements:

- Display content visually (we need to understand what the computer is doing)
- Communicate manually (to interaction with it)
- Enter information (text, for example)
- Process data (the actual calculation machine)

A desktop computer displays one-to-one mapping. For every functional element we have certain components: Monitor screen, mouse, keyboard, and tower. A laptop computer combines all functional elements in one component: A many-to-one mapping. The component is multifunctional.

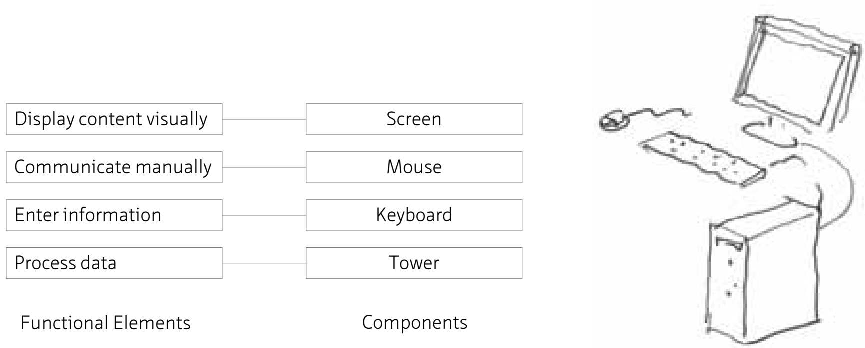


Figure 32
Function structure of a desktop computer: One-to-one mapping, modular architecture

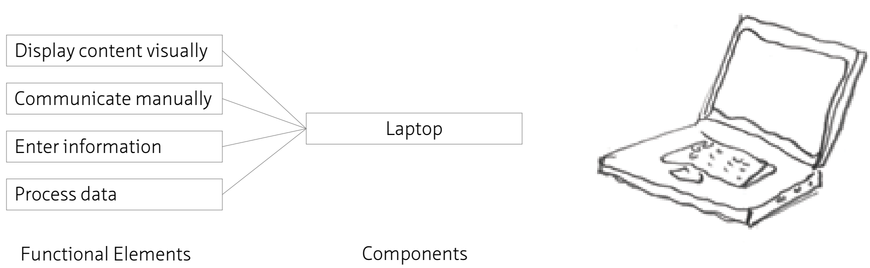


Figure 33
Function structure of a laptop: Many-to-one mapping, integral architecture

From experience, we know the implications. The desktop computer is large, but it allows for a greater choice of peripheral equipment. One can opt for a bigger screen or special keyboard. The tower can easily be upgraded with extra memory and hard discs. The laptop is lightweight and transportable, but it cannot as easily be adapted by the user.
Most products exhibit a combination of the characteristics, depending on the level of the overall system or the level of components or individual parts. The computer screen itself has an integral architecture, whereas the stand might be connected in a modular way and could serve also for other models with larger screen sizes. At a later stage, it will be necessary to define the different system levels for curtain wall constructions.
The implications of a modular or integral architecture are further specified in the following paragraphs. In chapter 6, façade constructions will be analysed in terms of this sort of interconnection between different components.

§ 4.3.3 Different interface typologies

Besides one-to-one mapping, the interface of modular architecture has another distinctive property in comparison to 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 components, a change to the other component is required in order for the overall product to work correctly. This can be illustrated by the example of the laptop above. If the manufacturer decides to equip the laptop with a larger keyboard, the casing will have to be adapted as well and the location of the DVD drive might also have to change. This example clearly illustrates that the type of product architecture used can have serious implications for the development possibilities of a product.
Not all functional elements have physical connections to other components. In software engineering, interfaces come in the form of protocols. Peripheral hardware can interact via a Bluetooth.

§ 4.3.4 Types of modular architecture

Ulrich differentiates between 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 organised.

Slot

Good examples of this type of modular interface are the connections of mouse, keyboard and printer (PS/2 and LPT) that have formerly been used. Every peripheral component had its distinctive connection. Another example is the car radio. In former times, car radios could be interchanged from car to car in the mutual interest of the radio and automotive industries. The car owner was able to select any device that met his or her particular requirements. Today, although a slot architecture is still used; often the dashboard design only allows brand conform devices.

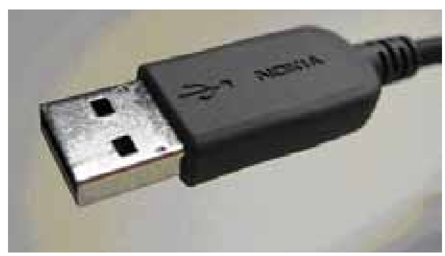


Figure 34
Slot architecture: Car radio

Figure 35
Bus architecture: USB – Universal Serial Bus

Bus

The characteristic of bus architecture is one element - a bus - to which all other components connect. An example of bus architecture is the USB – Universal Serial Bus. All peripheral computer devices such as hard drive, mouse, keyboard and printer use the same interface to connect to the computer. They can easily be exchanged.

Sectional

An example for sectional architecture is kitchen components. With a standard size they can be placed next to each other in any order, according to the needs of the individual kitchen layout. Also the notch and groove of the Lego blocks have a sectional architecture by which they can be connected to each other.

Figure 36
Sectional architecture – Lego bricks.

In most cases, the choice will not be between an entirely modular or entirely 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. The choice for certain product architectures has an influence on the material side and the immaterial side of a product. The design of an integrated product requires a different design strategy with a much closer collaboration of all involved parties, whereas modular architecture needs a better management of the systems and their interfaces.

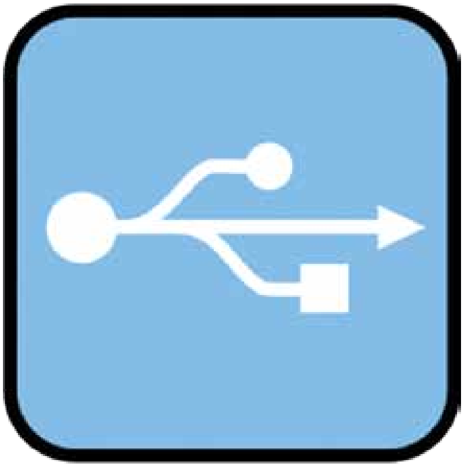
Side note

The USB Story

The development of the USB (Universal Serial Bus) tells a good story about the implications of interfaces typologies for the computer hardware industry in terms of product change, upgrade and standardisation. It was introduced to the computer market in 1996 by Intel. The goal was to replace all the different distinct slot interfaces in use at that time, such as the PS1/2 interfaces for computer mice and keyboards or the LPT interface for printers. Now it was possible to connect all different external devices to the computer by using a single element (bus).

Back than the USB was competing with the FireWire interface, developed by Apple. Although FireWire was initially faster, USB finally became the industry standard, when Apple switched to USB with the development of the iMAC. In 2000, USB2 was launched with a much higher data transfer rate and the connection of external hard drives and video devices was possible. Since 2008, USB 3.0 is available but it is still compatible with the older versions. Today USB dominates the market. The transition period equalled a revolution. For example, the old generation of LPT1 interface printers could no longer be connected to the newer generation of computers and were rendered useless.

The development of the USB plug is also of interest. From the early types A and B many different standardised and non standardised versions have evolved. The USB consortium tries to control the uncontrolled development. The USB also led to a development of many products such as USB powered lamps, vacuum cleaners and ventilators.The absolute dominance of the USB contributes to the compatibility of hardware products but at the same time prevents the introduction of new interface typologies to the market.



§ 4.3.5 The effect of different product architectures

Product architecture also delivers a range of arguments, showing the far reaching impact of design choices on the physical construction and on the managerial side of the process. The arguments can be divided into several major topics:

Product change

The architecture of a product determines how a product can be modified. If a component of the product is changed, it depends on the interface of the product whether other components need to be changed as well. Fully modular products could allow components to be changed without changing other elements. On the other hand, components of fully integral products cannot be changed without changing other components.

Ulrich's paper defines different types of modification 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 base unit. Those components are either produced by the same company as the base unit, or by a third party. The iPhone, for example, has an extensive list of add-ons, such as casings and external GPS modules.
- Adaptation: When a product needs to be used in a different environment, it can 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. Tires on vehicles are a good example for this type of change.
- Consumption: The difference of consumption and wear is that consumption is a typical goal of the product, while wear is not desirable. Examples of consumption are cartridges for printers and copiers, and film cartridges for cameras.
- Flexibility in use: Some products can be changed during use, in order to exhibit different capabilities. An example is a camera that can be used with different types of lenses.

Modular architecture of products allows for such changes. It is important to define local areas where a potential change is desired or necessary. Another strategy is to dramatically lower the cost of the product or subcomponent. One-way cameras have an integral architecture and are discarded after the film is exposed. Recycling would be an appropriate option with an integral architecture, such that the entire product can be discarded or recycled.

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.
Variety can be produced using two different strategies:

- Component process flexibility
  Process flexibility is achieved by flexible process equipment such as tooling machinery. Here, tooling costs and set-up times are determining factors. Rapid manufacturing, for example, principally offers endless variety opportunities. The variety is introduced by changing the input data. The costs are rather high at this moment, but once the 3D printer is bought they only depend on the time and material used, and not on the product properties.
- Product architecture
  With modular architecture, variety can be introduced without changing the process. What is needed is a certain flexibility in the in the final assembly process.

Standardisation

The definition of standardisation given by Ulrich is that component standardisation is the use of the same component in multiple products. Modular architecture increases the possibility of standardisation. If a product is being created with a one-to-one mapping, it can potentially be used in other products or product applications, both in a single firm and across multiple firms. An interface standard for different products can be adopted, and the same component can be used in a variety of settings.
Typically, standard components mean lower costs. The reason is a higher production volume. And the performance can improve due to learning processes and improvement of knowledge. No development is needed, when applying proven standard components, and potential uncertainties, lead times and control effort can be reduced. A disadvantage can be higher unit costs in comparison to special components if a larger capacity is chosen than needed for the particular application. Casings can be made bigger to allow more potential variety. Another risk of basing a product platform on standard components is that potential further development is blocked and potentially better technologies cannot be ,applied.

Performance

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

Often product performance is related to size, weight and shape of a product. There are two common strategies to achieve optimisation in these fields: Function sharing and geometric nesting. The above described laptop follows the strategy of function sharing by eliminating redundant casings and other components in order to be transportable. Function nesting means a dense geometric packing of the components. Often, this is can only be achieved by function integration. The size and weight is an important product characteristic of mobile telephones. Minimising weight and size is a way to reduce material and transportation costs as well.
Another distinction made is local and global performance. The tire of a car (itself a highly integral product) is connected with a modular interface in order to allow it being changed easily. Here, Ulrich talks about a local performance, meaning a performance that is designated to a defined part, component or group of components. A modular standard component, for example, can also be responsible for a good local performance, if technical advancement can be exploited. But if it comes to questions of global performance, like the use of car fuel or passenger safety, an integral architecture is necessary. To absorb the shock of a car crash, the body of the car needs to be strengthened. This will have an impact on the design of the interior, and perhaps on the location of the engine. Maximum security will depend on the collaboration of all parts and their connections.

Product development management

Product development processes can be viewed as consisting of four phases:

- Concept development: this phase is the same for modular and integral architecture. Performance targets are set, technical working principles are chosen, desired features and variety are specified and, finally, an architectural approach is to be chosen.
- System-level design: for modular architecture this phase means the design of the component interface. For each component, the requirements and functional performances need to be determined. The component design could be done by different specialists for each component.
  For integral architecture this phase focuses more on the specification of the performance level of the overall system, and on dividing the system into a relatively small number of subsystems.
- Detailed design: for modular architecture this phase means the detailed design of each component. This can be done simultaneously in separate teams. Testing of the components can be done independently.
  For integral architecture this phase means the detailed design of the product as a whole. The designers all form teams and interact continuously in order to analyse the performance of the subsystems. Testing must be done on subsystems or on the whole system.

- Product testing and refinement: for modular architecture testing is to check whether there are any unforeseen undesirable interactions between components. For integral architecture this phase means fine-tuning. If however, the product needs to be changed in some way, it is likely that this is done on many parts of the product. Therefore, for integral architecture this phase is likely to cost more time than for the modular product.

The choice for either a modular or an integral approach of the product depends on several organisational issues. Highly modular designs allow firms to divide their development and production organisations into specialised groups with a narrow focus.

§ 4.3.6 Different product levels of façades

As mentioned above, the characteristic in terms of product architecture depends on the level of the components that make up the overall system. (A laptop has an integral architecture in terms of its overall system, but might display a modular architecture on a more detail level.) It is therefore important to determine the different typical levels of façade products before turning to the next chapter.

Eekhout (Eekhout, 2008) has defined a hierarchical range of industrial building products (Figure 37) that is suitable for the purpose of the research. The range starts with ´raw materials´ and ends with ´building complex´. A closer description of the different steps within the range and the product treatment is given, when changing between them. For example, the change from raw material (clay) to material (brick) needs refining. The change from building part (wall) to building segment (part of complete building) needs joining. Product development encompasses the range from sub-element to building segment.

Eekhouts´ range is generally made for all building products. The author has slightly simplified it to adapt it to the field of façades (Figure 37). Since a ´range´ describes a set of items with a defined lowest and highest boundary, the different steps in the range are called ´product levels´ from hereon out. The following product levels were classified:

- Materials are defined as the base ingredients without any further shaping or treatment such as glass or steel. Composite materials are also included.
- Standard materials are so-called intermediate goods, available in standardised form: Examples are I-beams, tubes, coils, bricks.
- A commercial material is shaped for the purpose of a special product or project, such as extruded aluminium profiles for window frames or rubber gaskets designed for a specific purpose.

- Elements are assembled from different commercial materials. An insulated glass unit is made of glass panes, aluminium spacers and silicone.
- A sub-component is a closed assembly of elements with single functional purpose, e.g. window frame, sun-shading device, building services component.
- Components are described by Eekhout as an "independent functioning building unit....built up from a number of composing elements". It is assembled "off-site and transported to the site". A unitised façade part is an example.
- A building part is defined as a collection of elements and components with identical technical main function, meaning a curtain wall or the primary load-bearing structure of the building.
- Building needs no further explanation.

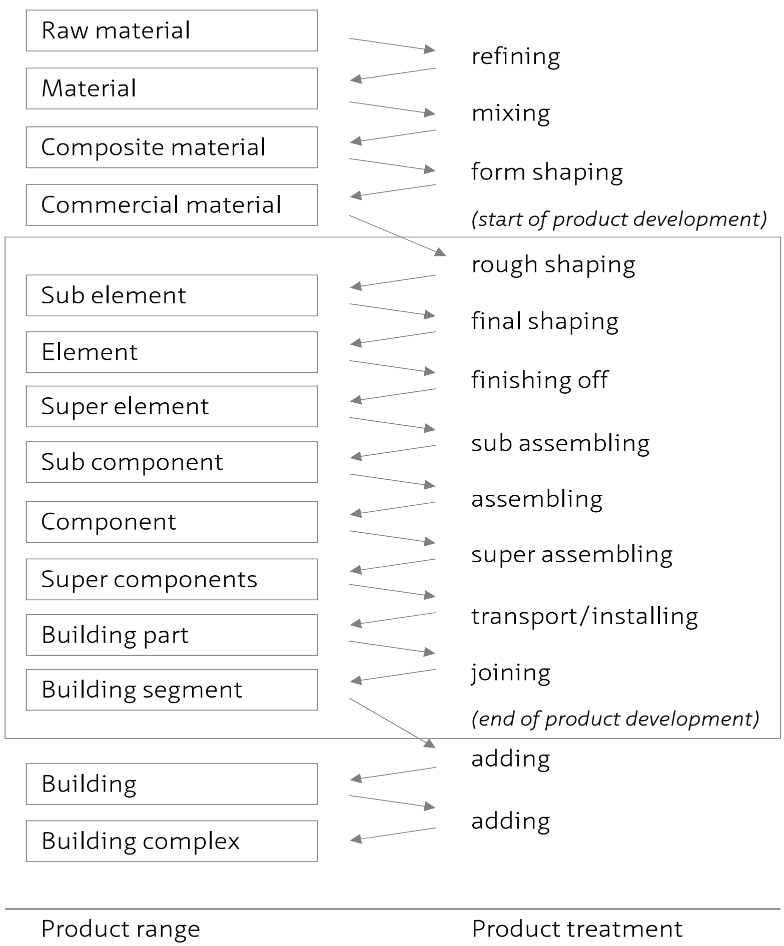


Figure 37

Hierarchical range of building products according to Eekhout

Product level	Example
Material	Aluminium/ steel/ glass
Standard material	Standardised I-beam/ Silicone
Commercial material	Extruded profile/ glass plate/ rubber gasket
Element	Window frame profile/ insulated glass unit
Sub component	Window/ sun-shading device
Component	Unitized façade piece
Building part	Curtain wall
Building	Building

Figure 38
Product levels for facades

The boundaries of the individual level can overlap. The following chapter analyses different curtain walls using the scheme of product levels.

§ 4.3.7 Summary

Ulrich's paper collects knowledge from different research communities such as design theory, software engineering, operations management and product development. He argues that the way in which components are arranged and connected is of great importance to the behaviour of a product on the market and therefore for the decision making of manufacturing firms in terms of product development. Ulrich's findings deliver the following vocabulary:

- All products consist of function elements that are represented by physical components. Their product architecture can be modular or integral with either a one-to-one or a one-to-many relationship between function elements and physical components. A function structure can be used to illustrate that relation.
- Different interface typologies are defined: Integral architecture has coupled interfaces. There are three types of de-coupled interfaces, called modular architecture: Slot, bus and sectional.
- The importance of the choice of product architecture for the following areas has been pointed out: Product change, variety, standardisation, product development management, and product performance.

- A modular architecture can enhance certain performance attributes by using standard components. Function sharing and geometric nesting are typical strategies for integral architecture; especially for reducing size, weight and shape.
- The local performance of a product can be improved by using a modular architecture. The improvement of global performance requires an integral approach.

Furthermore, it becomes clear that this vocabulary can be applied for different levels of a product. Based on Eekhout´s hierarchical range of building products, different product levels for curtain walls are defined starting with materials on the highest level at the beginning of the processing sequence and ending with a finished building:

- Materials
- Standard materials
- Commercial materials
- Elements
- Sub-components
- Components
- Building parts
- Building

Coming back to the goal of this chapter: In order to analyse façade construction, the idea is to conduct an inverted approach. Instead of using the vocabulary to design façades or façade related products, we can use it to analyse and understand in which way the different components of a façade construction are interconnected, and ultimately how it relates to the design and construction process.

§ 4.4 The role of function in construction

In order to understand façade construction, a detailed picture of the objectives a façade is actually built for needs to be sketched. Cross (Cross, 2008) describes the ´Objectives Tree Method´ as a ´brief´ for a design problem. Objective trees are also called ´function trees´. They basically are a list of desired product functions on general and more detailed levels. Whereas in the field of product design, a function tree is generated in order to set the foundation to create a new product, the goal of this part is to develop a more or less complete tree of façade functions that can serve for the analysis of façade construction in chapter 6.
This can be done by drawing function structures as described by Ulrich.
The above analysed literature gives examples of how functions are defined and how they can be categorised.

§ 4.4.1 Function as defined in the field of product design

Eekels describes function as follows: “The function of a product is the intentioned and conscious attached ability to transform the material environment of the product”. Thus the function says something about the desired behaviour of a product.
Simplified, Eekels and Cross as well as others describe functions in form of a ‘black box’. It contains all the functions that are necessary for converting the inputs into the outputs.

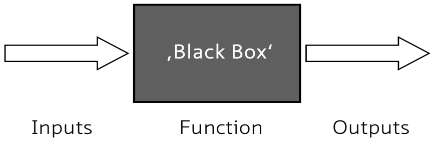


Figure 39
´Black box’ system model according to Cross

In contrast to a property that a product has independently from the goal of the user, functions can be described as requirements that a product has to fulfil.
In this context, Poelman introduces the term ‘functionalities’ to describe function. “A functionality is defined as ´something´ that a technology can perform. ...a function is defined as a set of functionalities which are deployed for some objective (Function = functionalities + objective)”. An example to illustrate the formula: A façade function would be supplying the interior of the building with fresh air (ventilation). An operable window is a functionality that could be used for this purpose. (Ventilation = operable window for the purpose to let air penetrate the building envelope). The function could also be fulfilled by different façade functionalities with the same objective (e.g. mechanical ventilation unit) and the operable window can be used for different objectives such as window cleaning.
Poelman has designed a method for defining functionalities - properties that can be used to fulfil a product function. It is an extensive procedure involving several steps with assignments and simulations. Applying it to the purpose of this chapter (the analysis of façade functions) would go beyond the scope of this work. Nevertheless, Poelman has categorised types of product functions that are very useful for the purpose of this dissertation:

- Primary and secondary functions
- Primary functions and support functions
- Positive and negative functions
- Functions meant for different users
- Technical and emotional functions

Secondary functions are applications of a product other than the primary function. For example, an umbrella does not only protect against rain but could also be used to defend oneself against attacking dogs. Support functions enable the primary function: An umbrella needs a handle to be carried around.
In addition to the intended end user, others usually have to cope with a product as well; such as manufacturers, transporters, retailers, recyclers and others. This can have a big influence on the product itself, for example on packaging. It is interesting that the literature on façades does not pay much attention to the end user (primary user). The end user is seen as an observer of architecture, or a user of the space behind the façade where he or she can expect a defined climate and change sun-shading settings or open windows. More attention is paid to the builder (building process), investor (costs) or the architect who is interested in the design possibilities and minimising of failures.
Every product has negative side effects. A negative function, for example of a car is the use of energy with its bad effect on our environment. It is therefore necessary to pay attention to these types of functions. The fuel consumption of cars today has become a primary decision factor for many end users. Negative functions in the field of façades are equally inevitable. A sun-shading device can block the view considerably, and reduce the ability to exploit day light. Whereas climate designers embrace sun shading systems, architects are usually very sensitive about the way they affect the design.
Technical (objective) and emotional (subjective) functions require thorough attention. The way in which a product fulfils its technical function can be measured. This is more difficult with emotional functions since they depend on the subjective perception of the user. Personal mental experience has a large influence. A product can perform well technically, but still might not be generally appreciated. Virtually every product includes some degree of technical and emotional functions. Poelman gives good examples to illustrate this point. Ball bearings, for example, must primarily fulfil technical functions. A car, on the other hand, needs to satisfy both technical and emotional functions, since its market success depends on technical quality as well as on image, beauty etc. Jewellery primarily satisfies emotional functions. In the context of façade construction emotional values are mostly achieved by architectural design.

§ 4.4.2 Function in façade related literature

Examining façade related literature in terms of the above categorised types of functions from the field of product design proved interesting:

In the book ´Façades` (Knaack et al., 2007), functions are described as different requirements a façade needs to fulfil. No further separation into the above mentioned function types are made. The following functions are mentioned without a hierarchical order:

- Insulation against heat, cold and noise,
- waterproofing
- providing natural light for the interior,
- protection against light,
- resistance against wind loads, interior loads and self-weight,
- vapour management,
- visual contact to outside and inside
- architectural appearance.

All these different kinds of functions are named on the same level. For optimal functioning, the façade should thus not be a static construction but change in response to influencing factors. Therefore, adaptability should also be included in the list of functions.

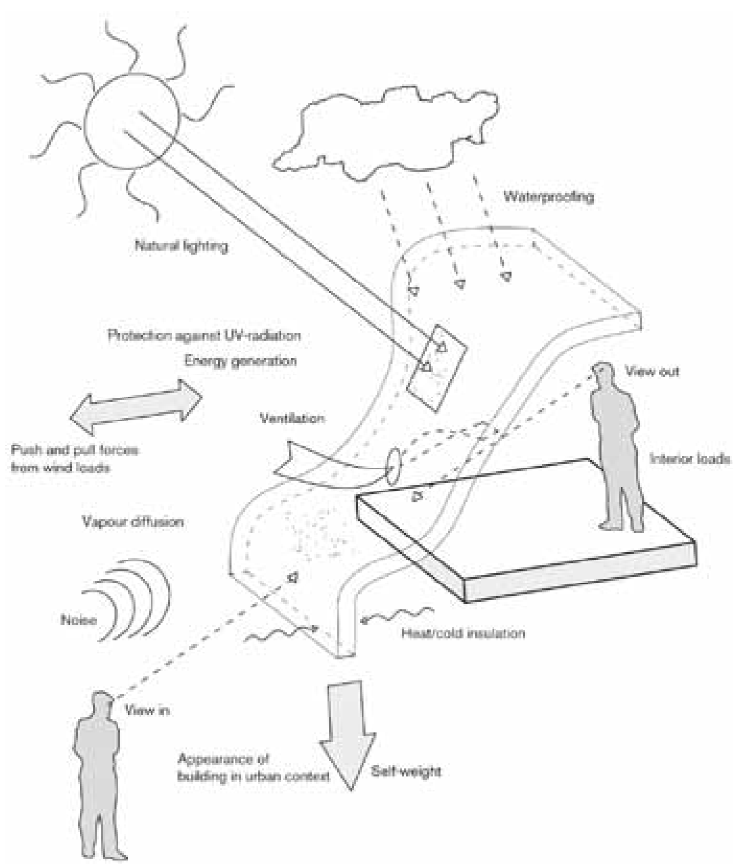


Figure 40
Requirements on façades according to Knaack

Rentier, in his book, divides functionality into primary function (separating the interior from the influences of the outside - rain, wind, heat, cold, noise, and burglary, etc. -) and secondary function which provides information about the function or the owner of the building and could be translated with architectural intention of the façade. It is interesting that the book emphasises technical functionalities. This attitude can be explained with the technical background of the book. An architect would typically choose the opposite order by emphasising emotional functions (architectural design).

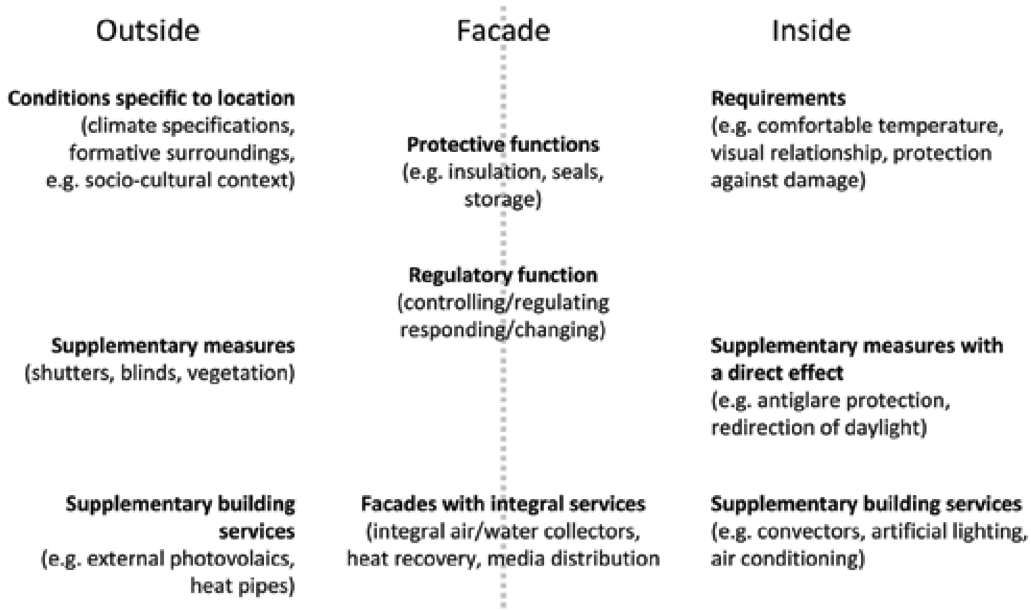


Figure 41

Requirements on façades according to Herzog (Herzog et al., 2004) The scheme is reproduced in a shortened way.

The ´Façade Construction Manual´ gives an interesting representation of façade functions.
The overall façade function is defined as follows: "The façade is a separating and filtering layer between outside and inside, between nature and interior spaces occupied by people". A graphical scheme is chosen that includes the outside and inside of the building as well as the façade as separating component. The requirements of the inside (this corresponds to the actual façade functions according to Poelmans concept) result from external conditions that are specific to the location. To fulfil the requirements, Herzog gives the façade protective and regulatory functions (passive or active constructions). In the above discussed context the term functionalities would be more appropriate.

Supplementary measures such as sun-shading devices or blinds on the inside or outside can enhance façade functionality. It is interesting that the author also includes building services as supplementary measures if the façade alone cannot deal with the outside conditions. These can also be located outside, in the interior, or on the inside of the physical façade construction.

Herzog also makes a first step to lay the link between aspects of the façade and its geometry. Aspects are points of consideration. For him "Façades are primarily vertical and planar .... structures positioned between the external and internal environment". But still, the third dimension of the façade still serves special purposes. He writes:

"Aspects to be considered in the plane of the façade:

- type of surface
- allocation of performance profiles
- load bearing ability
- design principle
- jointing

Aspects to be considered perpendicular to the plane of the façade

- realisation of the performance profiles
- construction in terms of layers and leaves
- joining of layers and leaves"

The term ´performance profiles´ is not further defined. It could be interpreted as follows: the decision of where façade functions should be located is made in the plane, and the realisation of the desired functionality happens perpendicular to this. For example the level of insulation: It is located planar, but its performance depends on the third dimension; the rule is the thicker the better. The construction façade needs joining in three dimensions.

§ 4.4.3 Summary

Functions are essential when analysing or developing products, or in this case curtain wall constructions. Literature in the field of building technology provides us with a basic list of potential façade functions. However, the behaviour of a product on the market is determined by the way parts, components and elements are arranged and connected, and more detailed understanding of façade functions is required to develop a function structure, for example. The field of product design discusses functions more in-depth.

In this research, the theory about functions is only presented briefly, but it provides a valuable vocabulary:

- A function is defined as a ´black box´ converting the inputs into outputs.
- Poelman specifies this: A function is defined as a "set of functionalities which are deployed for some objective (function = functionalities + objective)".

Poelman further defines different types of functions:

- *Primary, secondary and supporting functions*.
  This can be explained with façade construction terms: If the creation of a durable construction is the primary function, one of the secondary functions is enabling water and vapour management within the construction. This is supported by the function of allowing an interior drainage system.
- *Positive and negative functions*.
  Whereas a positive façade function can be the reduction of heating energy demand, a negative function is that a façade will have to be disassembled, recycled or put on the landfill at the end of its lifetime.
- *Functions meant for different users.*
  It is clear that certain parts of a construction will always be dedicated to enable an efficient construction process - a function that does not concern the end user of the building.
- *Technical and emotional functions.*
  A technical function can be measured, such as the insulation of a façade; whereas emotional functions are represented by architectural design or haptic qualities.

The role of different function types becomes clear. When analysing (and developing) façade construction, one should be able to allocate certain components to the function types as mentioned above. To clearly understand or improve a construction, we need to be aware which parts, components and elements are related to the builder or the user of a façade; and which relate to technical or architectural functions

Side note

Sony Walkman – Design variety through modular components

The Sony Walkman was the first portable audio device on a small scale for everyday use. It was introduced to the public in 1979 and featured many new functionalities such as stereophonic sound and lightweight headphones with soft foam instead of the old earmuff like versions. It introduced the Japanese high tech culture into the daily world. One main component of the Walkman advertising campaign was personalisation of the device. Potential buyers had the opportunity to choose their perfect match in terms of mobile listening technology. The sales strategy was so successful that the Walkman became synonymous with ´headphone stereo´ and shortly after was listed in well-known dictionaries.
In 1995 the production reached 150 million. Over 300 different models were produced.
The concept incorporated the idea of a changeable casing. This allowed the product to regularly adapt to a new design for the market without changing the main technical components. The Walkman example demonstrates the importance of modular product components, when it comes to design variety and product upgrade.

Sony Walkman throughout the years

GAY, P. et al (1997) Doing cultural studies - The story of the Sony Walkman, London Sage
SONY (2012) The Walkman. Available at: http://www.sony.net/SonyInfo/CorporateInfo/History/SonyHistory/2-06.html.

§ 4.4.4 Façade function tree

The façade function tree is organised in 5 categories with increasing level of detail: Main function, primary and secondary functions, supporting functions, and detailed supporting functions. Whereas the first three categories show a more general description of functions, supporting and detailed supporting functions are indications on how to solve the functional requirements.
It has to be noted here that this tree does not claim to be exhaustive. Especially when it comes to the more detailed categories, a different organisation and other/ additional functions might be useful. The function tree aims at providing an overview of the complex requirements a façade has to fulfil; it should serve as a basis for the constructional façade analysis in chapter 5.
The overall function is defined in a rather broad way according to Herzog: ´Separate and filter between nature and interior spaces´. Since the expectations on façades are multi-facetted, a number of primary functions are listed.
The list of primary functions refers to Vitruivius´ idea that a building must be built with due reference to durability (´durable construction´, ´...reasonable building methods´, ´...handling of sustainability´), convenience (´...comfortable interior climate´, ´... use of the building´) and beauty (´spatial formation of façade´). The functions are also chosen to accommodate different types of users. For example, to ´Provide a comfortable interior climate´ is directed at the end user of the building. The function ´Responsible handling in terms of sustainability´ is a societal concern and to ´Allow reasonable building methods´ is a primary function that is of interest for planners, builders and investors.
´Spatial formation of façade´ as a primary function in this context is meant as the overall goal of architectural design and refers to emotional values. It does not fully comply with the other four primary functions. The detailed supporting functions show which measures the designer has at hand to fulfil this primary function.
All these functions will have an impact on how a façade is constructed in detail.

The supporting functions enable primary and secondary functions, which show a more detailed listing. For example: ´Allowing the separation of components' enables `Reuse and recycling´ and therefore also a ´Responsible handling in terms of sustainability´. Detailed supporting functions are the deepest level of this function tree. From here on the connection to actual physical components which will fulfil certain functionalities can be made. They have a rather concrete character und might differ for different façade constructions. For example: ´Create internal drainage system´ is a function that applies to today's curtain walls, but might be something that future construction do not need. There is the danger that such a detailed description hinders potential development. Therefore, they are merely listed in an exemplary way.

The different functions might conflict with each other and must be weighted against each other. The building method such as an expensive free-form design can be justified for certain building types. ´Reasonable´, ´responsible´ or ´durable´ are relative terms that reflect this relation.
Adaptability is not considered as a primary function but as a supporting function to minimise the energy consumption during use, and to keep the climate within a given range.

In the graphic illustration, the tree splits up in one direction, but it becomes clear that some of the secondary functions can serve for several primary functions, such as ´Provide sun protection´ which is a function that can be used to reduce the energy demand of the building as well as ensure a comfortable interior climate.

As mentioned before, the detailed definition of supporting functions is the basis for thinking about physical components. There are several models that describe the process of executing this step. The methods of Cross (Cross, 2008), for example, incorporate the following steps:

- “Draw the system boundary that defines the functional limits of the product or device”. In façade terms one would speak of façade or subcomponent.
- “Draw a block diagram showing the interactions between subfunctions”. This is often called a function structure and means identifying the functional or geometrical ways the components could interact.
- “Search for appropriate components for performing the subfunctions and their interactions. Many alternative components may be capable of performing the identified functions.”
- Additionally, exact performance specifications will have to be determined, and Cross provides a method to achieve this.

However, showing function interactions and searching for appropriate components does not only a require thorough technical knowledge, but also knowledge about the behaviour of their functionality and connection to each other in terms of e.g. performance, standardisation, prefabrication, upgradeability or, in short, all arguments important for the development and market success of façades. Here lies the link to the theory of Product Architecture.

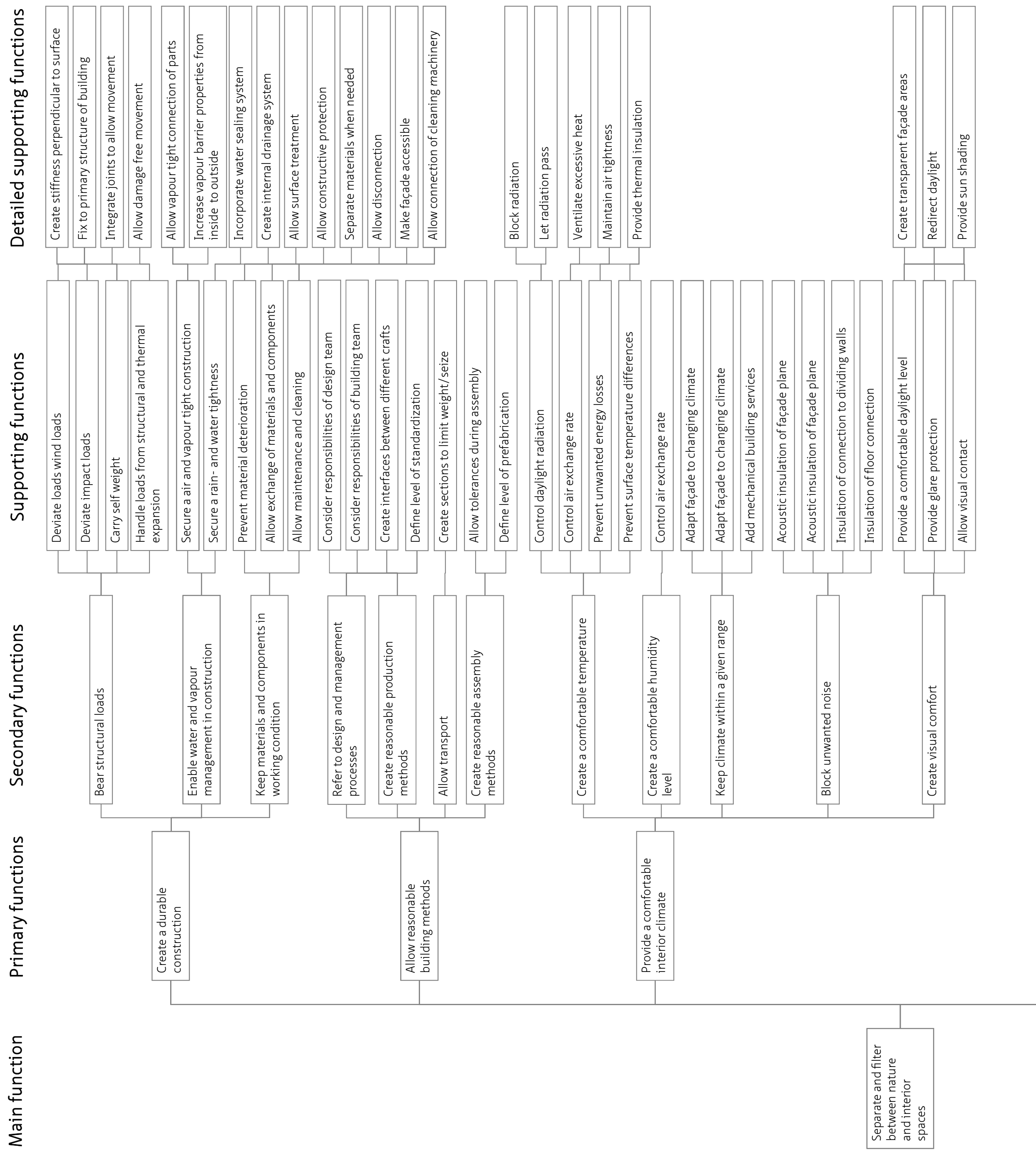
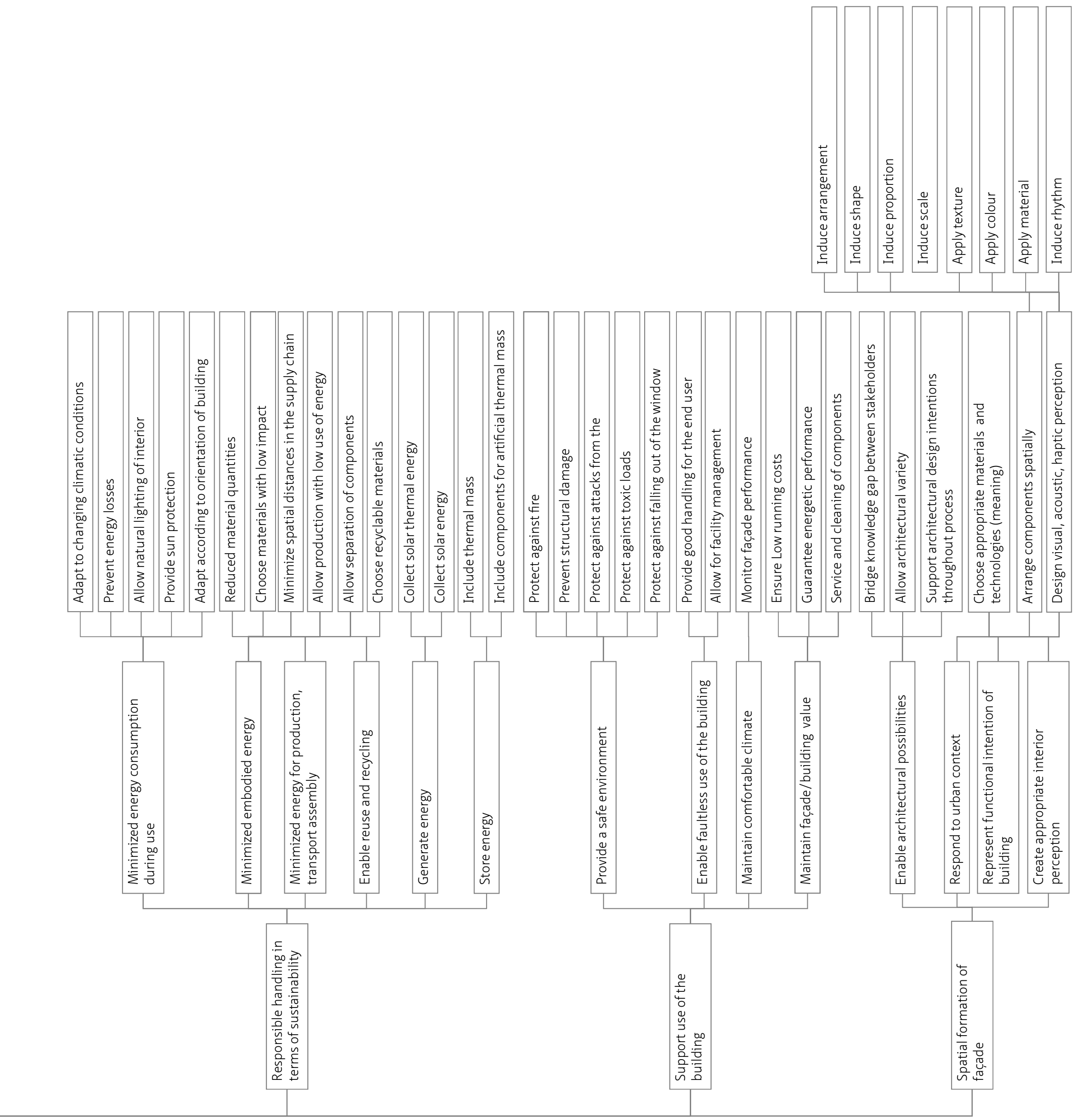


Figure 42

The façade function tree. It was developed on the basis of the graduation project of Joep Hoevels (Hoevels, 2007)


Responsible handling in terms of sustainability
Minimized energy consumption during use
Adapt to changing climatic conditions
Prevent energy losses
Allow natural lighting of interior
Provide sun protection
Adapt according to orientation of building
Minimized embodied energy
Reduced material quantities
Choose materials with low impact
Minimized energy for production, transport assembly
Minimize spatial distances in the supply chain
Allow production with low use of energy
Enable reuse and recycling
Allow separation of components
Choose recyclable materials
Generate energy
Collect solar thermal energy
Collect solar energy
Store energy
Include thermal mass
Include components for artificial thermal mass
Support use of the building
Provide a safe environment
Protect against fire
Prevent structural damage
Protect against attacks from the
Protect against toxic loads
Protect against falling out of the window
Enable faultless use of the building
Provide good handling for the end user
Allow for facility management
Maintain comfortable climate
Monitor façade performance
Maintain façade/building value
Ensure Low running costs
Guarantee energetic performance
Service and cleaning of components
Spatial formation of façade
Enable architectural possibilities
Bridge knowledge gap between stakeholders
Allow architectural variety
Support architectural design intentions throughout process
Respond to urban context
Represent functional intention of building
Choose appropriate materials and technologies (meaning)
Create appropriate interior perception
Arrange components spatially
Design visual, acoustic, haptic perception
Induce arrangement
Induce shape
Induce proportion
Induce scale
Apply texture
Apply colour
Apply material
Induce rhythm

§ 4.5 Summary

The aim of this chapter is to define a systematic for the constructional façade analysis. This systematic should provide insight into the relationship between construction details and the structure of the design and construction process. A literature study was conducted for two reasons: Firstly to see how this relationship is reflected in educational and professional literature, and secondly to develop a useful vocabulary for the systematic.
The above discussed books show only a small selection of the available literature on building technology as well as other disciplines but it is a representation of literature that is used at different faculties in the Netherlands and Germany for the education in the master programs and for professionals.

§ 4.5.1 Relationship between façade construction and the design and construction process

Looking at the analysed books makes it clear that architectural design is seen as an assembly of existing construction methods for the purpose of a specific project. The compatibility to the building market is given by using approved methods. The success depends more on how a type of construction or a building product enables architectural design than on how it is perceived by the end user. It is not surprising that the questions about the relationship between construction detail and the design and construction process cannot explicitly be found in this context.
In contrast, product design aims at developing new or improved products. It naturally has the ambition to penetrate the existing market structure or even to create new markets. When trying to understand the relationship between façade construction and building market, the literature on product design therefore provides much better and precise insight.

§ 4.5.2 Vocabulary for the analysis

It becomes clear that functions are essential when analysing or developing products in general or in this case curtain wall constructions. Literature in the field of architecture does provide us with a basic list of façade functions. However, the field of product design discusses functions in a more intensive way and provides a more valuable vocabulary for the façade construction analysis.
A function is defined as a ´black box´ converting the inputs into the outputs.

- Poelman specifies this as: A function is defined as a "set of functionalities which are deployed for some objective (Function = functionalities + objective)".

Poelman further defines different types of functions:

- Primary, secondary and supporting functions.
- Positive and negative functions.
- Functions meant for different users.
- Technical and emotional functions.

A Façade Function Tree was developed. It does not claim to be complete, and could, in principle, be organised differently. Its purpose is to create an understanding about the countless functions a façade has to fulfil, and it tries to create order within this complexity. The Façade Function Tree is the basis for creating function structures. Ulrich's theory of product architecture provides concepts of how functional elements can be translated into physical components and how they can be connected. In fact, the way how parts, components and subcomponents are connected is crucial. The effect of a certain choice of product architecture on the managerial side is described. The following vocabulary can be borrowed and transferred to the field of façade construction. It serves as the basis for the following analysis.

- All products consist of function elements that are represented by physical components. Their relationship can be mapped in a function structure. The product architecture can be modular or integral with either a one-to-one or a one-to-many relationship between function elements and physical components. A function structure can be used to illustrate this relationship.
- Integral product architecture has coupled interfaces. De-coupled interfaces, called modular architecture are divided into three types: Slot, bus and sectional.
- Product change, variety, standardisation, product development management and performance.
- Standard components. Function sharing and geometric nesting
- Local performance and global performance

As mentioned above the characteristic in terms of product architecture depends on the level of the components within the overall system. (A laptop has an integral architecture in terms of its overall system, but might display a modular architecture on a more detailed level.) Eekhout´s range of building products has been adapted for the purpose of this research. The following product levels have been defined:

- Materials
- Standard materials
- Commercial material
- Elements
- Sub component
- Components
- Building part
- Building

§ 4.5.3 Systematic for a constructional façade analysis

A systematic with three key components can be used for a comparable analysis of different façade constructions:

1. A Façade Function Tree has been developed on the basis of the function related vocabulary. It does not claim to be depletive but can serve as a guideline to understand which functions a certain construction aims to fulfil.
2. The hierarchical scheme of product levels can show how a construction is composed from material to elements and components to building parts.
3. The above mentioned theory of product architecture can be used to describe the relationship between the construction and the structure of the building market.

The constructional façade analysis can be executed in six steps, using the three key components:

1. Collect information about the construction
2. Use the function tree to define which functions the construction aims to fulfil
3. Create specific function structures that map the relationship between different parts and components (according to Ulrich and Cross)
4. Categorise parts and components by using the scheme of product levels
5. Describe the interfaces between the components
6. Use the theory of product architecture to understand the relationship between construction and the building market, such as managerial aspects as variety, standardisation and product performance

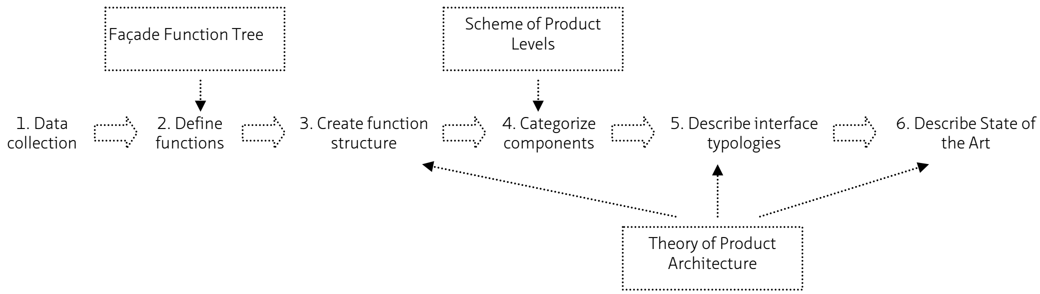


Figure 43

Applying the systematic to analyse façade constructions

5 Analysis of curtain wall product architecture

§ 5.1 Introduction

The goal of this chapter is to answer the following research questions:

- *What is the state of the art of curtain wall constructions and how is it linked to the façade design and construction process?*
- *How can contemporary curtain wall construction tackle the challenges formulated in chapter 3?*

Fifteen different constructions are analysed; beginning with historic examples, to contemporary constructions to building services integrated concepts. Entire façades as well as individual elements are analysed. The difficulty is to create comparable results. The systematic developed in the previous chapter is applied for this purpose. Depending on the type of construction to be analysed it is not always necessary to execute all of the six steps described in chapter 4.

§ 5.2 5.2 Historic curtain walls

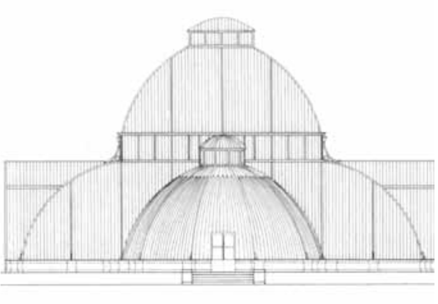
§ 5.2.1 5.2.1 Rolled-steel construction: The Palm House

Richard Turner and Decimus Burton, 1844-1848, Kew Gardens London

Step 1 – Data collection

The development of the greenhouses in the 19th century has to be seen in close relation to the cultural background of the industrial revolution, which not only brought about new technological possibilities, such as the development of new steel

processing technologies, but a new mind set: The absolute taming of nature. While the environment was increasingly destroyed by exploiting natural resources, an ideal image of nature was captured in man made enclosures: A romantic place where humans could harmonise with a strange and exotic nature. The greenhouse was used as a winter garden for private use, exhibition space, space for public enjoyment, but also for scientific purposes. The industrial revolution provided new technical possibilities to realise this new type of building. In his book ´Das Glashaus´ (Kohlmaier and Sartory, 1981) Kohlmaier writes: “The carefully controlled culture of plants was deployed with the help of glass, iron and steam”. At the time they where built, greenhouses represented extremely expensive and luxurious buildings.
Interestingly, this new type of building was not directly embraced by architects but rather by gardeners and engineers such as Josef Paxton or John Claudius Loudon. It was simply too machine-like, and with the absence of mass they were not seen as architecture. Designing a space simply according to the rules of engineering and technical possibilities was not considered adequate for the art of architecture.
Optimising the transparent surface by minimising the construction was one of the driving forces for the development of greenhouses. Research was conducted about the optimal orientation relative to the sun to heat the large interior spaces. Greenhouses did not have to hide their functional character, and were in total opposition to the conventional architecture of the time.
Nevertheless, this new typology of functional building had a revolutionary impact on the perception of architecture. It was never designed for its functional purpose alone. Kohlmaier puts it in the following words: “We can justly contend that the history of the sensual perception of architecture plays a significant role in the spatial design of the greenhouses. The aesthetic design, ... , also becomes a particular purpose of building”.



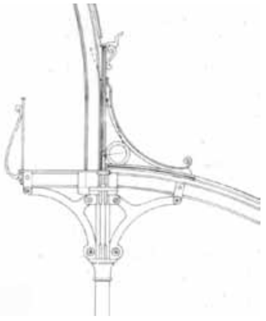


Figure 44
Side elevation of the Palm Houset

Figure 45
Detail of connection between colum and main structure

Figure 46
Exterior view of the Palm House

The main structure of the façade consists of I-shaped, bent wrought-iron beams with a height of 22.8cm and a length of 3.6m bolted together to form beams of an overall length of 12.8m. The distance of this main grid is 3.81m. It is subdivided by wrought-iron and cold bent mullions that follow the entire length of the quadrant shaped envelope.

Figure 48 shows a sketch of the façade mullion. Its structural height is 5cm. The overlapping glass panes are 24.1cm x 97.2cm large and approximately 3mm thick. They are fixed with putty. Although not executed in this building, the sketch shows an integrated gutter to drain condensate. This feature was proposed by John Claudius Loudon as a principle solution to prevent harmful cold condensation water dripping on the plants.

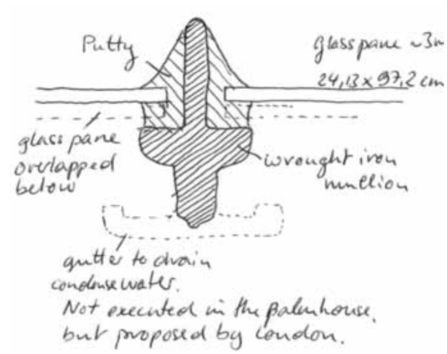


Figure 47
Interior view of facade and mullion

Figure 48
Sketch of mullion, Palm House

Step 2 – Façade functions

The function tree (Figure 42) has been adapted from the façade function tree shown earlier in chapter 4. For the sake of simplicity, this exercise only focuses on the secondary functions ´Create a durable construction´ and ´Provide a climate for tropical plants´. Sustainability as a primary function was not an issue at the time.
Primary and secondary functions typically represent global performances that have to be fulfilled by all parts of the façade or even the entire building. Local performance, however, can be allocated to certain components. The climate, for example, is kept within the desired range by operable windows as well as the central hot water heating system.

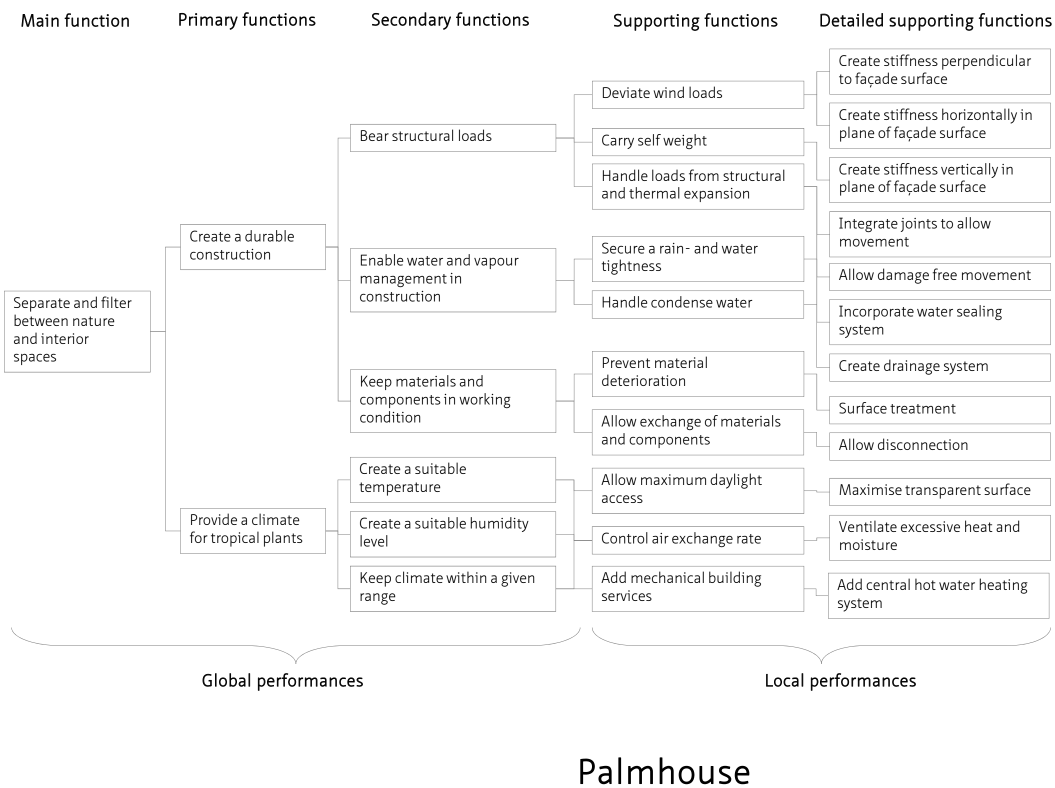


Figure 49
Function tree of the façade of the Palm House.

Step 3 – Function structure

Figure 50 shows the function structure with a focus on the façade mullion. It shows a typical integral architecture with a one-to-many mapping. The mullion itself fulfils multiple functions with its specified size and shape. Its cross-like shape allows the attachment of glass panes. (Other greenhouse façades are made of sheet steel with screwed on, L-shaped profiles for the same purpose). Its stiffness is created by the profile height, width and shape. Even though not intended, in some constructions the glass panes can stiffen the structure as a whole. Transparency is ensured by the narrow width of the mullions (owing to the particular shape that provides stiffness) and the glass panes. The necessity to deal with condensation is a typical negative function as a result of the moist and warm interior climate and the choice of highly conductive façade materials (steel and glass). Therefore (to create a drainage system), Loudon has proposed a mullion with integrated rain gutters that was not executed in this building but is shown in the sketch. The putty serves as the interface between glass and mullion. In Ulrich´s terms we can speak of a coupled, integral interface. Owing to its changeable shape, the material is modelled into place on-site. On the other hand, one could also call it ´super modular´ since it can potentially connect everything in a reversible manner. In fact, putty has ambiguous properties in the sense of the definition of interface typology. However, the performance of the overall construction is owed to function sharing and geometric nesting.

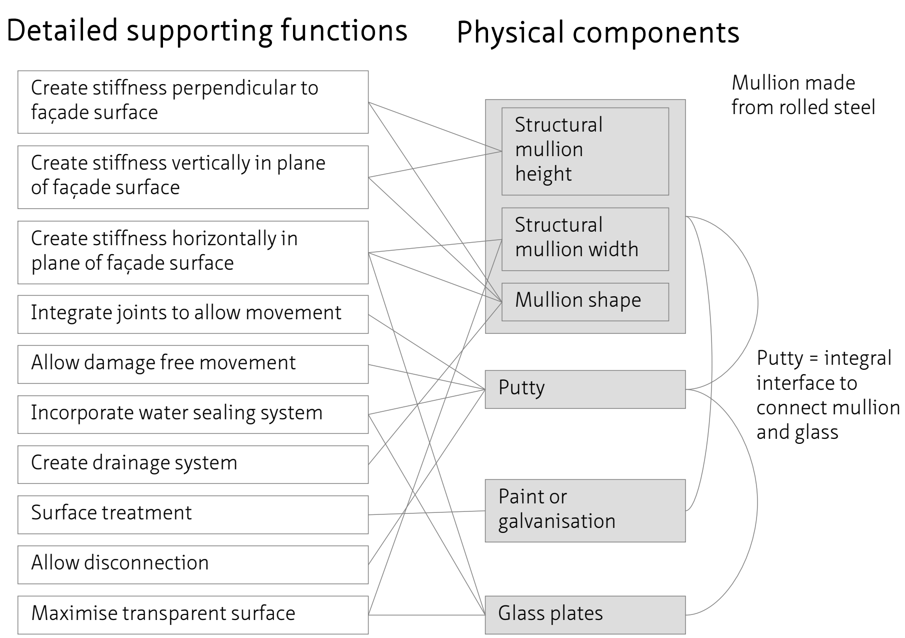


Figure 50
Detailed function structure of the façade of the Palm House

Step 4 /5 – Product levels and interface typology

When inserted in the scheme of product levels (Figure 51), it is interesting to see that the façade is directly assembled from standard or commercial materials. Putty is made from linseed oil and whiting, and thus a standard material according to the definition above. The mullion is industrially produced with a roll forming process for this particular project. Even though the glass panes are custom made as well; both are classified as commercial materials in this context. Using these elements, the façade is directly assembled on-site.

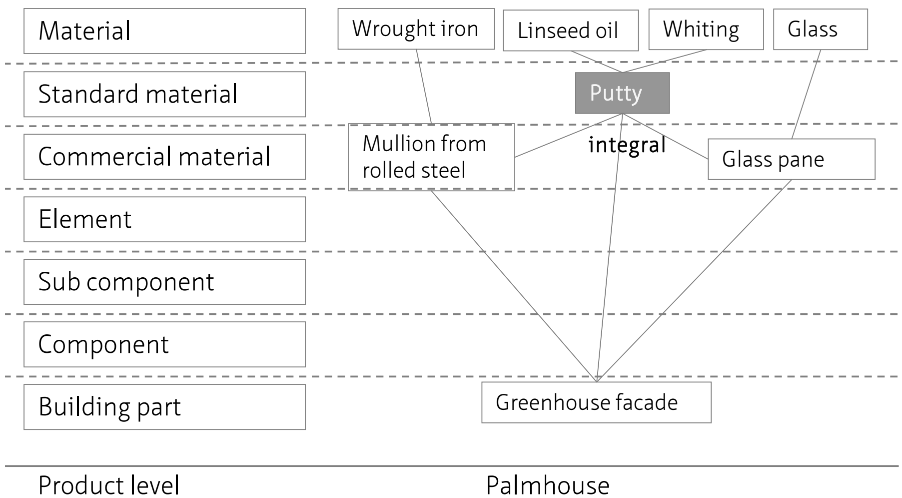


Figure 51
Product levels of the façade of the Palm House

Step 6 – Description of the Palm House construction

The façade is a typical ´early´ curtain wall. It only consists of six main components, even if we include the connection rods and upper and lower rails. Although similarly used in other projects, the mullion is uniquely designed. The ´many-to-one´ mapping of functions and the interface typology show a very integral construction.
The lack of the product levels ´element´, ´sub component´ and ´component´ indicates that there is no pre-assembly off-site. The construction is predominantly handcrafted, even though the base components mullion and glass panes show a certain level of industrial production. The putty is a very integral and intelligent interface component. In addition to sealing the façade, it allows flexibility and tolerances during assembly and use of the façade.

§ 5.2.2 Standard steel profiles: Crown Hall

Mies van der Rohe, 1956, IIT Campus, Chicago

Step 1 – Data collection

With Crown Hall, Mies van der Rohe challenged the limits of construction of his time, and realised his first "Universal Space" (Spaeth, 1985). The column-free space of 66m by 36m was created by a construction suspended from a 18m grid of 36m spanning beams. No divisions for fire protection where needed, and the space is only subdivided by free-standing, movable walls. The size of the room allowed different uses at the same time without great disturbance.
The building shows a metal-glass façade. Strictly speaking, it is not a curtain wall because it forms an integral part of the external load-bearing structure of the building. Its functionality is very basic compared to modern curtain walling systems. It acts as a weather shield with a high level of transparency. The insulation capacity is very limited and sun-shading is only provided by internal sun screens; actually separated from the façade. The detail shows that it is composed of standard steel profiles and glass sheets that are fixed by putty and steel glazing beads. The entire façade is assembled on-site and the different parts are joined by welding and screwing. Every part of the façade was designed by the architect (perhaps with help of a structural engineer) and executed by a metal builder, directly following the the architect's plans. It is an individually crafted construction and we cannot speak of a product in the sense of Ulrichs´ description.

Figure 52
Crown Hall, Mies van der Rohe, Chicago 1956.

Figure 53
Corner situation

Figure 54
Detailed exterior and interior views show welded connections. Only glass beads are fixed by screws.

Figure 55
Detailed exterior view.

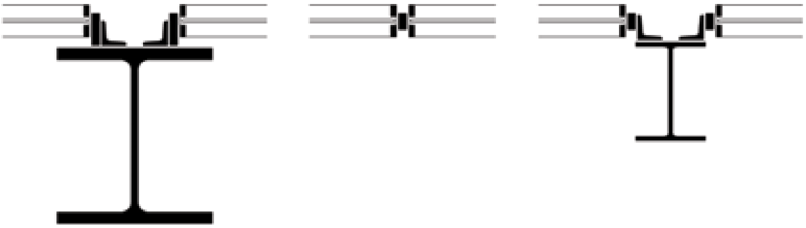


Figure 56
Facade detail

Figure 57
Crown Hall seen from inside

Step 2/3 – Façade functions and function structure

Again, the function tree has been simplified to the basic principles. However, in this case functions have been added that are fulfilled by other components of the building, such as heating, cooling and ventilation (fulfilled by a central HVAC system).

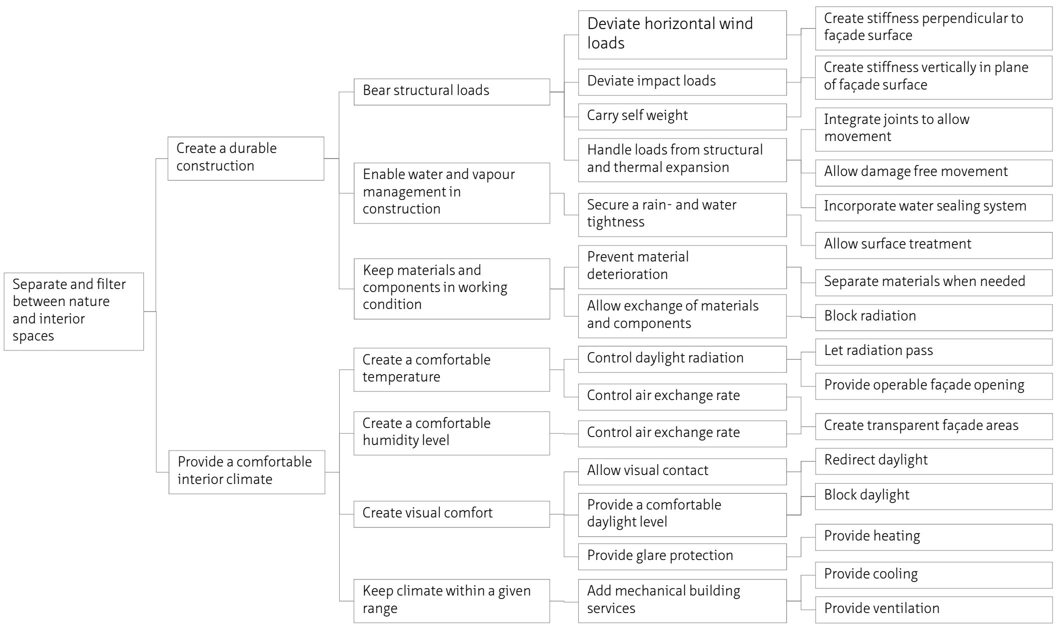


Figure 58
Function tree Crown Hall

The main structure is composed of I-beams, L-profiles and flat irons. These form an integral structure. The putty serves several functions: It allows movement, helps fixing the glass panes and seals the system. The glazing beads are decoupled by being screwed into place; they allow the glass panes to be exchanged in case of damage.

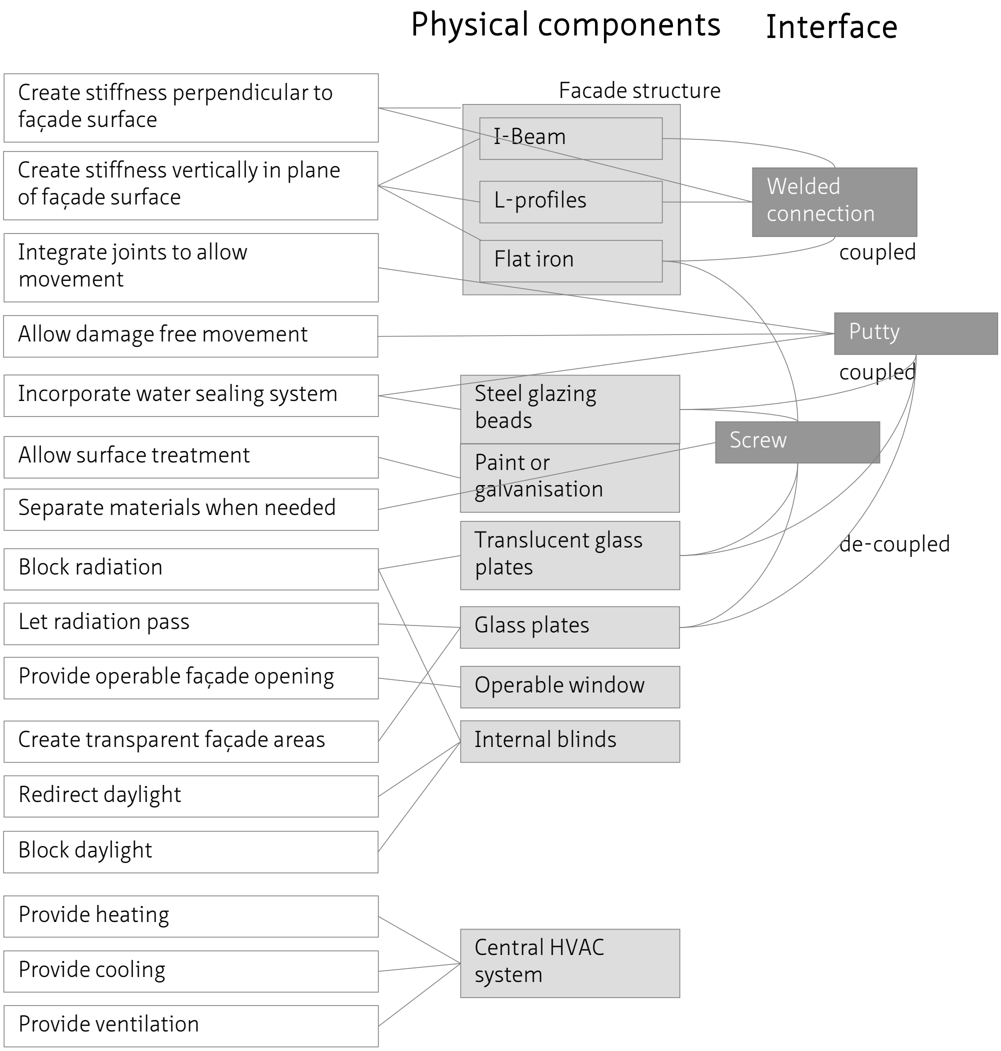


Figure 59

Detailed function structure of the façade of the Crown Hall.

Step 4 /5– Product levels and interface typology

The operable windows are categorised under ´Elements´, although they are fabricated by standard and commercial materials. But they are also closed assemblies (except the glass pane which was mounted on-site) with a single functional purpose and thus bear the characteristics of a ´sub component´. The confusion here is the result of the non-product like character of the façade.

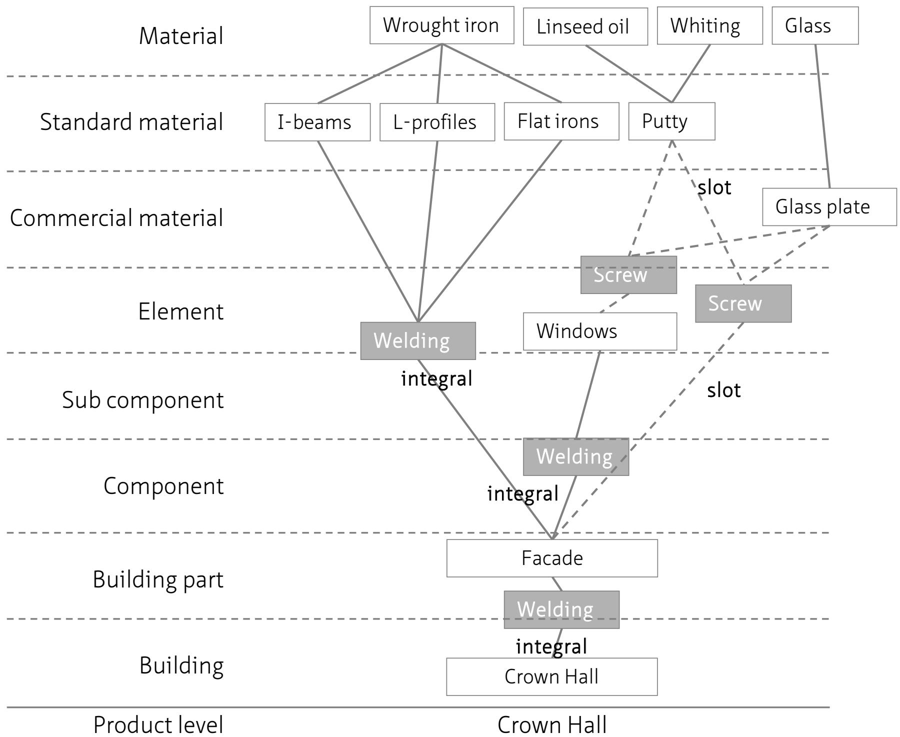


Figure 60
Product levels of the façade of Crown Hall

Step 6 – Description of Crown Hall construction

The façade is more complex and consists of more parts than the Palm House façade. The different level of industrialisation is reflected by the fact that this façade covers more product levels. It is composed of standardised profiles which are integrally connected by welding. The windows form elements which are most likely built in a workshop. The glass panes are quite large, and are connected with a modular slot interface (screws) that allows replacement. It is a purpose-made construction and an integral part of the primary structure of the building.

§ 5.3 Contemporary curtain wall façades and components

Contemporary curtain walls are descendants of the Palm House and Crown Hall façades. The only particularity is that they do not fulfil load-bearing functions. The architectural concept is still the same: A lightweight construction with a potential for high transparency.
In terms of the structural concept, Knaack (Knaack et al., 2007) defines "three main areas of construction" for curtain walls:

- Primary structure forming the main load-bearing structure of the building
- Secondary structure, which is the load-bearing structure for the façade (curtain wall) and constitutes the connecting element between levels one and three
- Infill elements

The primary structure takes on the load-bearing function of the entire building and transfers the loads from the façade to the foundation. The secondary structure comprises the load-bearing structure of the façade. It transfers its loads onto the primary structure. At this 'interface to the interior' the differing movements of the structure of the building and the façade need to be balanced. In addition, these two structures are typically assigned to different subcontracts; the structure of the building usually falls under the subcontract for concrete work whereas the façade is assigned to the metal subcontract. As these elements are manufactured by different companies, there is a need for special coordination at these interfaces. Manufacturers' tolerances of the shell of the building (concrete) lie within the centimetre range whereas the façade (metal) tolerates only deviations of millimetres.
At the same time, infill elements such as glazing, panels etc. are mounted on the secondary structure. This 'interface to the exterior' has to fulfil its own functions: the elements have to be windproof, resist water penetration, or it must be re-channelled to the exterior, movements between the elements and the secondary structure have to be tolerated and thermal bridges have to be avoided. Thus, the secondary structure is a very complex component. The actual space enclosure is created by the infill elements. These can comprise glass panes for lighting and view, panels for heat insulation and opening flaps for ventilation.

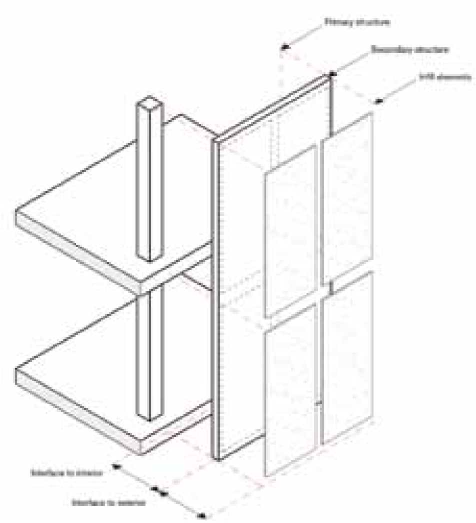


Figure 61

General layout of curtain walls, primary, secondary structure, infills and interfaces between them according to Knaack

§ 5.3.1 Curtain wall system

Step 1 – Data collection

The analysis now focuses on the ´secondary structure´ according to Knaack – the actual curtain wall.
Figure 62 shows a exploded view of a cross joint of a typical curtain wall façade. The systems of other manufacturers, though all having their particularities, are basically composed of similar components. For someone who is not familiar with façade construction it needs to be said that a simple section does not represent the full complexity of this construction. Curtain walls consist of 120 to 400 pieces, typically shown in a system catalogue, all on the level of ´commercial materials´.

To illustrate the level of standardisation, a selection of DIN EN standards and norms relevant to curtain walls in Germany are added to the detail of a curtain wall by Alcoa Architectural Systems. Every component has to be designed and tested separately as well as with the system as a whole to guarantee that it has the proper technical conditions. The mullions are fixed first; then they are connected by transoms. Inner rebate gaskets and connectors are preassembled, but are connected at the cross joints on-site. Finally, outer rebate gaskets, glass panes, pressure plates and cover caps are attached. In some instances, the systems are preassembled in form of separate ladder-like elements, which are connected on-site.

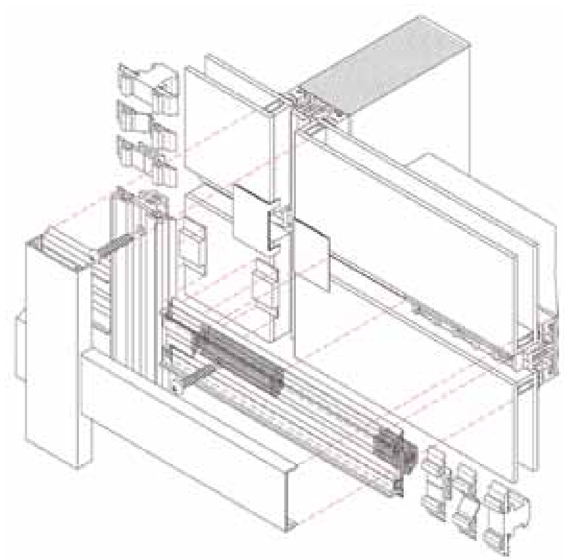


Figure 62

Perspective of a typical cross joint of a curtain wall (Raico, 2008)

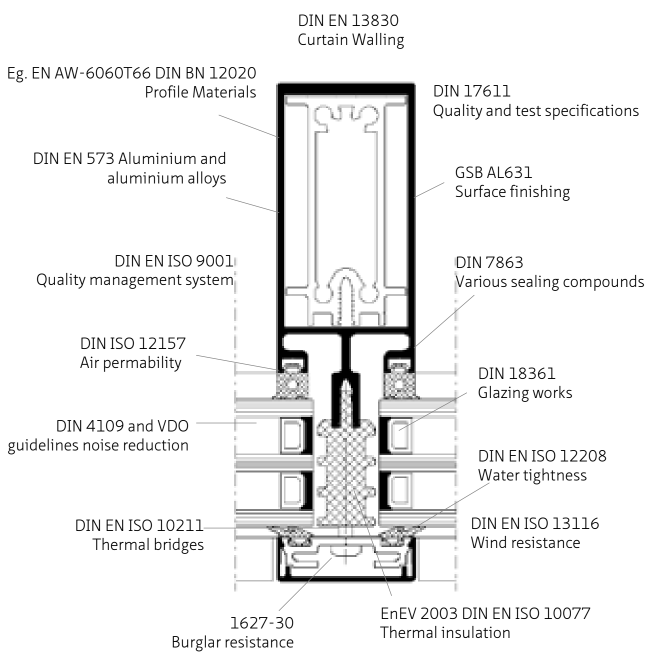


Figure 63

Horizontal detail section of curtain wall (AA100HI, Kawneer Alcoa, 2012), showing relevant standards and norms (in this case DIN EN)

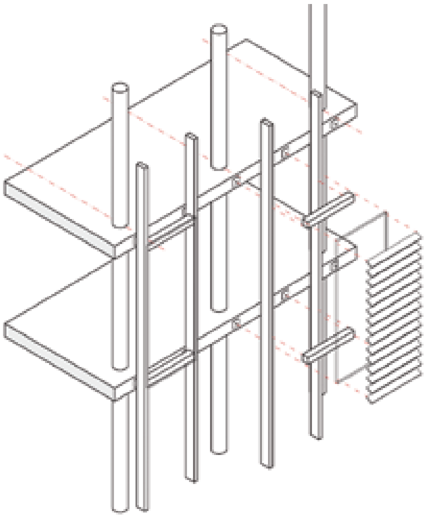


Figure 64
Assembling a curtain wall on-site

Figure 65
Curtain wall with pre-assembled ´ladder`

Step 2/3 – Façade functions and function structure

The function structure (Figure 66) shows the complex mapping with decoupled interfaces between different physical components. Certain supporting functions such as burglar protection, blast and fire resistance are not even shown. The limitations of this graphic model become obvious. However, when compared to the function structure of the Palm House it becomes clear that the increasing number of functions has a direct effect on the construction.

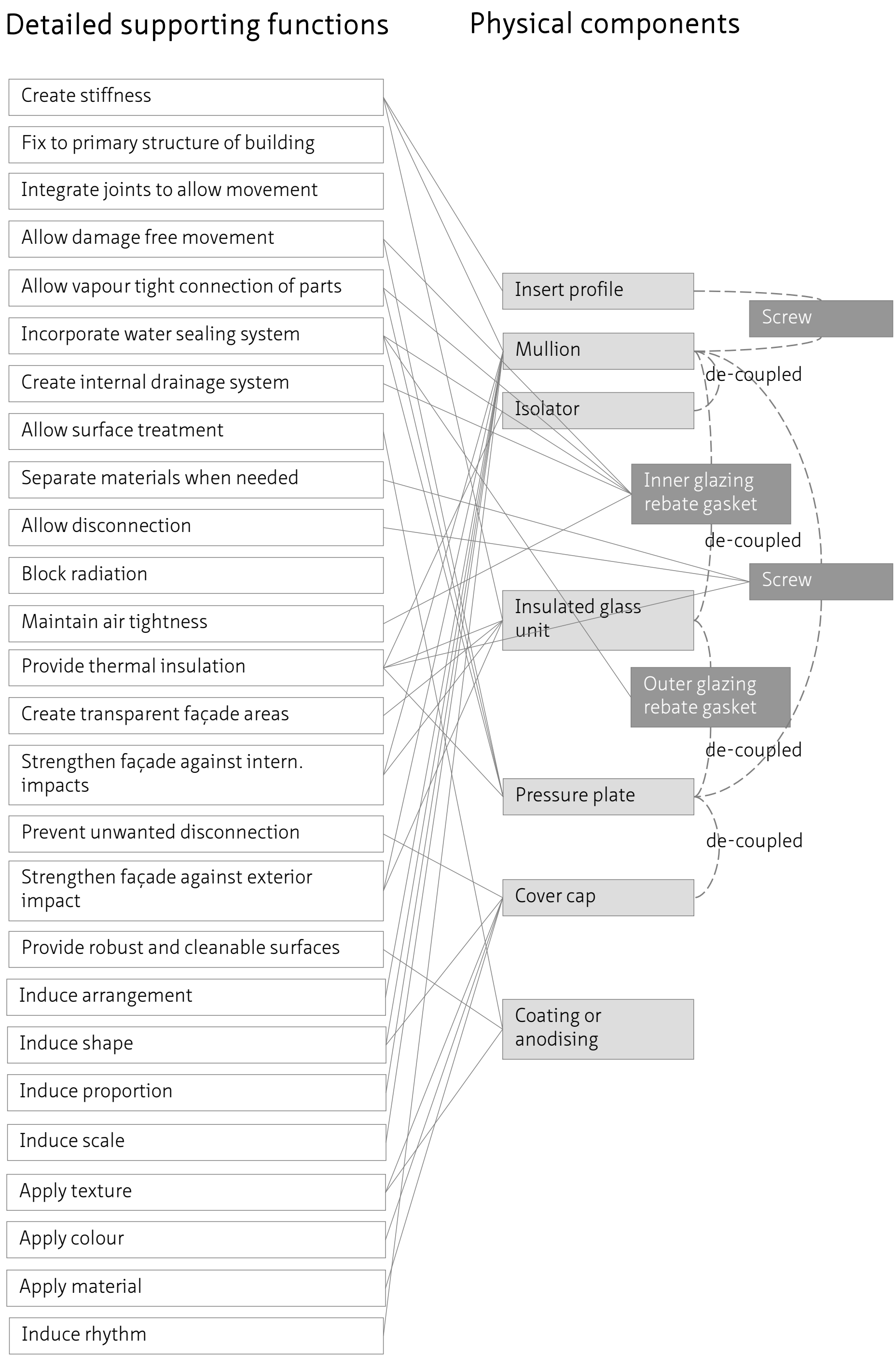


Figure 66

Function structure of contemporary curtain wall

Figure 67 highlights which physical components are responsible for the functions water tightness, architectural design, thermal insulation and structural stability. It also shows the different stakeholders that are responsible in designing a curtain wall. The architect designs the overall façade layout. Together with the façade consultant or the builder he makes he chooses a particular system. After the choice is made he has limited design possibilities, which are basically reduced to the shape and colour of cover cap and mullion. The structural engineer and the façade builder are responsible for the structural integrity of the system. The building physics consultant decides about the thermal and acoustical performance. That the systems must comply with current norms and regulations lies in the responsibility of system supplier and façade builder.

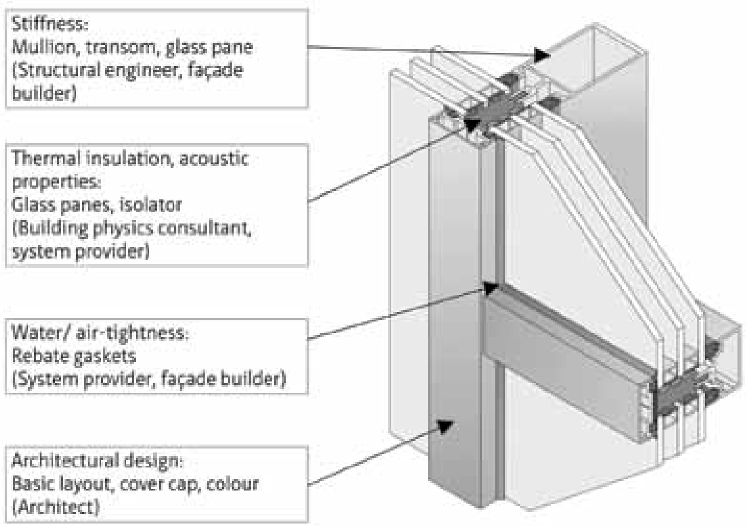


Figure 67

Perspective view of a curtain wall system, showing functions of different components and stakeholders involved in the decision making process. (AA100HI Kawneer Alcoa, 2012)

Step 4 /5– Product levels and interface typology

Almost all of the parts on the level of commercial materials have an integral architecture; demonstrated by the rebate gasket (Figure 68). The function ´Incorporate water sealing system´, for example, can be further subdivided into functions such as ´Connect sealing component´ or ´Compensate glass tolerances´. The shape, size and material properties of the single gasket are deliberately chosen to create the according functionality.

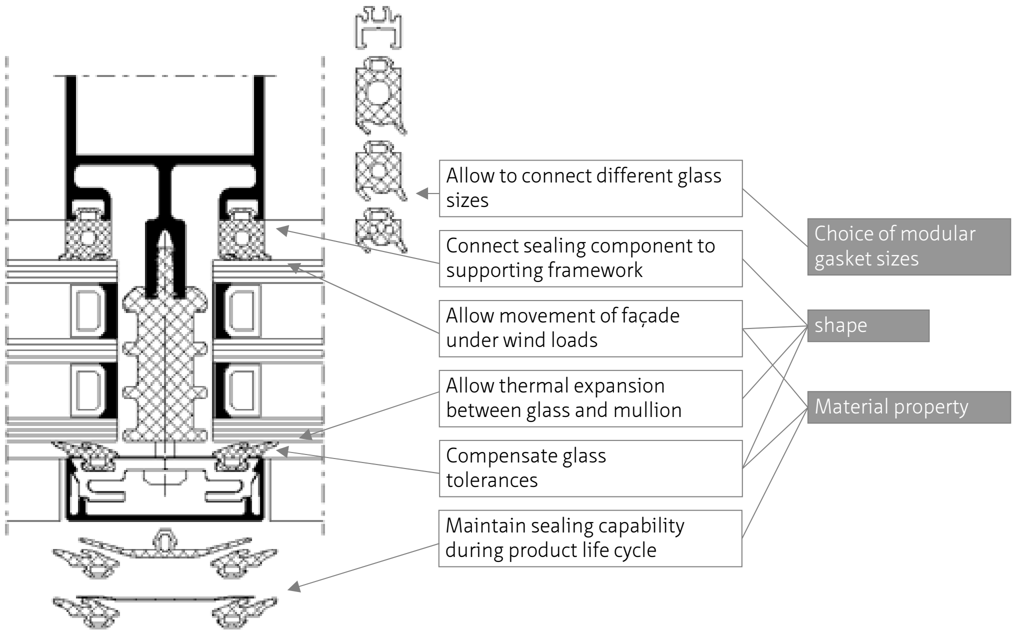


Figure 68

Functions of a rebate gasket. It displays an integral product architecture on the level of ´commercial materials´.(AA100 HI, Kawneer Alcoa

However, on all other levels the curtain wall represents an entirely decoupled architecture (Figure 69). Gaskets, isolators, mullions, cover caps can be ordered according to the project needs: Load-bearing concept, insulation level, glass thickness and others. The different parts connect to each other with ´slot´ interfaces. The glass pane is held by inner and outer gaskets. Its dead loads are transferred by glazing supports connected to the transom. These also differ according to the glass loads. The gaskets form a ´bus interface´ that also allows the connection of different windows and/or opaque panels.

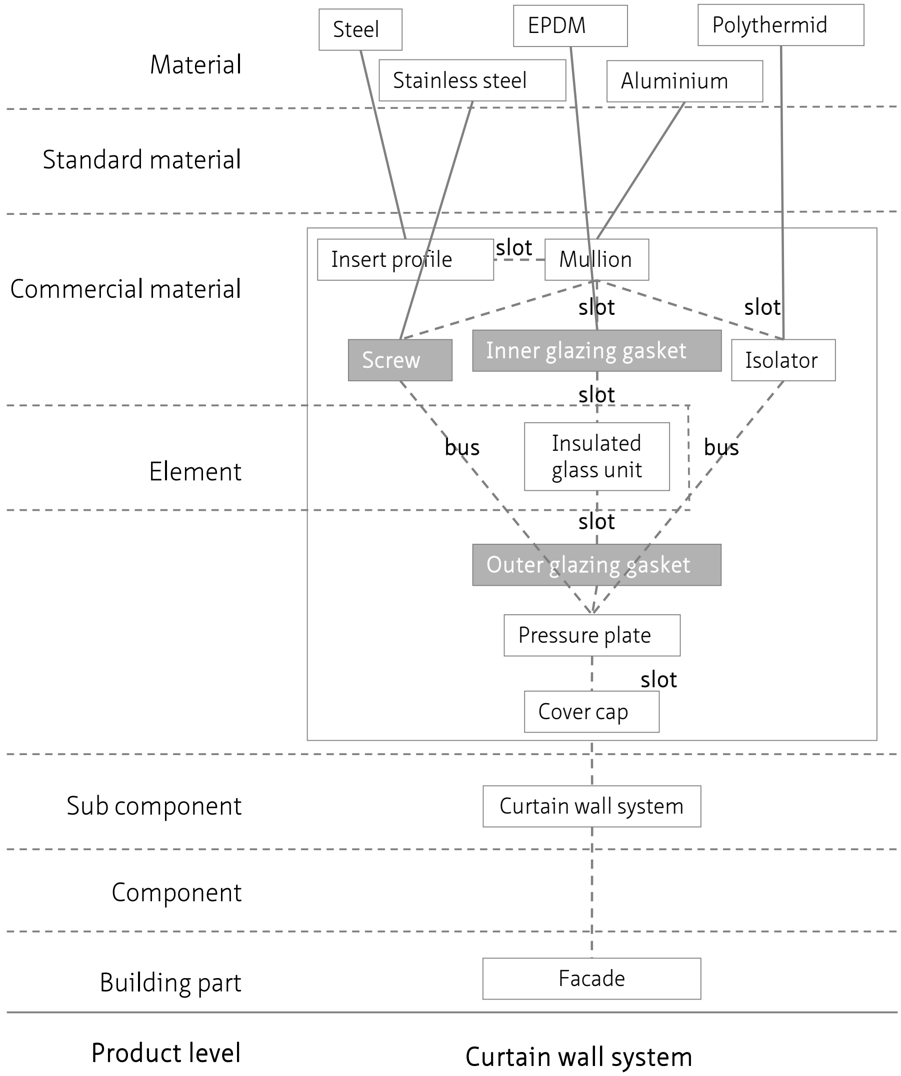


Figure 69
Product levels of the curtain wall

Step 6 – Description of curtain wall system

Looking at the vocabulary of product architecture provides us with an interesting insight: Modern curtain walls have a typical modular product architecture with a one-to-one or one-to-many mapping of functions and components.

Side note

The joint - from meaningful architectural tool to jointless desires

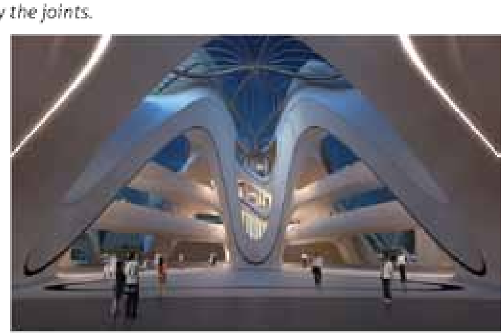
In the building trades, a joiner is a type of a carpenter who prepares, sets out, and manufactures joinery components. Although today the term is almost obsolete it demonstrates the importance of the joint in architectural construction. Joints are needed to bridge the limitations of components in terms of their size. They are needed to connect different materials and to assemble buildings on site. They allow thermal expansions or exchange of components. Logically, the joint has always been in the focus of architectural design. The delicate wooden joints in traditional Japanese buildings do not only serve functional purposes but have evolved to architectural symbols.

Joints in buildings are omnipresent. Mortar is used to connect bricks to a homogenous wall. Bolts structurally connect steel members. Increasing building physical requirements make joints in façades very complex design tasks. Entire industries have developed around the topic joint. For example, watertight expansion joints for roofs and parking desk are expensive products. The joint in unitised façades are sophisticated constructional elements.

In architectural terms, it seems that today the joint has developed from a meaningful design tool to a jointless connection - or at least to an invisible joint. This is a complete negation of traditional building methods. Architects today seek seamless production methods as if buildings are cast in homogeneous futuristic materials.

On a trip to Japan, TU Delft students trying to understand wooden joints

Cloud Gate is a public sculpture by British artist Anish Kapoor in Chicago. Cloud Gate's exterior consists of 168 highly polished stainless steel plates. It is 10 m × 20 m × 13 m large and weighs 110 tons. To reach a state of dematerialisation, millions were spend in polishing away the joints.



Changsha Meixihu International Culture & Arts Centre, China, Design Zaha Hadid Architects

Product change

Typically, changes in curtain walls are only needed when a glass pane brakes. The panes can easily be exchanged. Upgrades are possible as well but are rarely executed. When projects are refurbished after 30-40 years, usually the entire façade is exchanged. In most cases, the old curtain wall structures are not strong enough to carry the extra loads of insulated glass units, and on top of that they exhibit poor insulation properties.

Product variety

The system suppliers hold available the huge selection of parts and components that a façade system consists of, and provide it to the façade builder. The modular architecture allows the façade builder to create variety by composing the curtain wall according to the project needs. Architectural variety can be achieved by designing different grids and arrangements on the façade plane. Different types of infills can be chosen. And the designer can opt for special parts, such as cover caps or the shape of the mullion. Thus, the curtain wall can be adapted to almost all projects, but architectural variety is limited to a given number parts.

Standardisation

The level of standardisation is very high. This is necessary because curtain walls must meet numerous standards and regulations on a project by project basis. System suppliers have all standardised components in stock or are at least able to produce them within a couple of days. This requires a high level of logistics as well as storage area and pre-investments. But it reduces lead times and control efforts.

Performance

Global performance such as thermal insulation depends on several components: Profiles, isolator, pressure plate, gaskets, screw material and of course, the insulated glass unit (IGU). Here we are talking about the theoretical U-value. DIN ISO 10077 regulates in which specific way the calculation has to be conducted. The real U-value depends on even more factors. The same can be said about other global performances such as water tightness and structural stability which also depend on various components.

Product development management

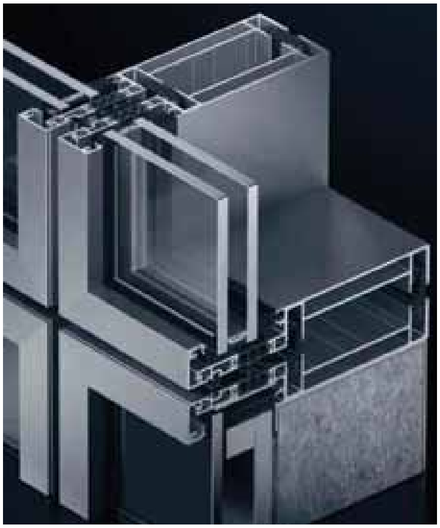
The modular strategy has the advantage that all parts can be developed independently as long as the interfaces between them are not changed. IGU´s are manufactured by different entities; they are developed and tested independently from the curtain walling system. The performance of curtain wall systems is increased by a combination of different isolators, pressure plates, etc. Whereas the thermal performance of IGU's has been improved rapidly by adding a third layer of glass, the curtain wall system reaches its maximum performance and is the weakest part of the façade. In order not to increase the size of the system, the components are geometrically nested. Upgrading is no longer possible. Here, the curtain wall construction can be seen as the interface between the filling elements (glass panes), and it is becoming the performance blocker. The only way to increase the product performance has been by locally improving the parts on the commercial materials level. The limited size of curtain walls (architects demand slender profiles!) has resulted in geometric nesting of parts that has reached its maximum. Curtain walls have hardly been improved, e.g. in terms of U-value, over the last years and are falling behind the development of infill components such as glass. Further improvement can only be found in a radical change of the entire system; however, this would mean a more integral design and would compromise the compatibility with the current market situation.

§ 5.3.2 Unitised systems

Unitised façade systems belong to the family of curtain walls but follow a slightly different strategy. In order to be able to manufacture the façade in the workshop, it is built in components. Therefore, a sectional interface needs to be introduced that allows the connection of the components on-site.

The benefit is obvious: The complex production process can be executed in the dry and clean factory. The quality can be controlled. Assembly times at the construction site are reduced and therewith the dependence of wind and weather. On the other hand, a higher logistical effort is required, and adaptations at the construction site are virtually impossible. Transportation is more elaborate.

The unitised approach results in a different constructional strategy: Instead of a mullion, a more complex frame system is needed. The size of the combined frames is usually bigger than that of a single mullion, and more material is needed to stiffen the units during transport. But still, especially for large and complex projects unitised systems can result in overall cost savings.



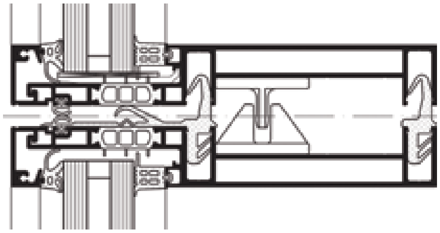


Figure 70
Perspective view ...

Figure 71
and vertical section of unitised façade (USC65, Schueco)

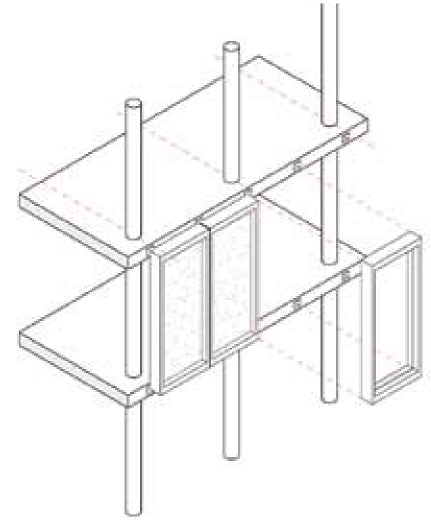


Figure 72
Assembling a unitised system

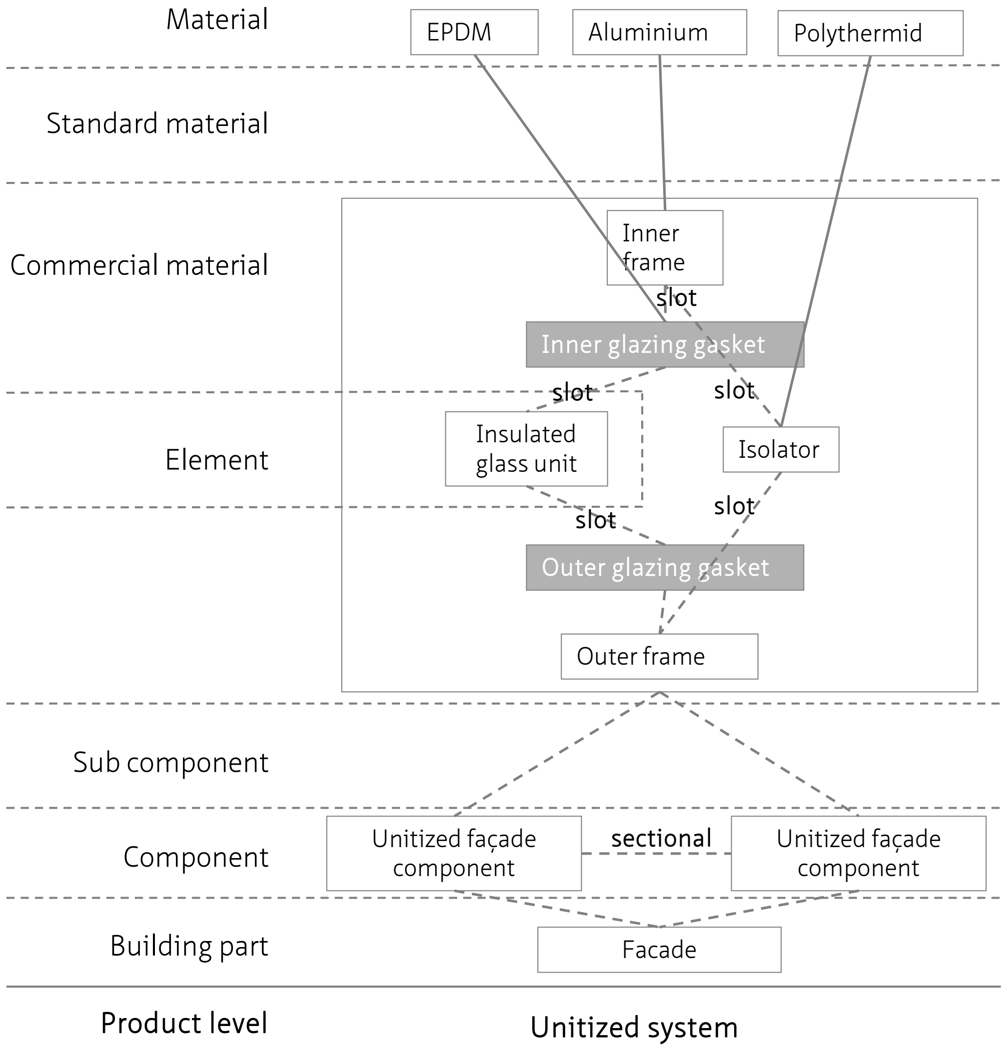


Figure 73

Product levels of a unitised system. Even though similar to curtain walls, it shows a sectional interface on the component level.

§ 5.3.3 Frameless systems

With the curtain walling system being complex and, in terms of thermal insulation, the weakest spot in façades, frameless structures made from insulated glass units seem a logical step. These systems have been in existence for quite some time. In fact, this development is architecturally motivated by the strive for more transparency. But the same functions have to be fulfilled.

Glass panes come in limited sizes; which is a disadvantage but is also useful in terms of handling the parts. They need to be joined with water, wind and moisture tight connections. These connections should also have appropriate thermal qualities. The glass panes have to be connected to a load-bearing structure. This connection has to allow tolerances and movement.

One type of frameless systems is the so called ´Frog hand´ or ´Spider´ façade. Several systems exist on the market, which include the construction of the structural spider and the point fixing.

The connection between spider and point fixing has to handle tolerances and movement, and the connection is a typical slot interface. After being bolted to the inner or inner and outer glass pane, the point fixings are integrally glued to the glass. Depending on the thickness of the glass, the joint is sealed by an EPDM backfill profile and than closed with a silicone joint.

Figure 74
Frameless facade system. The Glass panes are held by a steel ´spider´ (Prinsenhof, Delft, Octatube).

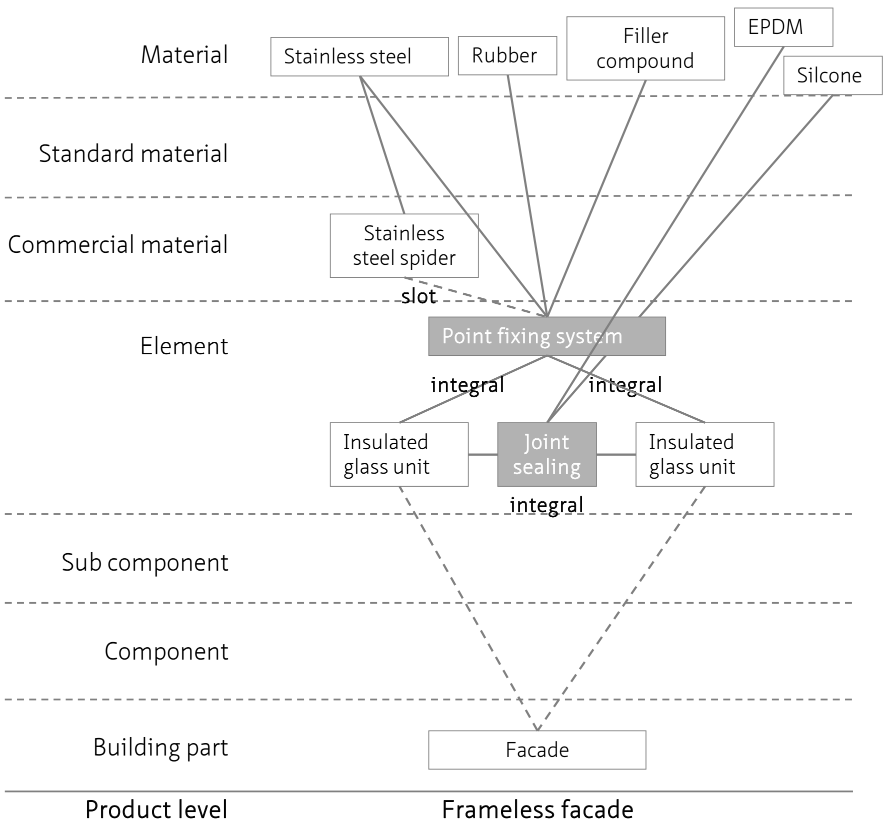


Figure 75
Product levels of a frameless structural glazing system.

Frog hand façades have a rather integral product architecture compared to standard curtain walling systems. The result is a high degree of transparency and flush finishes. Frameless systems have the disadvantage as well; one of which is that they do not allow the attachment of dividing walls. This, in combination with high costs is the reason why its application is limited to entrance halls or buildings with representative functions.

§ 5.3.4 The insulated glass unit

An insulated glass unit uses a strategy of layering to reach a better thermal performance. It consists of layers of glass which can be enhanced with certain coatings, depending on the requirement. A typical edge of the unit is made out of several subcomponents: spacer, desiccant to absorb moisture within the glass space to prevent condensation, interior sealant (butyl to connect glass and spacer) and exterior sealant to fully seal the unit. The spacer can be filled with different gases such as argon or krypton to improve the insulation value.

Float glass in different thicknesses is processed into security glass. It is cut to size, coated, receives different edge treatments and is finally assembled into an insulated unit. Depending on the requirements, it is composed of different glass types, sizes and coatings. The final product therefore only differs in size and weight; and any façade system is designed to accommodate it.

If a glass breaks, the entire unit is replaced. Three layered units with a high insulation value are becoming the current standard. A fourth layer would theoretical further improve the U-value, but glass manufacturers hesitate to take this step. The glass thickness will have an impact on the visual quality, and unit sizes and weight can no longer be integrated into today's framing systems. On top of that, the gain in thermal improvement does not relate to the additional costs.

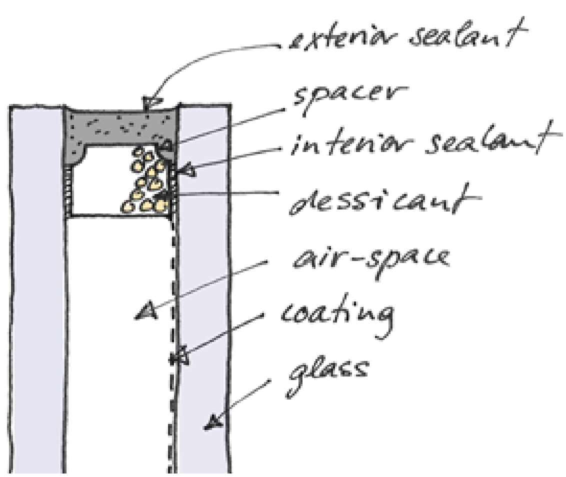


Figure 76
Edge detail of insulated glass unit

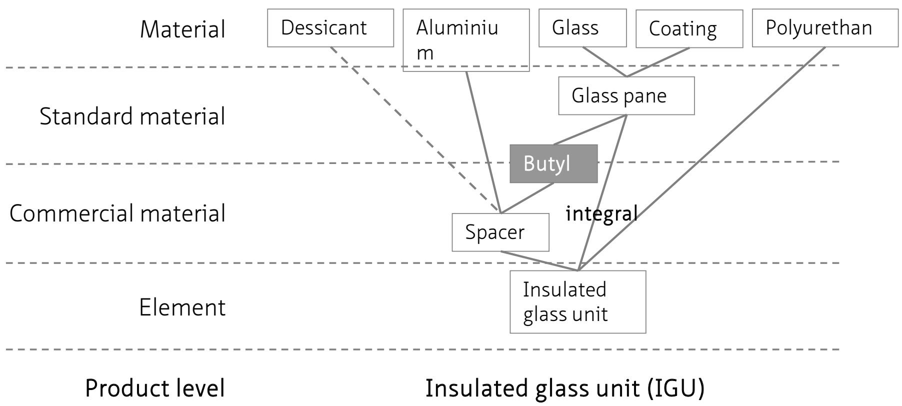


Figure 77
The product levels of the insulated glass unit show an integral architecture.

The construction is integral (it cannot be taken apart after assembly), but the glass unit is highly standardised. Different IGU products can be placed in all standard curtain wall systems. It owes its variability to a highly flexible production process and is customised for each project, each different window.

§ 5.3.5 Double façades

The traditional arrangement of functions within the physical façade space is either side-by-side, layered or a combination of both. The insulated glass unit, as described before, uses a strategy of layering on the ´element´ level - double façades on the level of ´building parts´.

With double façade, the construction is extended by a second glass layer that acts like a rain and wind shield to protect the sun-shading system. This can be very important for high rise buildings. Outside sun-shading systems are very efficient and will still be in operation under high wind loads. Double façades are also used to block traffic noise or to allow natural ventilation of buildings. In winter, they can provide an additional thermal layer.
However, the concept brings with it several downfalls: The cavity works like a greenhouse and needs controlled ventilation to prevent overheating. Condensation on the inner side of the outer glass pane can occur, if windows are opened in the inner, thermally insulated layer during cold outside conditions. Cleaning costs are high. This is why double façades only make sense in noisy locations or for high rise buildings where the investment is justified.

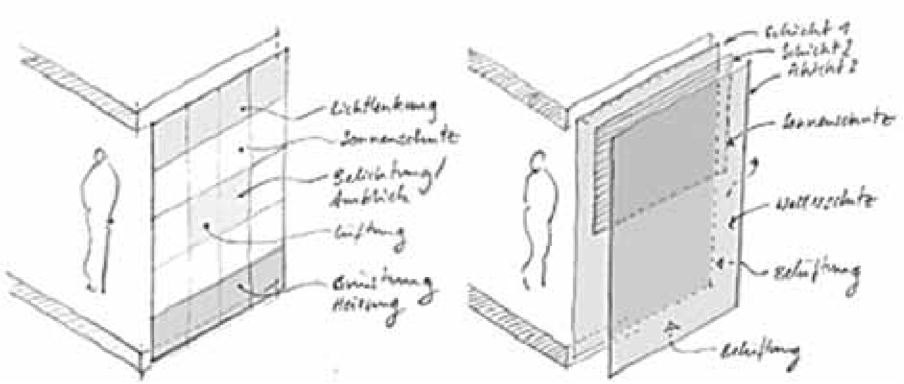


Figure 78
Classical arrangement of façade functions: side by side or layered.

There are different climatic strategies for double façades: The cavity can be separated horizontally in extension of the floor slabs (See figures80 - corridor façade). Each façade unit of the RWE Tower (Figure 85) is individually ventilated (box façade). The second skin of the Ramboll building (Figure 87) forms one cavity (chimney façade) and is not unitised.
But alternating concepts are conceivable as well. They have boxed windows in combination with single layer areas that have direct operable parts (Figure 91). New double façade concepts show sealed cavities. The reason is a reduction of cleaning costs, particularly in desert regions. Overheating is an issue of concern.

Figure 79
Stadttor Düsseldorf, Petzinka, Overdiek und Partner, Düsseldorf 1998

Figure 80
Detailed view

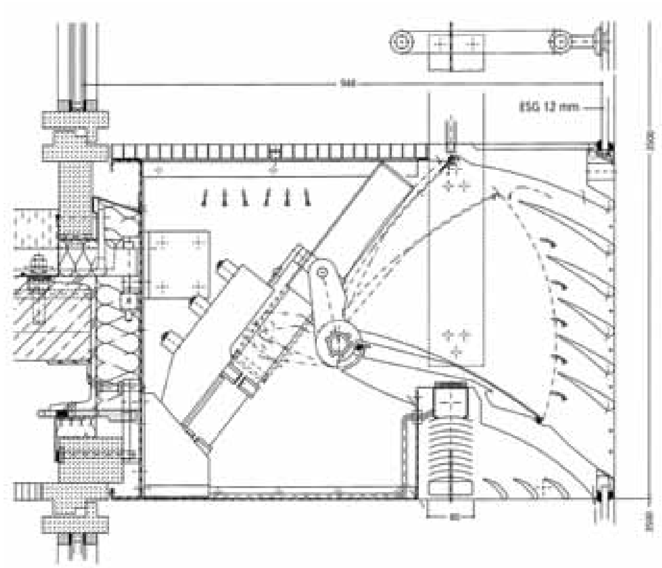


Figure 81
The cavity is horizontally separated. It is ventilated via vertical adjustable ventilation grilles.

Figure 82
RWE Tower, Ingenhoven Overdiek Kahlen & Partner, Essen, 1997

Figure 83
Detailed view

Figure 84
Each façade unit forms a separate cavity (box façade) and is individually ventilated through vertical and horizontal gaps.

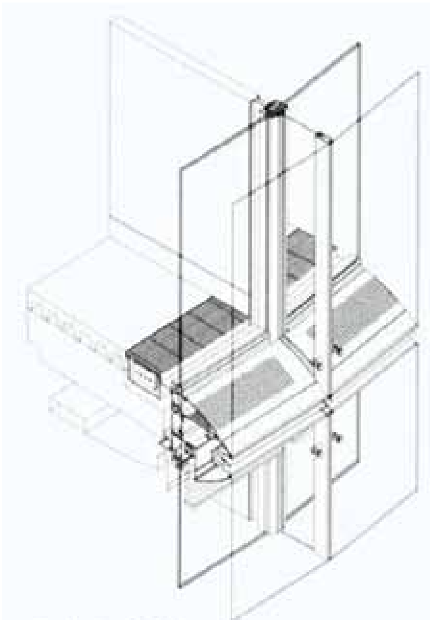


Figure 85
Perspective drawing of facade unit.

Figure 86
Head Office, Dissing+Weitling Architecture, Copenhagen 2010

Figure 87
Corner situation

Figure 88
Rotating flaps in form of glass louvers allow controlled ventilation of the cavity (chimney façade).

Figure 89
Debitel Stuttgart, RKW Architektur + Städtebau, Stuttgart

Figure 90
Corner situation

Figure 91
Alternating façade: Boxed windows with internal sun-shading alternate with vertical operable windows that are protected by fixed louvers. These cannot be opened in strong wind conditions.

The functional extension of double façades requires a large constructive effort. Double façades are usually custom made. Most constructions belong to the family of curtain wall or unitised systems. The outer layer is specially designed.
Interesting for this research is the fact that the design of double façades is interwoven with the building services concept and that, in most cases, the façades are combined with decentralised or central HVAC systems. Therefore they require a design team of architect, building physics consultant, climate designer and façade consultant.

§ 5.4 Integrating building services

Another strategy to enhance façade functions is to integrate building services. The idea is to provide the interior space with heating, cooling and ventilation through the façade. In certain cases, such a decentralised approach has advantages over central HVAC systems such as direct individual control, or less space required for the central shaft (Bilow, 2012) (Mahler et al., 2008). The strategy has been applied mostly in office buildings in combination with curtain walling façades. Offices are subjected to high comfort requirements; and, generally speaking, high investments in building services and façade can make decentralised concepts feasible.

The goal of this chapter is not to discuss the advantages and disadvantages but rather to examine the effect of building services integration on the construction of curtain walls.

§ 5.4.1 Mur Neutralisant

Concept for an active window, Corbusier, 1929

During the 20th century, the development of the climatic active façade accelerated. The box window is one of the developments - 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 that closed of a volume to prevent, depending on the climate, hot or cold air, from entering. In this way the wall neutralized the outside temperature and other exterior influences. His idea was, however, never realised into a satisfactory product. It was simply ahead of its time. With a single layered outside glass pane one can assume that heat losses would have been extensive. He failed to introduce the system to different projects, and later turned to the idea of passive measures such as the ´brise soleil´. (Solla, 2012, Corbusier, 1991)

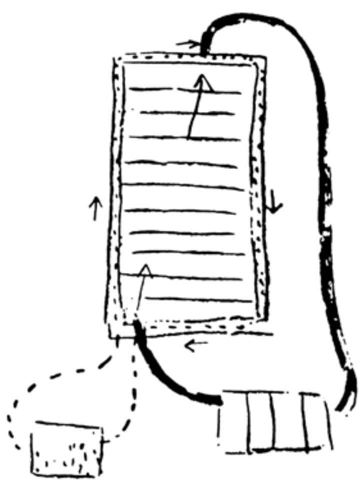


Figure 92

Mur neutralisant by Le Corbusier

§ 5.4.2 Lloyds of London

Richard Rogers Partnership 1978-1986, London

The structure as well as the building services are moved to the outside of the building in order to create large uninterrupted, column free interior spaces. It is the first time that the façade of a building of that size is actually part of a central building services concept. The façade has a cavity with a layer of double glazing on the outside and single glass layer on the inside. The exhaust air is extracted from the rooms through the cavity. The cavity provides comfortable façade surface temperatures on the inside pane. Ducts lead the air to the central HVAC system where heat is recovered. Fresh air ducts also run on the outside of the building. Built shortly after the Centre Pompidou, the building is another nice example of ´high tech architecture´ of the 80ies. Technology was displayed as a means of architectural expression (ArchDaily, 2010, Kilaire, 2012). Façade construction and building services integration:

Unitised, custom made aluminium façade. No building services are actually installed in the façade but are part of the central climate concept of the building. Exhaust air is collected in suspended ceilings and led through the façade cavity.

Figure 93
Lloyd's building, London 1986, designed by Richard Rogers

Figure 94
Detailed view on the external ventilation ducts

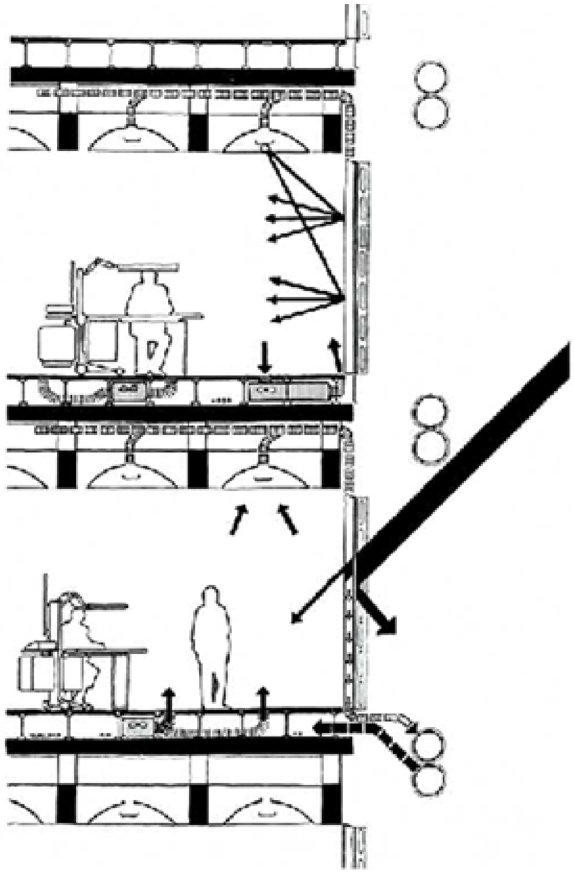


Figure 95
The energetic concept of the façade.

§ 5.4.3 Post Tower Bonn

Helmut Jahn Architects, 2003

The building is equipped with a double skin façade to protect the sun-shading system on the south side. The decentralised installation units are located on the floor slab directly behind the façade layer. They provide the interior with pre-heated or cooled fresh air which is taken directly from the façade cavity. The air is led to the sky gardens via doors and corridors, and is centrally exhausted from there. The base temperature in the offices is provided by activated ceilings, and decentralised units take care of individual temperature differences on a smaller scale. The façade cavity of the south side can be ventilated by operable flaps on the lower side of the scaled second layer.

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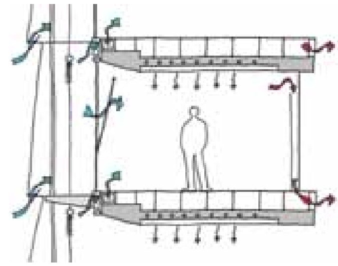

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Figure 96
Façade of the Post Tower, Bonn by Helmut Jahn

Figure 97
Detailed view of the decentralised ventilation unit

Figure 98
Climate concept of Post Tower. The decentralised unit is located on the floor slab on the inside of the façade. Fresh air is drawn from the façade cavity and pre-heated or cooled

Façade construction and building services integration:
Unitised curtain wall with custom designed exterior façade layer. Decentralised ventilation units are located on the floor slabs, separated behind the insulated inner façade layer.

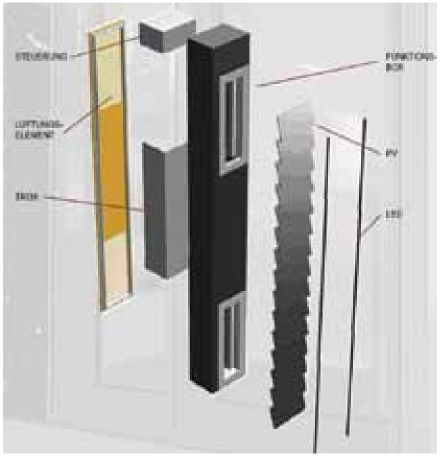
§ 5.4.4 TEmotion Façade

Unitised façade system, Hydro Building Systems, 2005
The unitised system has a transparent section in which sun-shading and elements for improving natural lighting are integrated, and an opaque section into which building services and solar cells are integrated. These two parts can be freely combined to allow a certain extent of architectural freedom. In addition, the system grid can vary and the relationship between the number of glass elements and functional elements can be chosen according to the needs of the room behind the façade. At least one functional element is required per room to provide sufficient ventilation, heating and cooling. The use of composite materials is limited, and the system can be dismantled to a great extent. This actually is true for most standard façade systems. The façade is completely prefabricated

Figure 99
Outside view of TEmotion mock-up (Hydro Building >Systems)

Figure 100
Inside view

The following decentralised services components can be integrated: Ventilation, heating, cooling, artificial lighting, devices to direct natural light, and PV cells for energy generation. Using a plug-in wire technology (plug & play) provides a high level of modularity. According to the producer, the amount of wiring in the façade is reduced by up to 60%, and the designers and users can choose whether or not to install a particular functional element in the beginning or at a later date, because elements can be added or removed at any time during use.
Mechanical ventilation, heating and cooling have been combined in one element produced by Trox/FSL. The size of this element is 0.30 m x 0.40 m x 1.30 m. 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. It can be controlled through a central building services management system or by the user him or herself. In addition, the façade controls itself and reports possible maintenance requirements to the control centre (Wicona, 2010).



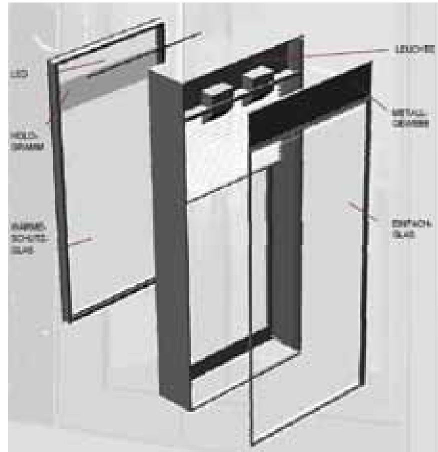


Figure 101
Component of TEmotion by Hydro Building Systems with building services components from TROX/LTG

Figure 102
Perspective view of facade system

Product architecture and building services integration:
Prefabricated unitised curtain wall. It is a system product distributed by Wicona. All building services are included in the physical façade layer. Modular product architecture allows the integration of building services components, including ducts for piping and wiring. The composition and choice of building services components allows a certain architectural variety.

§ 5.4.5 Smartbox Energy Façade

Joint R&D project by: ECN, cepezed, TNO Bouw & Ondergrond, Level Energy Technology, Glaverbel Westland, van der Vlught, 2006 (Smartfacade, 2006)
The Smartbox Energy Façade includes several features:

- The Smart Box, a decentralised system combining adiabatic cooling, heating and balanced ventilation
- Retro reflective interior blinds
- Glass spandrels with vacuum insulation
- Semi-transparent glass panels including PV cells

The Smartbox unit is positioned in front of the floor edge as an integrated part of the façade. This leaves room to combine the various kinds of panels.

Figure 103
Section through the Smartbox Energy Façade

Figure 104
The Smartbox

According to the inventors, the goal of more than 50% energy reduction can be achieved by using the following approach:

- Prevent the demand for energy (high insulation, no air leakage, solar shading, local HE heat and moisture recovery of ventilation air, etc.)
- Maximise the use of free, sustainable energy (passive solar energy, 'smart' day lighting systems, summer night cooling, PV electricity generation)
- Efficient use of remaining fossil fuel energy (local heating and cooling with efficient heat pumps)
- Energy generation by façade integrated photovoltaic.

The reference on what this reduction potential is based is not clear though. The inventors also claim that the decentralised system can save room for installations such as suspended ceilings, and can save up to 12% floor height and façade costs.
The Smartbox only needs to be connected to an electrical network. Water supply is necessary if the choice is to implement an adiabatic cooling device.

Product architecture and building services integration:
The Smartbox Energy Façade is actually a collection of integral elements and sub-components that can be combined with different curtain wall systems by modular interfaces. How the overall façade is designed to incorporate the unit or how fire protection issues are solved is not further defined and would be a task of the particular façade design for a particular project.
The Smartbox Energy Façade never went into production and remains on a prototype level.

§ 5.4.6 Integrated Façade, Capricorn Haus

Schossig and Gatermann, 2007
The façade has been designed specifically for this building, an office for the Capricorn institution. The façade is built up from specifically produced units enabling decentralised ventilation. They are prefabricated with dimensions of 2.70 m x 3.35 m. Each unit has a floor-high glazed part in form of a boxed window and next to it a closed panel containing a decentralised service module. Each room has at least one of these modules and interior walls can be connected to their sides.

Figure 105
Capricorn Haus, Düsseldorf 2005, designed by Gatermann and Schossig

Figure 106
Interior view

The façade contains the following features:

- i-modul: A specially designed decentralised unit for heating, cooling, ventilation and heat exchange
- Operable window
- Light shelf for light direction
- Venetian blinds for sun-shading in the cavity of the boxed windows.

The i-module requires an external power source and cold and hot water supply. The developers have tried to keep the size of the i-module at a minimum in order to let the module merge seamlessly into the façade. The width of the module is 104,9 cm, the height is 1065 mm and the thickness is 19 cm. Fresh air enters the module through a closable gap. The air enters the room through a grate in the parapet. The users of the façade can control the system individually (Schossig, 2012).

Product architecture and building services integration:

The façade is based on a unitised curtain wall system by Schueco and is specially designed for the project. The i-module is specially designed as well by TROX to meet the dimensional restrictions. It cannot be modularly replaced with service units with other properties.

§ 5.4.7 E² Façade

Schueco, Prof. Stefan Behling, 2007

All building services components are located in a designated space between the floor slab and the façade. For this reason, the façade is cantilevered with special arms. A box with the decentralised units can be installed between these arms. This box has an upper and lower compartment for servicing the room from the ceiling or the floor. Fire protection is solved in a layer between the two compartments. The façade can be equipped with cooling, heating and ventilation as well as heat recovery functions, depending on the interior needs. These services components are also developed by TROX.

Figure 107
Exterior view of the system.

Figure 108
Operable window running parallel to the outside plane and integrated PV-module.

Schueco has designed a new façade system that is a combination of curtain wall and structural glazing system. Window elements can open running parallel to the outside plane and, when retracted there is no architectural distinction between a fixed and an operable element. It is partly unitised and placed between the fixed horizontal elements that carry the installations. Along with the façade system, an integrated PV module and a CTB sun-shading system were developed that can withstand high wind forces and is hidden behind a cladding element when retracted (Schueco, 2010).

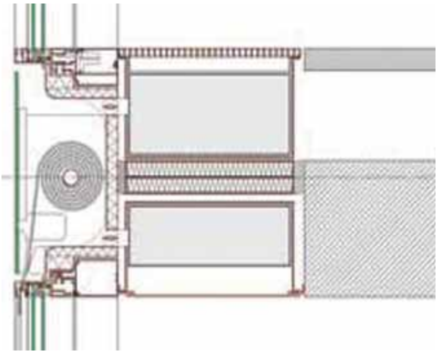


Figure 109
The arrangement of building services components with sun-shading device in front of the floor slab.

Figure 110
Facade section

Product architecture and building services integration:
The E^2 Façade is a curtain walling system which offers the possibility to integrate building services components at a designated space in front of the floor slab. Integral elements and sub-components are integrated with decoupled interfaces.
Features such as the hidden sun-shading device and parallel windows are also available separately but the system integrates them in a unique way. In terms of design, the closed horizontal cladding strip is mandatory and only the space in between the floors can be freely filled in.
Schueco uses the OEM strategy to market the façade which means that all parts and sub-components are distributed under one label. Schueco is responsible for product management, marketing, sales and is contact entity for liability issues. The complex system is difficult to communicate to clients.

§ 5.4.8 Product architecture of building services integrated façades

Figure 111 shows how the building services components are arranged in the case studies. In the Post Tower, their location is on the floor slab behind the façade. The only connection is an air intake nozzle. Façade and building services are integrally planned, but physically the components are not integrated. TEmotion and Capricorn have a decentralised unit located directly in the façade area. This results in an opaque panel, and the water pipes and cables have to be inserted into the façade construction from the inside. The E^2 façade and the Smartbox Energy Façade place the units in front of the floor slab. The benefit is an unobstructed outside view.

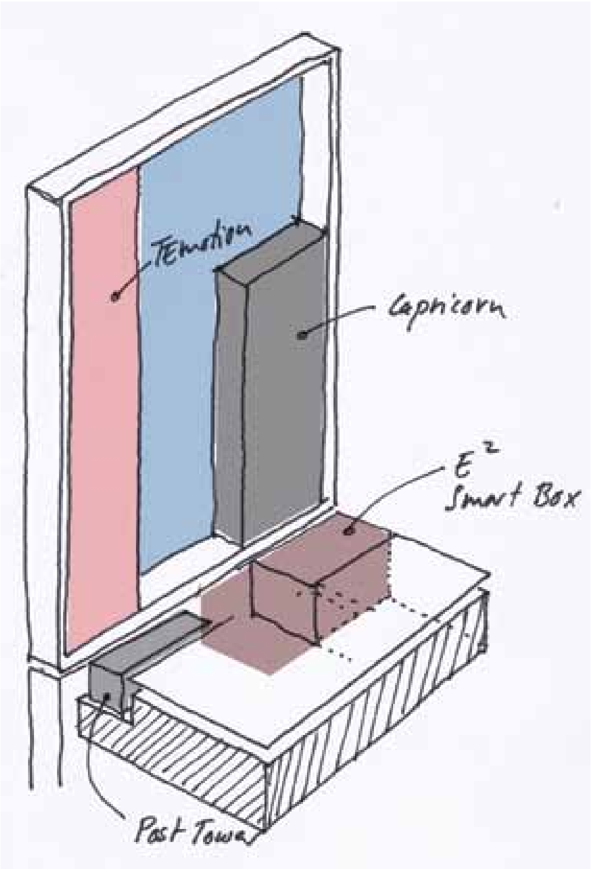


Figure 111
Arrangement of building services components in the façade examples

It is interesting to see that TROX was involved in three of the cases. TROX is a large German manufacturer of systems for air handling in buildings. In 2000, TROX bought FSL (Fassaden System Lüftung, Mannheim) which, founded in the 1970ies, already had a long history and therefore experience with decentralised installations in façades. According to the desired functionality and the geometric necessities, the decentralised units are composed of standard TROX components. Typically, a unit requires air valves and bypasses, filter elements, ventilators, components for heating, cooling and heat exchanging, silencers and devices for measuring airspeeds, temperatures, moisture a. o.. These components are tested and their performance is known. Thus, TROX is able to quickly create new designs.

The Smartbox is a completely new development. For the first time adiabatic cooling is introduced in a decentralised unit. For unknown reasons, the façade was only developed to a prototype level. The translation of such a new and technically complex

product into a mature building system in combination with production facilities and a distribution network is a difficult step. This explains the success of the TROX strategy. Existing components are simply combined in a new way.
Façades and building services are traditionally two different disciplines - the reason why these sub-components are locally separated or connected by decoupled interfaces. They are produced by different parties and the liability is distributed. And from a technical point of view this separation makes sense. The units need more frequent maintenance than the façade and they have to be accessed regularly. Their life-time is much shorter than façades. If a failure occurs it is relatively easy to exchange a decentralised unit.
By combining two different disciplines, the concepts show a new step in façade construction. Nevertheless, they rely on traditional façade product architecture. The idea is not to create a radically new type of façade, but to broaden existing possibilities without leaving the established ways of building.

§ 5.5 Curtain wall constructions and the design and construction process

In order to define the state of the art of curtain wall constructions and their relation to the building market, 15 façades and products have been analysed. The 6-step systematic that was developed in chapter 5 proves to be a valuable analysis method. Function structures and the scheme of product levels are graphic tools that help to understand in which way physical components are allocated to certain functions, what their role is for the overall system and how they are connected. The theory of product architecture provides insight into how these constructions are responding to the particularities of the design and construction process.
It becomes clear that contemporary curtain walls are rather complex constructions. The graphic tools are reaching their limits because it is impossible to completely map a construction that is made from several hundred parts. However, not all of the steps of the systematic have to be executed completely in order to gather the necessary information. It can be used in a flexible way, by focussing on a limited number of functions or on key components.

§ 5.5.1 Comparing different constructions

The product architecture of different constructions and products is described in the previous paragraphs. Their behaviour does not only depend on individual parts but also on the way they are connected with each other. Historic as well as contemporary product architectures are compared by sketching individual product profiles in the scheme of product levels (Figure 112).
On the horizontal axis, each product level is divided into integrated or modular. These are absolute terms, and it does not matter if a construction is located further left or right on the axis. The interfaces are either coupled or decoupled. All constructions are based on materials. These are neither integral nor modular. The scheme allows a comparison of the different constructions, although they cover different product levels. When comparing historic examples with contemporary curtain walls, it shows that higher requirements on energy performance and user comfort have led to a higher number of functions being integrated and to more complex and modular product architecture, spreading over more product levels.

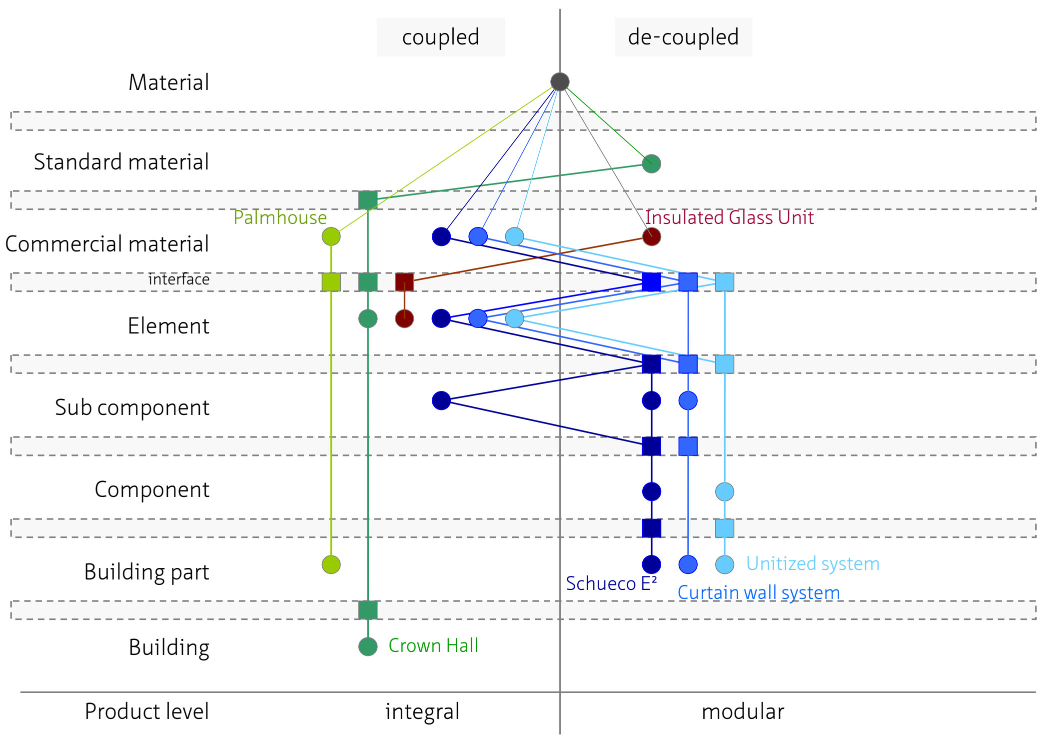


Figure 112
Comparison of the product profiles of the analysed constructions. The interface between different product levels can be coupled or decoupled. A relatively modular or integral architecture is indicated by the horizontal location to the right or left of the centre line.

Side note

The joint - from meaningful architectural tool to jointless desires

The bread bag clip is a device from our daily life that we seldom acknowledge. Its primary function is to close a bread bag in a reversible manner. Its predecessor was a flexible strip composed of two wires, connected by a plastic band. The new bread clip is constructed by a single material that deflects to open and then returns to its original shape. It is strong enough to perform this shape change often enough until the bag is emptied. The shape is designed to grip onto the plastic bag when closed and prevent it from sliding off. Its market success depends on one outstanding performance: Being ultimately cheap while maintaining the same functionality as its competitors. Later versions even have the expiration date imprinted: A truly multifunctional device and excellent example of integral product architecture.

read bag clip and strip

§ 5.5.2 State of the art in curtain wall construction

To begin with the historic examples: Both, the Palm House as well as Crown Hall are integral constructions with a low level of industrialisation. They are made from standard or commercial materials. The Crown Hall construction is even part of the structure of the building.

The insulated glass unit is a highly integral construction, composed of commercial materials. The standardised glass edge is designed in such a way that it can easily be connected to the bus interface of the curtain wall system.
Curtain wall systems and unitised systems belong to the same constructional family. Their smallest parts, such as rebate gaskets, are highly integral. They are made from single materials that serve multiple functions. For the rest, the architecture is extremely modular with decoupled interfaces. Elements such as IGU´s or panels can be attached by bus interfaces. They are standardised products of a system catalogue that can comprise as many as 150-200 parts (in comparison to the Palm House which is built from 5 different parts!). In essence, the systems are toolboxes for façade constructions.
The Schueco E² façade is shown exemplary for building services integrated façades. It shares its product architecture with curtain walls. The decentralised HVAC unit has an integral product architecture on the ´sub-component´ level which is connected by decoupled interfaces.

§ 5.5.3 Curtain walls and the design and building process

This process with which the standard curtain wall is designed can be described as ´reverse engineering´, meaning that a design problem is solved by applying proven constructions (tool box). It allows the distribution of tasks to different stakeholders and phases of the design process. This process has been described in detail in chapter 3. Whereas Mies van der Rohe is solely in control of the development of the Crown Hall façade, architects today need to rely on system products and the expertise of builders. Generally, the design process of curtain walls is as follows:

- System design
  The systems are designed to meet current regulations and to provide architects with a certain variety of design options. The modular architecture allows the integration of different infills, glass dimensions, etc.
- Architectural design
  The architect or consultants define the general layout and the specifications which are written down in the tender documents. These specifications are based on the existing systems.
- Execution design
  In the execution design phase these specifications are translated into façade constructions using the system catalogue.

The modular project architecture perfectly corresponds to this standard way of designing façades. Many different stakeholders are involved in the design of such a system. It is built on a project to project basis and must fulfil many different functions and regulations. Modular architecture is a strategy to create highly standardised and exchangeable components and still allow a certain amount of product variety.

§ 5.5.4 Technology development of curtain walls

Increasing requirements (functions) have resulted in an increasing complexity of the construction. Modular product architecture provides the opportunity to extend the product development to different subcontracts such as metal construction and glass components. This certainly has its specific advantages. Standardised interfaces allow for independent developments of the individual components. For example, new insulated glass units can easily be incorporated.
But the separation of functions also leads to less innovation. All providers of sub-components concentrate only on the improvement of a particular problem. Therefore components have grown more and more complex, rebate gaskets and isolators form the interface between them and have become less flexible due to their complexity. The analysis shows that an improvement could only be achieved by continuously complex nesting of parts. Radically new building methods or materials are hard to incorporate. Curtain wall system technology focuses on a broad application. It has become the benchmark system for architects and builders.

§ 5.5.5 Building services integration and the building market

The integration of building services is an answer to improve the global performance of façades and buildings. All built examples analysed in this work are customised solutions that required a certain development time, money and special commitment from all parties. The Schueco E² system and the Wicona façade are concepts for a systemised approach to the problem, but have rarely been applied. Both systems show modular product architecture which seems to be a logical choice, when looking at the design process described above.
The decision for such a strategy has a severe impact: Service components are traditionally planned separately and executed by installation companies. When integrated into the physical façade area, extensive coordination between the crafts is necessary: What performance and size do the decentralised components have? How are pipes and ducts run within the façade area? Who will install the services components? Building service integration could mean higher maintenance costs simply due to the number of decentralised units. It means shifting more of the investment amount to the

façade for the benefit of lower energy consumption of the building. The effect of such a decision for the functional layout of the building, user comfort, energy consumption, costs and the architectural design must be evaluated very early in the design process; a problem all by itself.
The number of realised buildings with services integrated façades is limited. Most of the known examples are built in Germany (approximately not more than 50). One reason here for could be that the regulations for architect's services in Germany give more responsibilities to the architects, as described in chapter 3. Conversations with participants of the Post Tower design in Bonn (Transsolar Climate Engineering) and the Radix Building in Wageningen (Architect DP6) confirmed this view by stating that architect and design team where the driving entities for these project solutions.
Up until this moment the author does not know of any buildings designed with the E^2 façade or TEmotion systems. This is an interesting observation. The failure to establish systemised services integrated solutions cannot be explained with the quality of the products, because the systems are based on existing curtain walling systems. But obviously the strategies fail to convince decision makers. However, more research is needed to ultimately explain the phenomena. But it supports the findings in chapter 3 that it is very hard to establish new concepts in the building market.

§ 5.5.6 Curtain wall product architecture and future challenges

Chapter 3 defined the challenges that the building industry will have to face in the future. These were translated into façade functions. Figure 113 illustrates the means with which curtain wall product architecture offers to fulfil these functions.
The basic characteristics of curtain wall systems can be used to conduct a generalised evaluation: They are established systems with known interface structures and responsibilities. Curtain walls constructions and their design and built procedures are evolutionary optimised. Please note that '+' and '–' in the evaluation column do not stand for an absolute judgement of curtain wall constructions. Rather, it is a way to indicate strength and weaknesses and to increase readability.

Future challenge	Function	Means of curtain wall product architecture		Evaluation
Minimize embodied energy	Choose materials with low impact	Replace parts with ones of lesser embodied energy (without changing functional properties)	-	Difficult without fundamentally changing construction
	Reduced material quantities	Optimize system structurally	-	Already structurally optimized system
	Offer recycle ability	Decoupled interfaces between commercial materials and elements / Develop re-use, recycle concepts	+	Modular architecture
Reduce operational energy	Improve level of insulation	Increase nesting of isolator architecture. Possible only with infill elements.	-	Only marginal possible. Mature system
	Adapt to climate	Integrate adaptable infill elements and sub components	+	Modular architecture
Predict façade performance in terms of	Embodied energy	Assessment of individual commercial materials, elements and sub-components and their interaction	+	possible prior to design process because of known catalogue
	Operational energy	Calculate the system as a whole in relation to building. Pre-calculate certain assembly options.	+	possible prior to design process because of known catalogue
	Comfort			
Create a faster process	Shorten design process	Faster declination of standard design procedure	-	Difficult because of inherited decision making structure.
	Shorten production and assembly process	Use broadly accepted technologies (tool box)/ Increase level of pre-fabrication	-	Difficult. Results in less flexibility for design
	Reduce external risks	Decoupled interfaces between system and infill elements. Maintain clear responsibilities.	+	Known system and clear responsibilities
Enable architectural possibilities	Bridge knowledge gap between stakeholders	Use broadly accepted technologies (tool box)/Provide different levels of information	+	Accepted technology
	Allow architectural variety	Enlarge system catalogues for design options	-	Always limited to product catalogue
	Support architectural design intentions throughout process	Specify design possibilities / make stakeholders aware	+	Known architectural implications
Stimulate innovation	Control innovation centrally	System management bound to inherited interface structure	-	rethink interface structures could mean complete change of product characteristics.
	Incorporate decentral innovation	improve commercial materials, infill-elements and components separately	+	All sub systems suppliers innovate separately
	Upgrade existing construction	De coupled interfaces between elements and sub-components to allow upgrade, exchange	+	All sub systems potentially exchanged separately

Future Challenges CW

Figure 113

How curtain wall product architecture can address future challenges.

The modular product architecture of curtain walls scores very high when it comes to functions that rely on the separation of commercial materials, elements and sub-components such as recycleability, climate adaptation, decentralised innovation and upgrade of constructions. The application of a well known façade system allows a founded prediction of façade performance before the design process has actually started; to bridge the knowledge gap between stakeholders and to support architectural design intentions throughout the process. The split responsibilities on the immaterial side help to reduce external risks.
However, the curtain wall system has reached a state of maturity and is structurally optimised. It is therefore virtually impossible to further reduce material quantities. And it is neither possible to simply exchange existing materials with materials of lesser embodied energy and same functional properties, because the entire construction, including the interface standards would need to be adapted. The same is true if a higher level of insulation is required. To shorten the design and building process is difficult and only possible if existing decision making structures are bridged. Such measures would most likely lead to less design flexibility. Finally, architectural design possibilities are limited to what the product catalogue offers, and controlled centralised innovation is limited by inherited interface structure. Rethinking these interfaces will potentially lead to a complete change of the product characteristics.

These results can be graphically condensed by using the scheme of the façade design and construction process developed in chapter 3. The resulting ´process profile´ focuses on mapping the interaction of the designing and building parties, and underlines the main features of the construction.

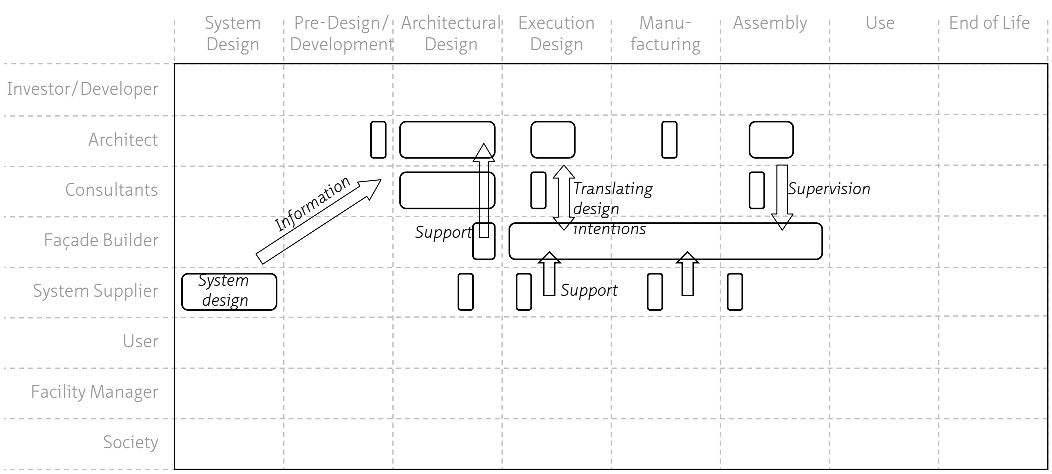


Figure 114
Process profile of curtain walls

The next chapter focuses on developing alternative approaches and on analysing cases with more integral product architecture, in order to understand in which way different product architectures, and accordingly different market strategies, will lead to constructions that will meet the future needs. Using individual process profiles helps to compare the approaches.

Summary

The analysis has demonstrated how the curtain wall has historically developed from craftsmanship oriented constructions towards highly systemised products. With increasing functionality, the systems have grown more complex. Whereas early curtain walls show an integral construction, contemporary systems are highly modular with decoupled interfaces. The tight correlation of its modular construction to the structure of the design and construction process with many different stakeholders has become clear. Furthermore, the analysis shows how curtain wall systems will potentially be able to address future challenges; where curtain wall systems will presumably perform well and where they will fail.

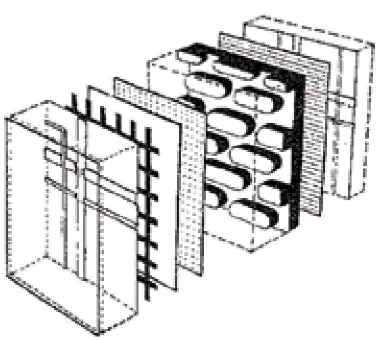
Side Note

The Polyvalent Wall

An important driving force for new façade technology is the ´Polyvalent Wall´. It is an idea of a new façade type, published by Mike Davies in his paper ´A Wall for all Seasons´ (Davies, 1981). The basis for Davies' idea was formed by the problems which were encountered during the energy crisis: the metal-glass façade appeared to be energetically insufficient unless new discoveries were made.

Architects realised that unlimited energy sources such as the sun could hereby play an important role, which resulted in architecture featuring glass on the south façade to let solar energy penetrate, and a closed north façade which limits energy losses. This strategy would strictly limit the use of glass to areas where its use would make energetic sense.

Davies, however, argued 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, view and contact with the outside world are still desired aspects, the use of glass remains to be very important. Besides that, he argued, silica - the base material for glass – is the most abundant element on earth.
He saw that the success of glass lies in the combination of this material with other elements, such as curtains to stop incident daylight and sound, shutters to reflect heat and blinds to prevent glare. The polyvalent wall itself was also intended to be built up from different layers on top of a glass layer to act as 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 ensure that the façade acts like an automatic responder to the outer circumstances on one hand and the inside users on the other hand, the façade needs to have a local micro-brain and sensing nodes connected to a control processor which carries information on usage schedules, habits and environmental performance data from the users of the building. Although Davies idea is described in an abstract way, we can get an idea about its product architecture: The Polyvalent Wall is a layered, multifunctional and highly integral construction.



The polyvalent wall by Mike Davies

Unfortunately the glass industry has never been able to realise this idea. But the idea was not without effect: it formed the basis for many new façade technologies and it could even be considered the preliminary idea for a totally services integrated façade.

DAVIES, M. (1981) A Wall For All Seasons. RIBA Journal, pp. 55-57.

6 Case studies for a new approach

§ 6.1 Introduction

The previous chapter showed that the mature and modular product architecture of curtain walls will make it increasingly demanding to meet all of the challenges façades will face in the future. This chapter aims at answering the following research question: What strategies can be found to overcome the existing design and construction procedures and the mature construction concepts?

It is based on the following propositions: First of all, there must be other and better construction solutions. Secondly, the answer can be found in more integral types of construction. It is clear now how closely tied the development of the curtain wall is to the design and construction process. This leads to the third proposition that any other type of construction will also demand a different decision making procedures and stakeholder roles.

In order to identify such strategies, a number of case studies are analysed. Some are of an explanatory nature by analysing existing façades and products; some exploratory such as the transformation of rapid manufacturing processes on the field of façade construction; and some are experimental in that certain product architecture modifications have been tested with student designs.

The cases have been grouped in categories according to distinctive features that distinguish them from standard curtain wall systems. The chosen categories relate to integral constructions, new materials, production technologies and stakeholder relations. Finally, experimental designs illustrate how a completely different approach to construction can have a large impact on façade performance in terms of the future challenges. Nevertheless, it shows that most of the cases differ in more than one aspect. When, for example, a new production technology is used, the relationship of stakeholders will automatically be affected as well.

In the previous chapters, graphical schemata have been developed that serve as a tool to compare the different cases. Function structures and product level schemata are useful to describe the product architecture of a case. Applying the scheme of the design and construction process is a way of mapping its process behaviour.

The case studies are analysed using a sequence of steps. Depending on the type of case study step 2 or 3 might not be applicable:

- Step 1 – Data collection
- Step 2 – Sketching functions, functions structures and/or product levels and interface typologies
- Step 3 – Sketching the impact on the design and construction process in form of a process profile
- Step 4 – Evaluation in terms of future challenges

Whereas this chapter concentrates on describing the cases in depth, the following chapter 7 focuses on a final comparison of the cases.

§ 6.2 Integral construction

Compared to the modular product architecture of curtain walls, integral constructions offer distinct advantages. Three cases show that different process profiles are a prerequisite. The builder Holland Composites uses glass fibre reinforced sandwich panels as a base technology for façades. The integral product architecture of the Inholland façade is optimised in terms of structural performance. The Smart Post is a study based on the idea to integrally combine a façade system with water supply ducts and electricity networks.

§ 6.2.1 Windesheim Gebouw X, Zwolle

Involved parties	Architect: Broekbakema Builder: Holland Composites Industrials
Time span of development/implementation	2010
Status	Build project solution

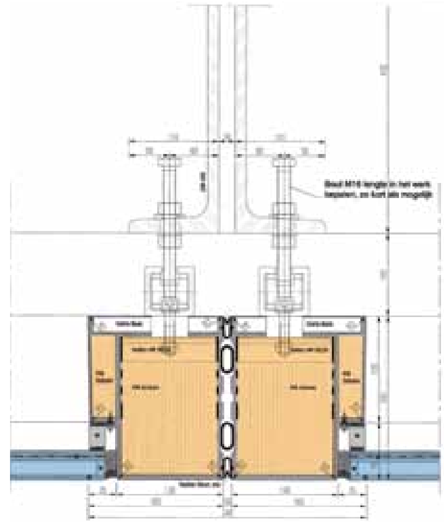


Figure 115
Assembly of the large pre-manufactured façade components

Figure 116
Standard detail of the construction

Step 1 – Data collection

The entire façade is made out of 3m x 12m large prefabricated GRP sandwich panels (glass fibre reinforced plastics). All the necessary window openings are integrally formed in. Special built-in parts such as fixing brackets are laminated into the panels. Glass panels do not have a special frame; but are glued to the sandwich with silicone. Working with composites requires a special planning and building process. First, a negative mould is created, which is expensive and requires several weeks. Thereafter, the production of the actual façade components can begin by placing fibre sheets into the mould, adding the foam core and built-in parts. Resin is injected under vacuum. The injection process takes a couple of hours, and a façade component can be produced within a day. After the production of the negative mould, building and assembling the façade is relatively quick as a result of the large components.
In this process, the entire design work needs to be shifted to the beginning. No changes can be made after the production of the negative form has started. A highly integral process is required because its final structural and thermal performance will depend on the thickness and shape of the panel, as well as the core materials and reinforcement layers. This is only possible because Holland composites signs responsible for design and product of the façade.

Step 2 –Functions structures and product levels

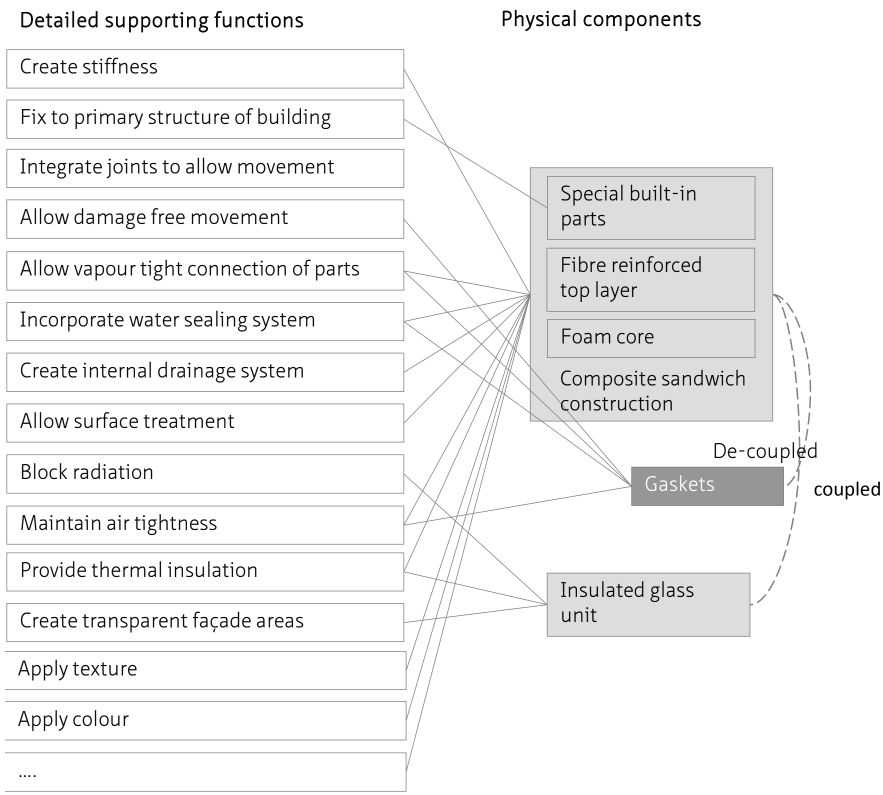


Figure 117

Function structure with many-to-one mapping

The façade of the Windesheim Gebouw has an extremely integral construction which shows in the many-to-one mapping of the function structure. Also, glass panes that can potentially break are integrally connected. But according to Holland Composites, the effort to cut them out of the frame is reasonable when considering potential risk. Modular interfaces are only provided between the components, which are designed for a maximum transportable size. This approach means that changes at a later stage or even disassembly at the end of lifetime will be very difficult.
The integral constructional concept requires flexible product facilities to create variety within a project or between different projects.

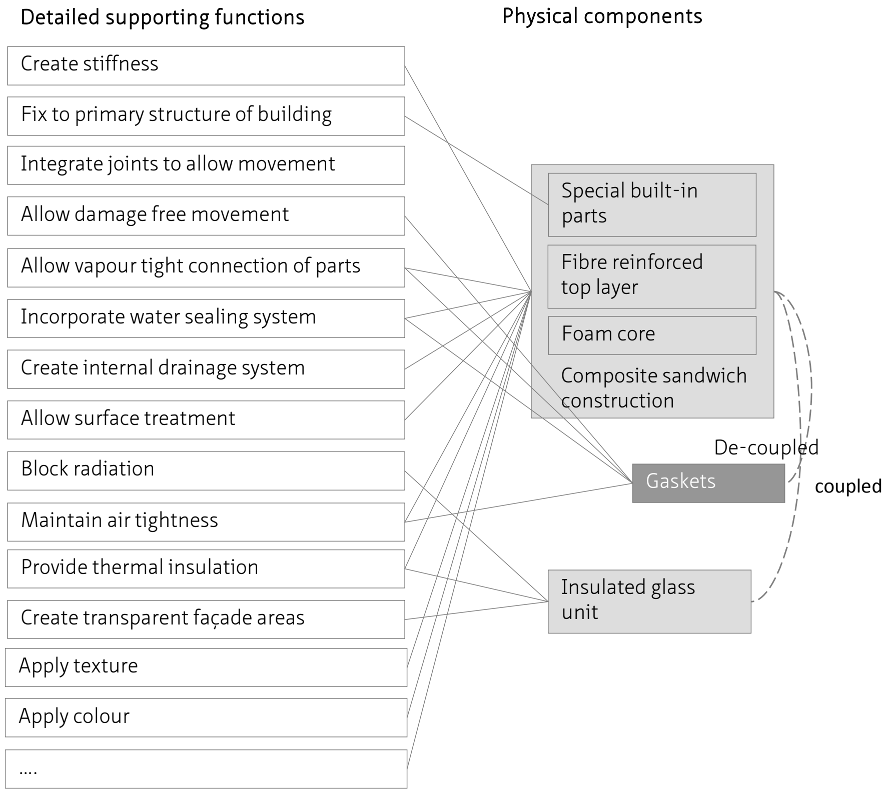


Figure 118
Product levels of composite façade. The façade is integrally produced on the component leve

Step 3 –Design and construction process

Although different external consultants were involved in the project, the builder was also closely involved during the architectural design phase with his engineering expertise. The manufacturing process demands that all architectural decisions are completed at an early project stage. When the execution design begins, and the negative mould is defined, changes can no longer be accommodated. It is interesting that there is no system design independent of the project. Rather, it can be considered the development of a technology, which has become the unique selling point of Holland Composites.
The energetic performance of the façade is relatively good, due to minimal thermal bridging and the insulation properties of the used materials. In terms of end of life behaviour, the technology needs further development. The integral construction can not be separated. To prevent it ending up on a landfill, bio based materials such as fibres and resins should be developed to create biodegradable constructions.

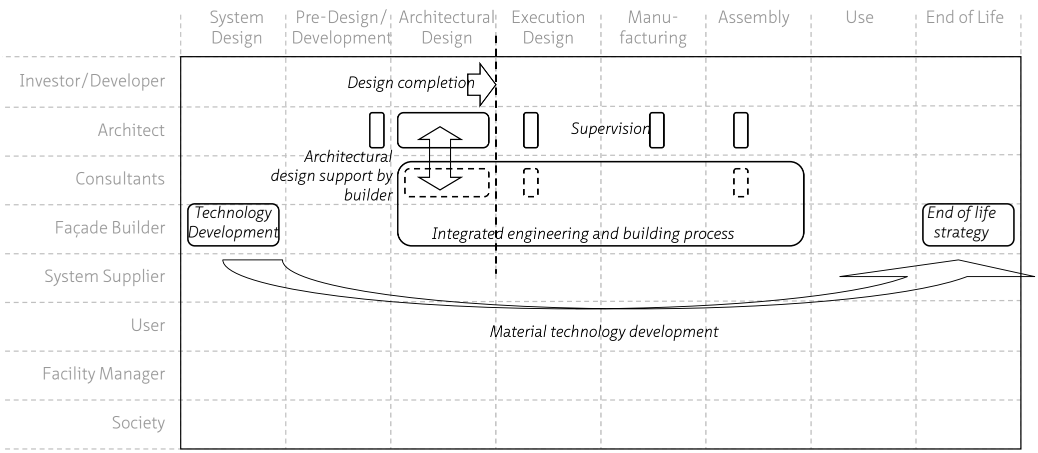


Figure 119
Process profile of the façade for the Windesheim Building

Step 4 – Evaluation

The façade is tailor made on the basis of a GRP sandwich production technology. Although regularly used in the 60ies and 70ies, it is a niche product in today's building market. The integral construction offers a good performance in areas such as energetic performance or weight. The decision for this type of construction needs to be taken at an early stage of the project. In order to create variety in terms of architectural design or different façade functionalities, a flexible production process is required. The architectural design possibilities are great but designs need to be frozen very early. Thorough integration of architectural design and engineering with the expertise of the builder is required. End of life strategies need to be developed.

§ 6.2.2 Façade for Inholland Polytechnic, Delft

Involved parties	Architect: Rietveld Architects Builder: Octatube
Time span of development/implementation	2009
Status	Build project solution

Step 1 – Data collection

This highly experimental façade is interesting, because it introduces composite materials as well as a new structural concept. The design goal was to create a very slender and transparent façade using composite materials in a structural way. This performance goal required an intensive integrated engineering and testing phase. The final concept introduced pre-tensioned aramide cables, run within the space of the insulated glass units to take up the wind loads; and stainless steel suspension rods to take up the deadweight of the façade. The entire system has a structural depth of only 50mm with the height of the façade exceeding 13m. However, the concept provided a number of serious technological challenges such as:

- A new concept for the spacer frame of the insulated glass units that are penetrated by the aramide cables
- A concept for the façade assembly, with glass panes being threaded like pearls on a rope.
- The bonding of the sealants to the glass and composite surfaces
- The use of composite cables in the building industry

This interesting development is described in detail by the specialist façade designer and build contractor Mick Eekhout (Eekhout and Rotten, 2010).

Figure 120
Façade elevation

Figure 121
Façade mock-up. The glass panes are threaded on the pre-tensioned cables like pearls on a string.

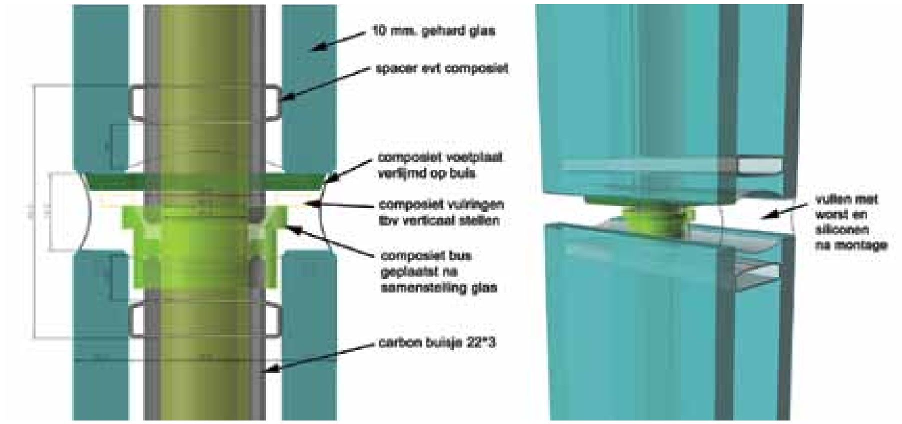


Figure 122
Detail of aramide cables within the insulated glass panes

The performance goal to minimise the structural depth leads to a strategy of geometrical nesting. Functions are not shared but the cables are arranged within the isolated glass unit. Eekhout comes to the conclusion that an experimental design and development process should be executed before the actual application. The short building process and the agendas of the different independent team players make a new integrative approach almost impossible. Nevertheless, according to Eekhout, the built façade proves that such a system could be realised within a few years

Step 3 –Design and construction process

The Inholland façade plays a unique role as a case study. The innovative construction was centrally developed by Octatube; who were responsible for the constructive design as well as engineering and building. Suppliers of materials and elements such as composite aramide cables and glass units supported the process. The architect had to maintain a certain openness in terms of the final design. After the design goals were set, the final design would consequently follow the outcome of the engineering results. The architect had the crucial role to communicate this special project to the clients. Since the primary goal of the façade was improving structural performance to an extreme, it is no wonder that the façade scores not as good in other areas such as recycleability or shorter design and built processes.

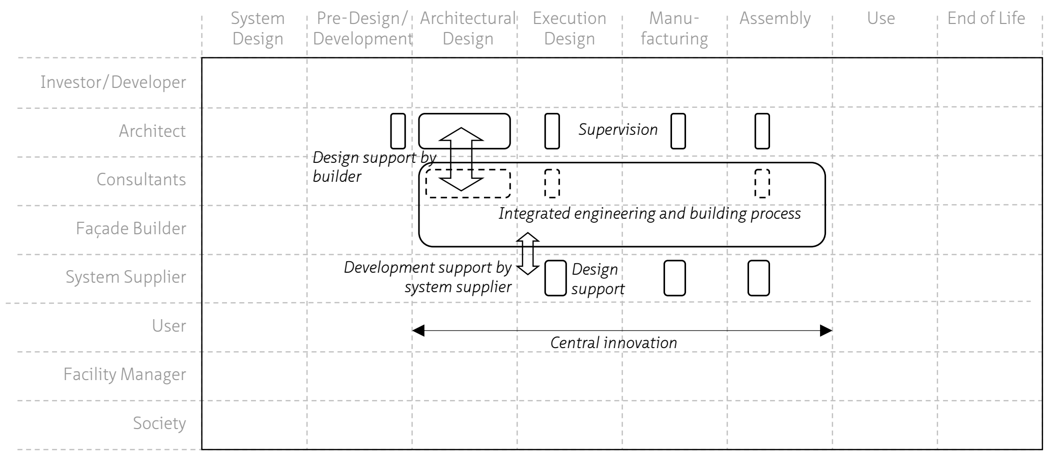


Figure 123
Process profile of the Inholland façade

Step 4 – Evaluation

The primary goal of the Inholland façade was to create a ´super slender´ construction. This is made possible by an integral construction with extreme nesting of components. Glass breakage, for example, will lead to a disassembly of the entire façade. An integrated design and manufacturing process is a precondition. The innovation is driven by one central entity.

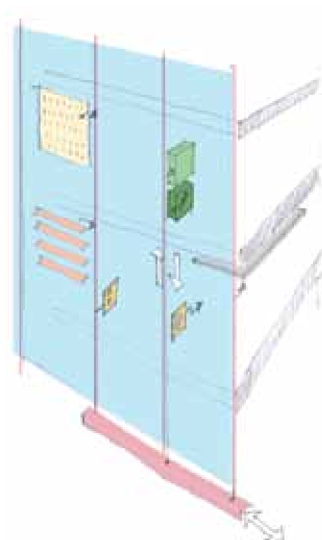
§ 6.2.3 Smart Post

Involved parties	Alcoa Aluminium Systems, TU Delft, Façade Research Group, Tillmann Klein, Joep Hoevels
Time span of development/implementation	2009
Status	Experimental façade system

Step 1 – Data collection

The idea of the ´Smart Post´ was to find out if a façade system could be developed that allows the integration of all kinds of building services. The façade post would accommodate all piping, cables and ducts so that all external components could be easily attached.

The project was supported by the graduation work of Joep Hoevels (Hoevels, 2007). And the contribution of the industrial designer Wim Poelman, who supported the project as a second mentor, needs to be mentioned.
The façade system should be able to accommodate the following functions: Ventilation, heating, cooling, energy generation, sun shading but also functions that would support the use of the building such as an 230 v electricity network, a data network or, for example, bookshelves. All ducting and piping would be running vertically. This way up to 4 storey high buildings could be served (Figure 124).
The final concept was based on an Alcoa unitised façade system. A façade coupling element was introduced to accommodate all pipes and cables, which are accessible from the outside (Figure 125). A special module was developed to transfer the media to the inside. In this manner, decentralised building services units and other devices could easily be plugged into the network.



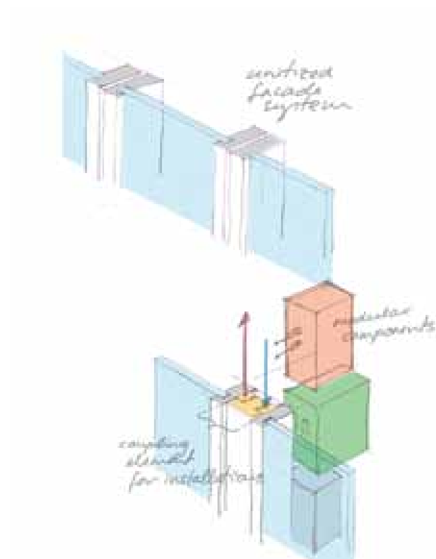


Figure 124
Cables and ducts run vertically up to four stories high.

Figure 125
A coupling element accommodates all media

A mock-up was built to determine the final size of the ´Smart Post´. It turned out that a minimum width of 180mm was required. A width of 230mm would allow attaching decentralised building services units.
Different design studies show the architectural variety of the system. The exterior design would offer many options. The interior could be available in custom designed

finishings, with, for example, wooden surfaces or an ´apple-like´ appearance with integrated control panels.

Figure 126

The mock-up was built to determine the final size of the ´Smart Post´. Components can be attached to the exterior and interior sides of the post.

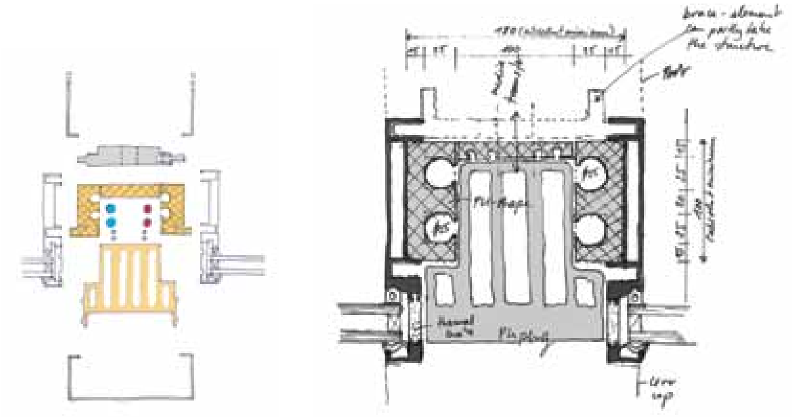


Figure 127

Concept details of the system

Figure 128
Architectural variations of exterior

Figure 129
Architectural variations of interior

Step 3 – Design and construction process

The concept of the ´Smart Post´ implies that the system is sold and built in the same way as the standard curtain wall. A positive feature is that the system could be adapted during use in terms of performance or interior design. For example, decentralised heating and cooling could be added. The interior design could be changed. However, the system also requires an intensive collaboration of client, architects, consultants and system supplier to define the initial configuration. Pre-installed ducting will lead to higher costs and the investment must carefully be considered. And the integration of building services (even at a later stage) has a considerable effect on the entire building concept.

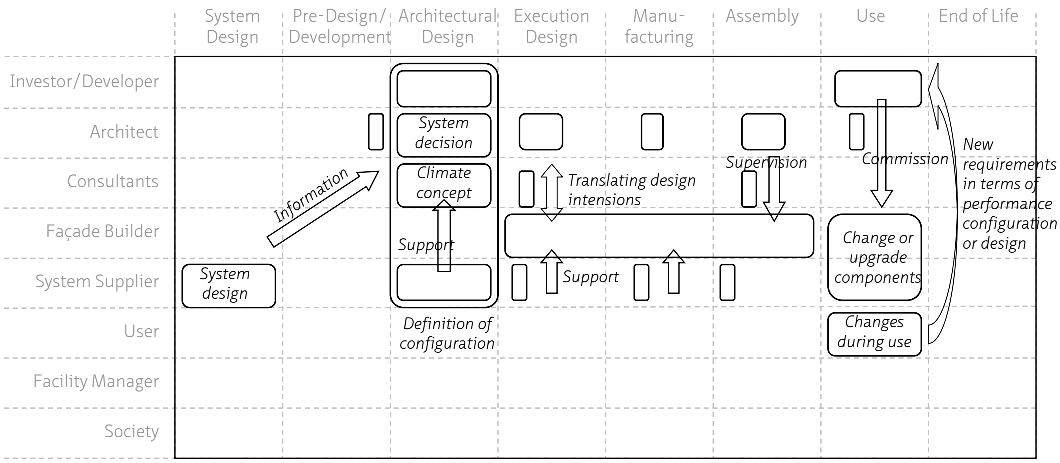


Figure 130
Process profile of the Smart Post

Step 4 – Evaluation

In terms of the future challenges, the ´Smart Post´ principally exhibits the same characteristics as standard curtain wall systems. The project is a good example of how the success of façade systems depends on the acceptance of architects. The project evaluation revealed an interesting aspect: In unison, architects argued that the ´Smart Post´ was much too broad compared to the slender 50mm standard systems. It was very difficult to communicate that the ´Smart Post´ has a much larger functionality. The judgement is rather owed to expectations than to the real need of as much possible transparency. The single negative function seemed to be decisive. The concept that the systemised solution could have a great impact on the interior design was not embraced by architects either; perhaps because of fearing limited design possibilities due to pre-designed features.

§ 6.3 Introducing new materials

The effect of new materials on façade construction is demonstrated by two examples. With the use of glass fibre reinforced plastics (GRP), the X-frame window system features a new type of product architecture. The Polyarch project deals with transferring nano technologies to the field of façade construction. A wealth of new constructional and architectural possibilities is emerging in this field.

§ 6.3.1 X-frame

Involved parties	Hansen Group
Time span of development/implementation	2010
Status	Available window and door system

Step 1 – Data collection

Though not a façade but a window frame, the X-frame is described here because of its unique and integrated product architecture. The product was originally developed for the Danish housing market by Hansen Group, a manufacturer of steel and aluminium curtain walling systems. The frame does not have the typical insulators to separate interior and exterior frame parts. Instead, the frame, as well as the operable part, is made from extruded glass fibre re-enforced plastics (GRP). The material itself has a low conductivity, yet is sufficiently strong. The insulated glass unit is structurally glued into the frame. It is part of the load-bearing concept and allows a very slender structure. It does not permit exchanging glass panes in case of damage. Instead, X-frame keeps a record of every produced frame and will reproduce and exchange the entire operable part according the stored data.

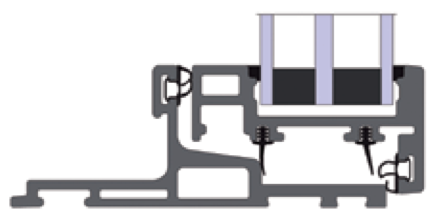


Figure 131
Image of X-frame

Figure 132
X-frame section. Extruded aluminium profiles can be attached for architectural reasons

Step 2 –Functions structure

There are a number of different base profiles to allow functionalities such as opening to the inside or outside. The EPDM (Ethylen-Propylen-Dien-Monomer) seals have a modular interface. Extruded aluminium profiles can be clipped on to allow architectural variety with different shapes or colours (Hansen, 2011).

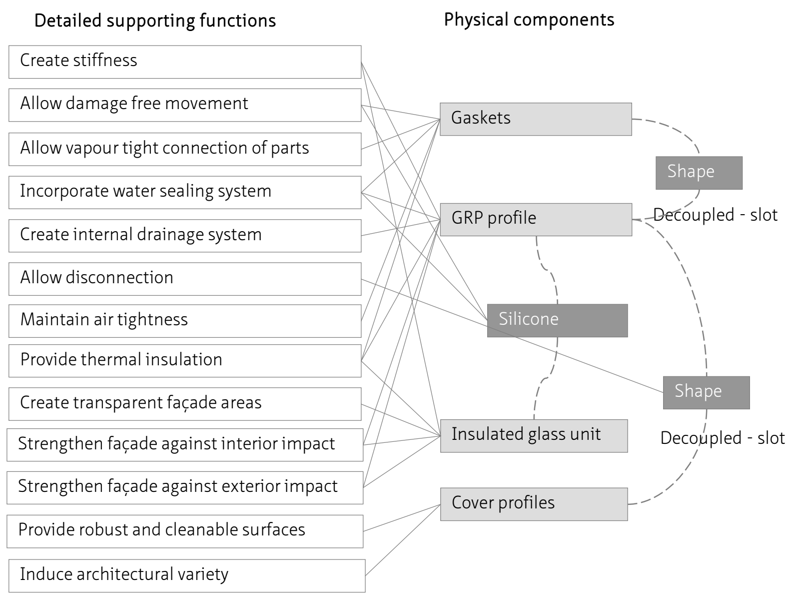


Figure 133

Function structure of X-frame with an integral frame-glass construction.

Compared to other standard aluminium window frames, it is a niche product, originally designed for the Danish market. The integral construction of frame and insulated glass unit results in a lightweight, slender and simple construction but does not allow high variety. The small number of parts allows an easy management of the system, but a product upgrade will require a complete redesign of the integral frame.

Step 3 –Design and construction process

The process profile of the X-frame is similar to the curtain wall. In fact, the system targets the standard market structure. But its relatively integral product architecture demands a strategy to organise the repair or exchange of the window.

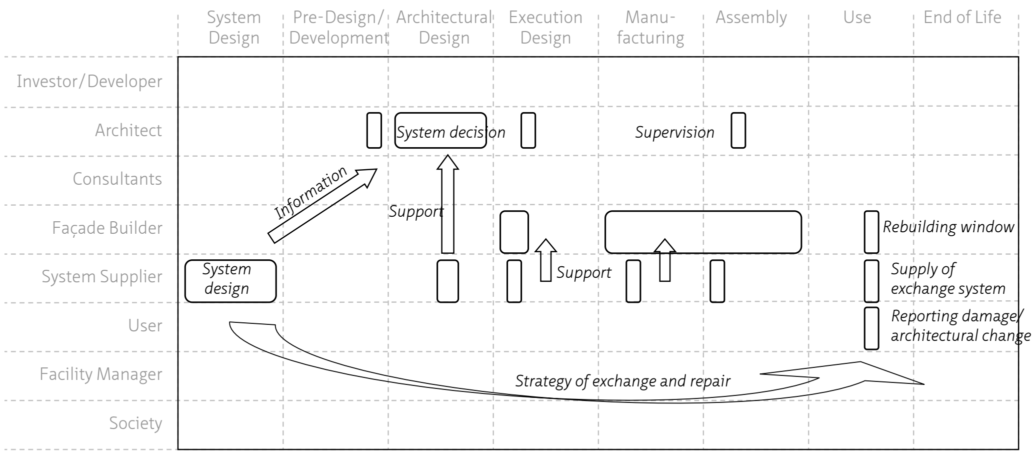


Figure 134
Process profile of the X-frame

Step 4 – Evaluation

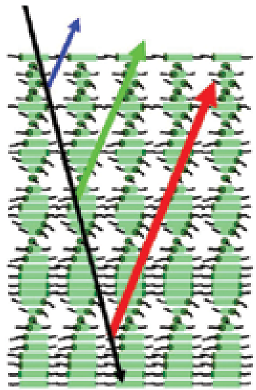
By using the material GRP, an integral base profile for the window system could be created that is structurally efficient and slender, and at the same time solves the problem of thermal separation of interior and exterior. In comparison to standard curtain wall façades and windows it requires fewer parts. It is completely pre-manufactured and is delivered to the site including the laminated insulated glass unit. In case of glass breakage, the entire window needs to be exchanged. A central database allows rebuilding of the window. Only a limited design variety is offered to the architect, but in return the production and management of the system is easier. Fewer parts must be kept on stock, the communication with builders is easier, and the risk of failures is lower. The cover profiles can be exchanged and potentially allow architectural change with different colours during the use phase.

§ 6.3.2 Polyarch

Involved parties	Collaborative project between TU Eindhoven, Department of Functional Organic Materials and Devices and TU Delft, Façade Research Group
Time span of development/implementation	start 2011
Status	Technology development

Step 1 – Data collection

The mission of the Polyarch project is to utilise polymer technologies in the field architecture. One of the aspects is daylight management. It deals with many, sometimes conflicting functions of the building. Generally speaking, a maximum of natural lighting is desired to reduce the energy consumption for lighting, which in today's buildings accounts for approximately 30% of the total electricity demand. But daylight contains a lot of energy. We need to block solar radiation in summer to prevent overheating, whereas in winter this incoming energy is desired to reduce the need for heating energy. There are several traditional strategies to control daylight. Metallic coatings on glass panes improve the reflective properties of glass; but they are not adaptable, which means that they also block energy in winter, when we potentially desire incoming energy. Exterior sunshades such as Venetian blinds are very effective if they are adaptable; but they involve considerable constructive effort and cost, and are vulnerable against wind and weather. This means they need to be retracted under windy conditions and are thus no longer functional.
This is the reason why double façade systems with an extra external glass layer are often used for high-rise buildings to provide a protective layer for the sun-shading device. The downfalls are a tendency of an overheated cavity in summer and the risk of condensation in winter. The costs are extremely high.
- Interior sunshades are much simpler and protected by the actual façade layer, but they are rather inefficient, because they block the incoming radiation after it has already penetrated the glass layer and the energy is trapped inside the room.
The existing daylight management strategies are rather inefficient or they involve considerable constructive effort, high investment costs, and high maintenance and cleaning expenditures. On top of that, the architectural impact of additional external or internal functional layers is large and they often do not meet the expectations of the designer.
The targeted technology of the Polyarch project is based on responsive polymers. With these materials, properties such as colour, reflection and heat transfer can be changed. Theoretically, the technology is available, but a considerable amount of material engineering is needed to develop new polymeric responsive infrared (IR) reflectors. They are based on cholesteric liquid crystals with controlled pitch of their molecular helices. Cholesteric liquid crystals exhibit one-dimensional band gap properties. The position of the stop band (reflection wavelength) can be accurately controlled by the pitch of the cholesteric helix which is determined by the amount of chiral dopant covalently bonded to the polymer. Heat and electricity will be used as triggers to toggle the reflection of the CLC automatically or manually.
The position of the reflection band in the electromagnetic spectrum can be dynamically shifted in response to temperature or light. Reflection can be shifted in the near infrared part of the spectrum; thus controlling heat flux without affecting transparency in the visible part of the spectrum. When applied on a glass window this film determines whether the heating part of sun light is being transmitted or reflected.



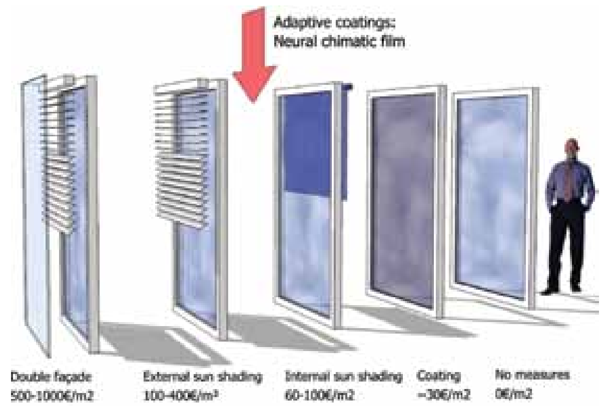


Figure 135
The pitch of the cholesteric helix will determine the reflection wavelength of the coating

Figure 136
Adaptive coatings might exhibit better performance than internal sun-shading systems

Step 4 – Evaluation

Since it is responsive, this technology will potentially deliver a much better performance than current static metallic coatings without the need for additional constructive effort for external sun-shading devices. The impact of this new concept on the established building process will be low. Polymers will be coated on glass panes, which are then simply installed like a standard insulated glass unit (IGU). A major difference is that individual logarithms need to be developed to control the reflection band in the electromagnetic spectrum according to the energetic behaviour of the building. The result would be a ´super integral IGU´ that also serves as a full sun-shading function. A high acceptance of decision makers can be expected.
The application of new polymer materials will enlarge façade functionality and lead to more integral constructions. The described example shows that when neural chimatic films are added, the same component can actively modulate daylight. The modular addition of a sun screen device is no longer needed. The façade will perform better while consisting of fewer materials, and will allow more architectural freedom. Architectural possibilities can also be broadened with colour changing coatings, for example.

§ 6.4 Innovative production technologies

Two new production technologies are introduced that will have a large effect on how we will construct and built future façades. Rapid Manufacturing is a quickly developing technology already used to produce customised goods in other industries. The case illustrates the far-reaching effect that this technology will have on façade construction. Gramazio & Kohler at the ETHZ have developed the technology for a brick laying robot and demonstrate how traditional craftsmanship oriented manufacturing could be automated with the benefit of customised onsite production.

§ 6.4.1 ´Additive Manufacturing´ technologies

Involved parties	Various
Time span of development/implementation	Ongoing
Status	Available production technology

Step 1 – Data collection

Additive Manufacturing (AM) belongs to the family of additive production methods. They are characterised by adding material layer by layer, resulting in the fabrication of finished products that are usable immediately, without the need for subsequent production steps or the need of a production tool ("tool-less": for example, no matrix is needed like in extrusion processes). All parts and components are digitally designed. The data files are transferred directly to production via a specific software.
AM processes can be compared with conventional desktop printing; except that processing materials are used instead of ink, and the process is not two but three-dimensional. The technology is developing fast, therefore today's limitations in productions speed, materials selection and size of the process chamber will be optimised during ongoing evolution.

Figure 137
The image shows a sintering facility where a large number of AM systems (so called 3D printers) manufacture parts 24/7. The maximum size of manufactured parts is limited to that of the processing chamber inside the printer. (Image: Holger Strauß: at FKM Sintertechnik, Biedenkopf, Germany)

This production method has two very distinctive features. First of all, it does not target mass production but allows customised production. Secondly, some AM systems can produce different materials and material combinations in one step and right next to each other. With further development of the technology, anything that can be virtually designed with modelling software can be directly produced. The dissertation by Holger Strauß ´AM Envelope´ (Strauss, 2013) points out the effect this technology will have on façade construction in the future.
Strauss predicts a development of AM technologies for façades in 3 steps:

Step 1. “An application, promptly realisable, with a practical aspect”.

Here he talks about conventional parts and components that will be substituted with those produced by currently available AM technologies, because they show a clear advantage, for example in terms of costs or customisation.

Step 2. “A modular component that complements conventional building technologies.”

Here he means the complementation of conventional construction methods with AM manufactured parts. An example is shown in Figure 138. It shows curtain wall connectors for 3-dimentionally deformed facades, developed by Holger Strauss for Kawneer Alcoa Architectural Systems. On the left side is a standard extruded aluminium connector, in the middle a customised three-dimensionally designed prototype made of ABS plastics, and on the right the final functional 3D connector printed in stainless steel.

Figure 138
A standard extruded aluminium connector on the left in comparison to 3D printed connectors from ABS plastics and stainless steel

Step 3. "The AM building envelope (AM architecture) that migrates from design to building construction in one step".

Entire façade parts or components could directly be produced with RM technologies.

Step 3 –Design and construction process

The direct use of AM technologies within façade systems (Step 1 and 2) is likely to happen during the next few years. One of the reasons is that it matches the traditional market process. In contrast, using the technology for direct fabrication of architectural façade designs would pose a real challenge on the traditional process. The complex requirements of façades would require building a broad knowledge base of the potential and the performance of the application of AM technologies in the field. Basically, anything might be possible, but it certainly will not be wise to completely reinvent the wheel. Project independent (because shorter project durations do not leave enough time) questions such as the following must be addressed: Which solutions prove to be durable? Which combinations with conventional systems or production methods are useful? Knowledge about all functional, legal and constructive aspects as well AM technologies are required to answer these questions. It will need a very close cooperation of architect, structural engineer, building physics consultant, façade consultant and AM specialist.
The architectural and execution design phases will be integrated. Here, the team must make a choice out of a wealth of opportunities and define the type of construction and product architecture that will meet the project goals in terms of use and end of life concept. The façade builder will be come a manufacturer specialised in AM technologies.

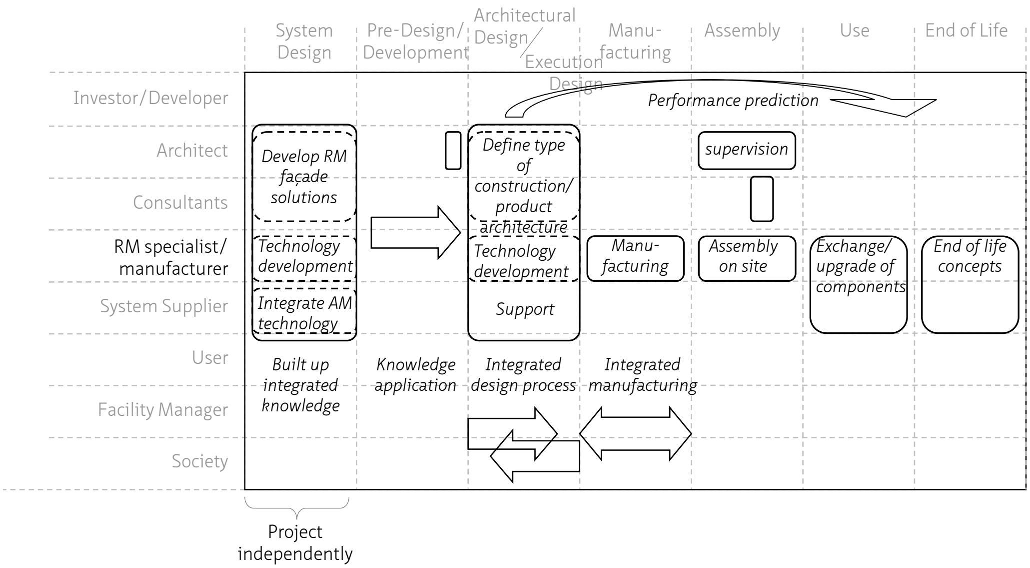


Figure 139

Process profile of AM based façades.

Step 4 – Evaluation

The technology will definitely boost integral constructions: Initially, specialised parts will find their way into façade construction. Over the next decade, entire façades can possibly be built with RM technologies. This will potentially lead to structurally or energetically high performance solutions. Architectural design possibilities will be enhances because of the potential for customised solutions. It is likely that the technology will be used in combination with other and cheaper means of mass production. The interesting prospect is that in addition to highly integral constructions decoupled interfaces could be introduced as well: Thus, implanting the benefits of modular product architecture where the most benefit for future challenges can be gained. If AM building envelopes can actually be built (Step 3), this requires a highly integrated technology development and design process.

§ 6.4.2 Robot-based brick manufacturing

Involved parties	Gramazio & Kohler, Architecture and Digital Fabrication, ETH Zurich
Time span of development/implementation	2008-2010
Status	Experimental production and assembly technology

Step 1 – Data collection

Robot-based brick manufacturing is a project by Gramazio & Kohler at the chair of Architecture and Digital Fabrication, ETH Zurich. Using an industrial robot, digitally designed systems are built on a 1 to 1 scale. Although the technology used in this project cannot simply be transferred to industrial fabrication of curtain walls today, it offers an interesting perspective on what might be possible in the future.
Brick is a classic building material, used for millennia, that still belongs to the contemporary architectural repertoire. Its main characteristic is its generic modularity. Being fabricated independently from the project, it is used to create onsite wall solutions in a repetitive manner. Laying bricks requires skill and is time consuming. A gluing technology was developed, especially adaptable for each brick laid; making bricks suitable for robot-based manufacturing. A measuring and correction loop is incorporated in the process, allowing the robot to even out all natural inaccuracies of the brick size. This way, façades can be built at calculable speeds and prices, independent of geometric complexity, and at a quality level that can not be matched by hand.
The production of preassembled components is thinkable as well, as an assembly onsite without any factory work needed. The size of components is limited to the moving range of the robot and its arm.
(Gramazio and Kohler, 2012) (Giera, 2011)

Step 3 – Design and construction process

When the base technology is developed, in this case gluing, it is necessary to understand the possibilities and limitations of the fabrication method. How much overlap is needed for different brick sizes? How high can a wall be and how much curvature can be introduced? During the architectural and execution design phases, the individual wall must be integrally designed according to the limitations of the system. No offsite manufacturing phase is needed. Little working preparation is required for the onsite manufacturing process. The process itself is clean and calculable.

Figure 140
Onsite fabrication of the Pike Loop Installation. It is a self supporting double curved installation in New York.

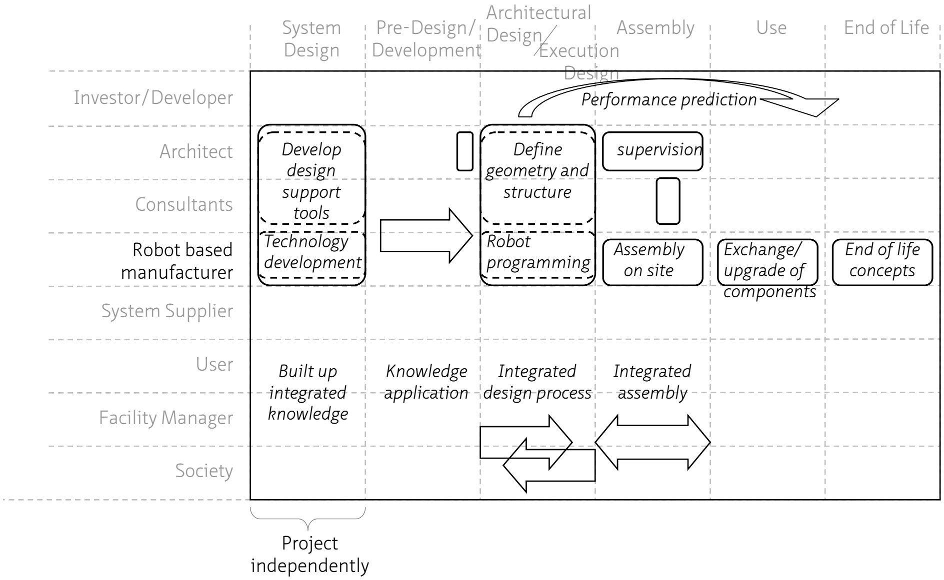


Figure 141
Profile of the robot-based manufacturing process

Step 4 – Evaluation

Due to its integral design, robot-based manufacturing potentially allows efficient and optimised constructions. In principle, performance can easily be predicted and use and end of life scenarios can be designed, although in the case of Gramazio and Kohler these aspects are not considered. Compared to craftsmanship oriented building, the assembly process will be rather quick and calculable, but depends on the building speed of the robot.
It can enhance architectural possibilities and allows a great variety. Similar to ´Rapid Manufacturing`, the optimal use of this technology requires building up knowledge before starting real projects and an integral design process.

Figure 142
Prototype of Flexbrick Façade system on a 1:1 scale as pre-manufactured façade panel .

§ 6.5 Targeting stakeholder relations

New façade concepts can be realised if we depart from the traditional stakeholder separation. The Next Active Façade is a building services integrated façade concept by an alliance of system suppliers. The concept aims at bridging the separation of different crafts. Solarlux unifies the roles of investor, architect, façade builder, system supplier and user to realise a low tech, energy efficient façade solution.

§ 6.5.1 Next Active Façade

Involved parties	Alcoa Aluminium Systems, Somfy, TROX, cepezed, Hurks, Delza, TU Delft, Façade Research Group, Tillmann Klein, Eric van den Ham
Time span of development/implementation	2010
Status	Available façade system

Step 1 – Data collection

Next Active Façade (NAF) is an approach to building services integrated façades. The project was initiated as a joint effort of ALCOA Architectural Systems, Somfy, TROX/FSL and the Façade Research Group, TU Delft. Together, the parties offer a broad range of knowledge and all components necessary for building services integrated façades. ALCOA provides unitised curtain walling façade systems. TROX/FSL offers an extensive portfolio of decentralised components, from simple integrated ventilation units to "all in one" components for heating, cooling and heat exchange. Somfy builds sun-shading systems and control units.
The architectural office cepezed has supported the project with its expertise in architectural design and technology. Further involved are Hurks Gevelbouw as façade builder and Delta Nederland B.V. as builder of sun shading systems.

The potential of a building services integrated façade is already discussed in the previous chapters. The idea behind Next Active Façade is to provide an open yet integrated system solution. Whereas the E² Façade, which comes as a completely new system with new design features, all distributed as a ready made product by one company; NAF aims at openly combining different existing systems, thus bridging the gap between traditionally separated disciplines.

The system can be used for new buildings as well as refurbishments. A number of standard façade building services configurations are pre-defined. It starts with a concept including a simple decentralised ventilation unit and ends with fully integrated HVAC including heat recovery. Depending on the presence of parapets, the climate units can be arranged vertically or horizontally. Different types of interior or exterior sun shading devices complement the concept.

Step 3 – Design and construction process

Since the Next Active Façade is based on conventional curtain wall technology, the function structure and product levels are similar to the standard curtain wall. However, the process profile shows some major differences. The alliance of system suppliers and possibly façade builders allows bridging the knowledge gap and shortening complex design processes that are necessary to develop services integrated façades. An early involvement, best before the architectural design process has started, is crucial, because the decision for the systems will have a big impact on the entire climate concept of the building. TU Delft has developed a calculation tool that helps to communicate the energetic and comfort benefits of the systems (Figure 145), meaning that it predicts the expected energetic and climatic performance of façade and building.

Step 4 – Evaluation

Obviously, the NAF concept will potentially offer low operating energy consumption. The prediction of energetic and comfort performance is actively supported by the system providers. Façade and building services combined are the most important factors when predicting the façade and building performance. Design and production process can be kept in a short range, due to predefined interfaces between the different system options. As soon as the decision for a certain product combination is made, the manufacturing of building services components can begin, even before the final design is completed.

The aim of the NAF is to provide architects with the same architectural variety as they expect from standard curtain wall systems.

Interviews with stakeholders show the following major challenges: firstly, clients like to work with one single responsible party. Secondly, when offering a modular product portfolio there is a high risk that decision makers try to get cheaper competitive products, not seeing the benefits of the originally synchronised system combination. In this regard, the NAF faces the same difficulty as the E^2 façade or the TEmotion concept: Even when providing systems based on known constructional concepts, the existing fragmented market structure reacts very reluctantly. When traditionally separate disciplines are to be combined, parties are sceptical despite the fact that a better energetic or comfort performance can be gained. Nevertheless, systems like the NAF must be seen as an attempt to change inherited and limiting procedures for the better by introducing concepts for a more integrated process.

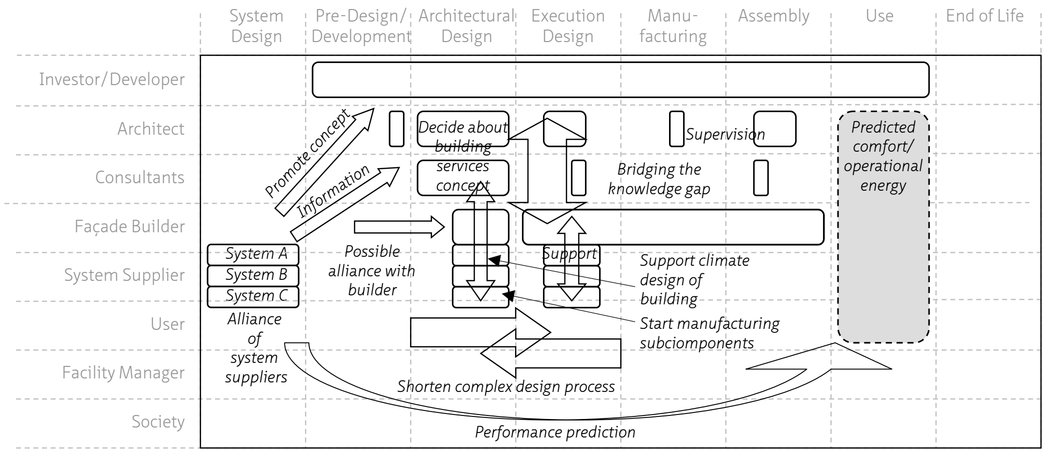


Figure 143

Process profile of the Next Active Façade

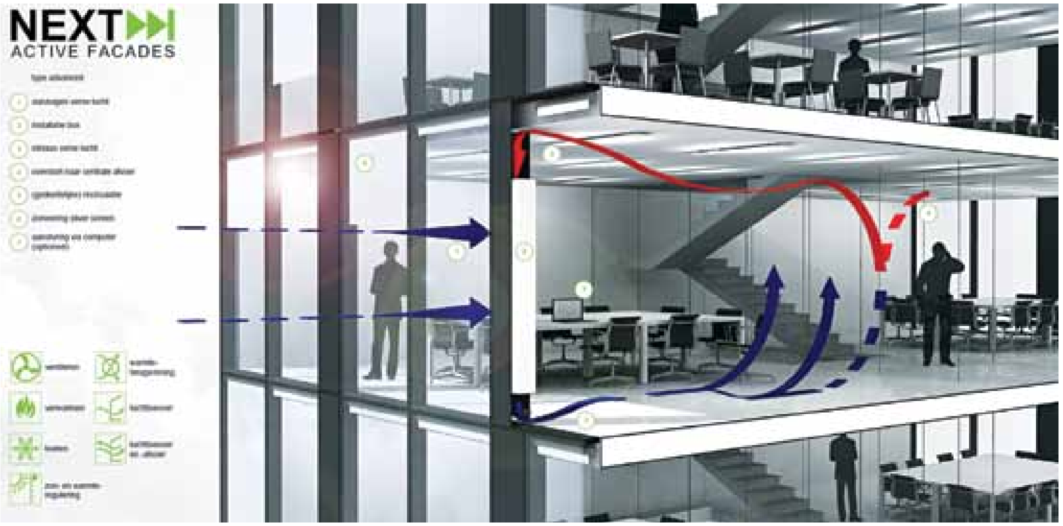


Figure 144

Perspective rendering of thr Next Active Facade working princile.

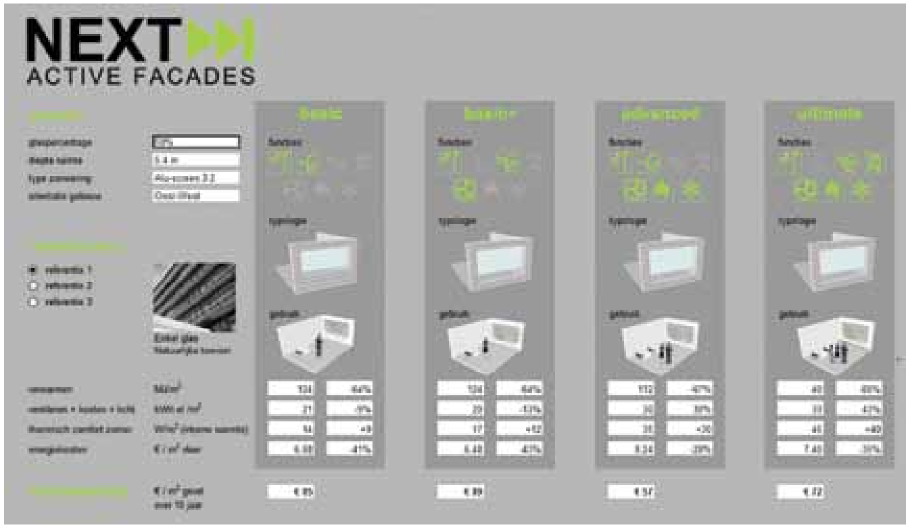


Figure 145

A calculation tool helps to communicate the benefits of the Next Active Façade to investors, architects and consultants

§ 6.5.2 Solarlux CO^{2}mfort Façade, Nijverdal

Involved parties	Architect: Wolfgang Herich (design), Solarlux, TU Delft Façade Research Group, imagine envelope façade consulting, Transsloar Climate Engineering, Thiemo Ebbert Builder: Solarlux
Time span of development/implementation	2010
Status	Build project solution

Step 1 – Data collection

In the course of a cooperation between the Façade Research Group/TU Delft, imagine envelope Façade Consulting and Transsolar Climate Engineering, a façade concept was developed for a new building for the Dutch sales office of Solarlux Aluminium Systeme GmbH, a German manufacturer of folding and sliding windows. The goal was to use company-owned products, and to achieve the highest possible comfort level using natural resources.

Figure 146
The picture shows the façade cavity with the inner insulated leaf opened.

A double façade was designed with the interior leaf made of a wooden, foldable insulated system. The outer leaf is made of a single layered foldable all-glass system. Venetian blinds are placed in the cavity to provide sun shading. For glare protection, a curtain is placed on the inner side of the inner leaf. The fully adaptable double façade wraps the office wing on three sides.
Overheating due to warm outside temperatures is prevented by opening the outer layer. In winter, the closed cavity provides extra thermal insulation. When outside and inside temperatures are equal, only the outer single leaf is closed. Opening both of the storey-high folding walls creates a sensation of working on a balcony.

Figure 147
The façade is adaptable; depending on wind and weather conditions, it can be fully opened.

The building is ventilated with manually operable windows alone. The thermal updraft in two atrium spaces supports the airflow. Geothermal energy is used for heating and cooling with low temperature activated ceilings. In rooms with particularly high heating or cooling demands, radiators can be connected on demand via simple plug-in couplings. Additionally, the waste heat of the server room can be fed into the heating system.
A share of the electrical operating energy is gained through a building-integrated photovoltaic system on the atrium roofs.
The lack of automatic control units requires the user to actively use the façade. User behaviour is always a problematic aspect; training and a thorough understanding of the functionality of the façade are required to achieve optimum comfort levels in the offices. If the user is passive and does not adjust the façade according to current weather conditions, the office space can easily overheat. The customised solution for Solarlux' own facility in Nijverdal promotes a critical examination of the company-owned building and products. For third-party customers and building projects, however, solutions with mechanical adjustment of the exterior glass layer are being developed.

Step 3 –Design and construction process

This energy efficient and low-tech façade was only possible due to the unique stakeholder situation. Solarlux is investor, façade builder, system supplier and user in one entity. The building was even designed by a company architect. The project was supported by an external architect and consultants. The concept requires continuous manual operation to ensure best comfort and energy performance. Therefore, the performance needed to be monitored during the initial phases of use, and the building behaviour was studied. In parallel, the users received feedback on how their actions impact the building performance.

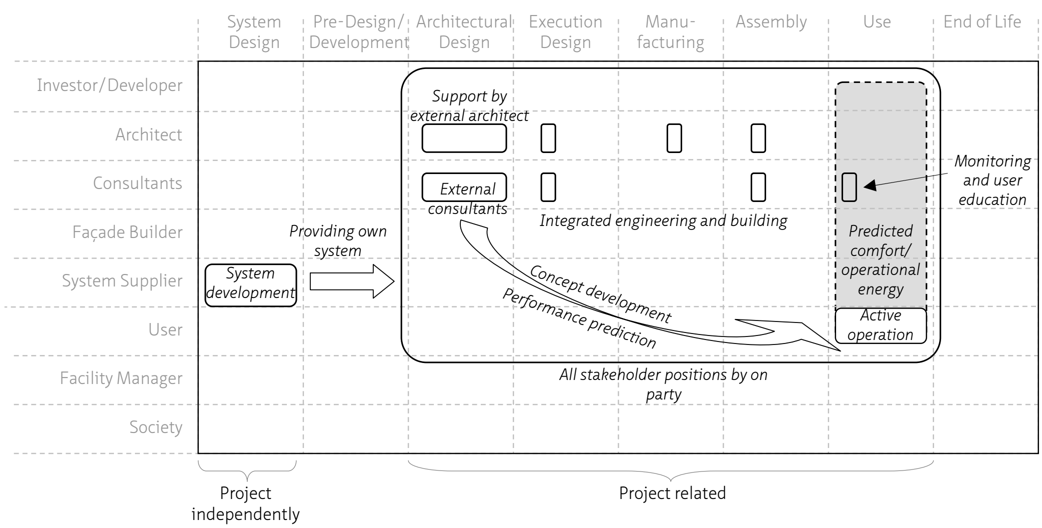


Figure 148
Process profile Solarlux facade

Step 4 – Evaluation

The façade construction is based on existing façade systems. The main invention is their combination to a fully adaptable double façade. The good climatic performance is reflected by the low measured energy demand of the building. Making the user a responsible factor of the operation of the building bears many possibilities. Firstly, it made this rather radical concept possible. But in addition, it saves the cost for complex control systems and leads to strong user identification with the building. However, it also involves certain risks. The entire project was only possible because basically all stakeholder positions were held by Solarlux as a single party, even though supported by external architect and engineers. An integrated design process made it possible to keep the development time for the new concept, including performance predictions and risk evaluations within a reasonable range.
The Solarlux Co²mfort Façade is a good example for what is possible when the traditional separated stakeholder situation is broken up, and a single party decides to take responsibility.

§ 6.6 Experimental student designs

These designs have been developed during 2009/2010 with students from the International Façade Master Program at the Faculty of Architecture, TU Delft.

(http://bk.tudelft.nl/index.php?id=15064&L=1)

The task was to take a new approach to façade construction, departing from the traditional "stick and filling" idea of curtain walls. Naturally, the focus did not lie on a fully functional façade, but a good representation of functionalities.
One example: If the task was to create a vehicle that can fly to the moon, the initial planning phase would not require a detailed drawing of the landing gear. An idea for a rocket is needed that transports the astronaut out of the field of gravity of the earth. Furthermore, a transport module in which he or she can stay during the travel time, and finally a landing module to approach the moon's surface. One may not yet have the proper material available, but can certainly define basic requirements.
Four scenarios were developed; each being different from a constructional point of view.

1. A façade that solely consists of components;
2. A façade made out of a continuous, graded material into which all functions are embedded;
3. A façade that is made out of different layers with the properties and the arrangement of the layers creating the desired functionality;
4. A façade concept that combines the positive product architecture features of component and layered façades.

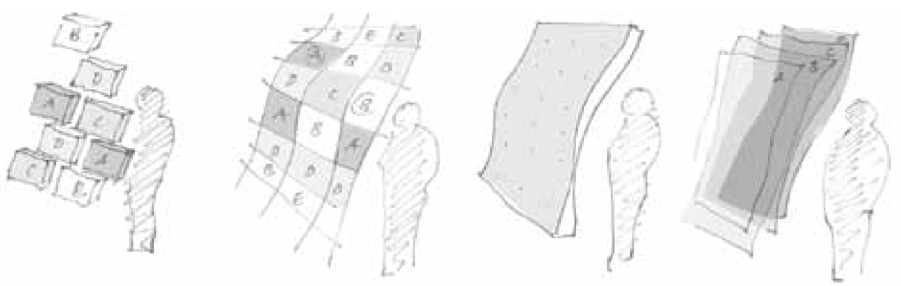


Figure 149
Four different constructional scenarios

The different scenarios were elaborated into schematic façade designs. Function structures and process profiles help to interpret the results.

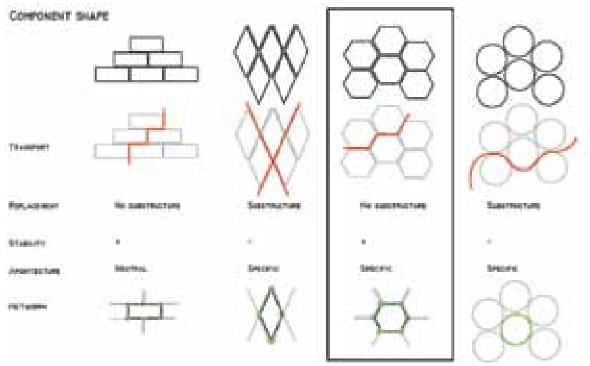
§ 6.6.1 Component façade – Leonie van Ginkel

Involved parties	Leonie van Ginkel, TU Delft Façade Master Program
Time span of development/implementation	2009-2010
Status	Experiment

Step 1 – Data collection

This scenario is based on the idea that the façade itself does not have an independent load-bearing structure but consists of equally shaped components that are connected with each other. The result of a form study (Figure 150) showed that the optimum shape for such a component is a hexagon. In nature, we find hexagons in honeycomb structures that contain maximum amount of honey with minimal amount of bees wax (Figure 151). However, each hexagon forms an independent component. In principle, each component can fulfil a different function such as energy generation or visual contact (Figure 152).

The final size of the components has not been determined. It would depend on the desired functional resolution of the façade. Alternatively, each component could be further subdivided. The biggest constructive challenge lies in designing the interface. Since the components should be arranged and exchanged arbitrarily and, at the same time, a special sealing system had to be developed. Leonie van Ginkel has schematically examined two possible construction methods for the components: a construction with an aluminium frame and a formed element made of polycarbonate (Figure 153). Both must have devices that interlock after placing the component and allow load transfer.



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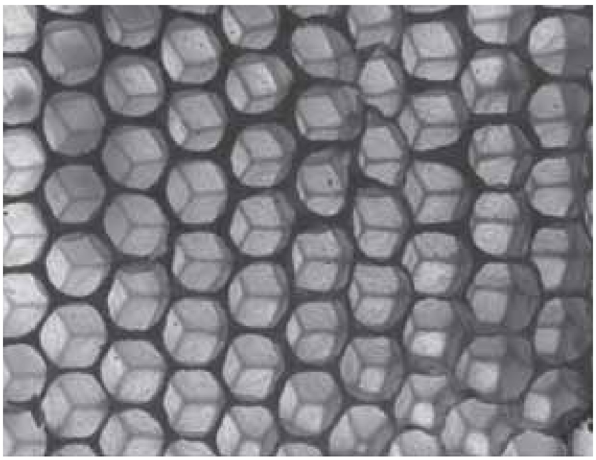

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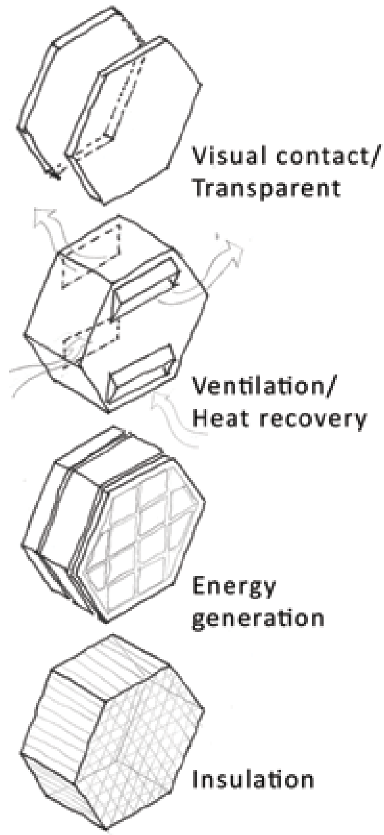


3

Figure 150
The hexagon shape, derived from honeycomb structures (1).

Figure 151
It proved to be an efficient starting point (2).

Figure 152
Each component can fulfil a different function (3).

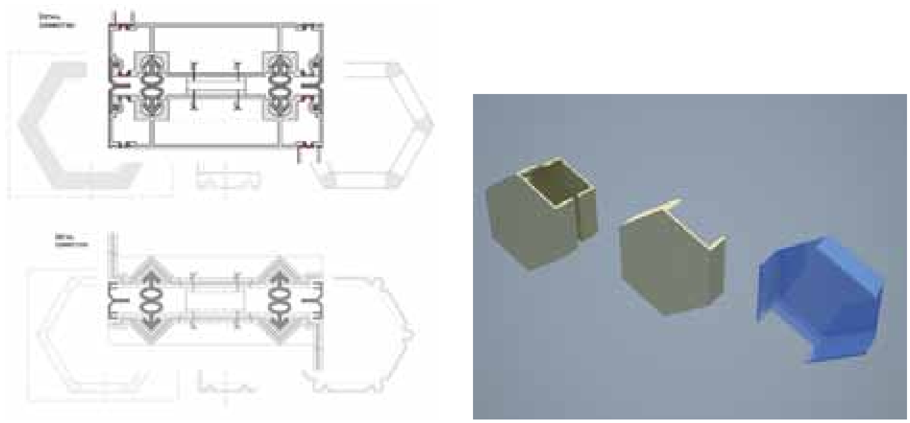


Figure 153

Schematic construction of the components with aluminium frame and polycarbonate material

The components are controlled via wireless communication. The information is analysed at a central location and then converted into action guidelines for each component Figure 154).

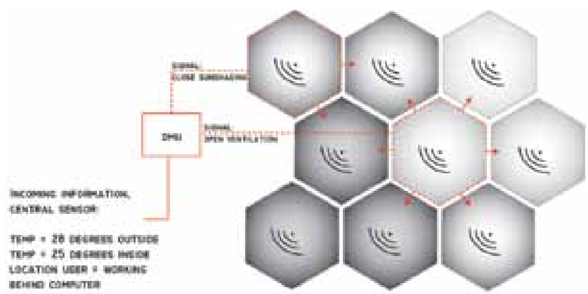


Figure 154

Control concept via wireless communication

Step 2 – Product levels

The unit frame box is the central constructive part of the scenario. It forms the interface between infill units and components, and proper specifications are of critical importance. All component manufacturers must adhere to these specifications to be able to seamlessly integrate the product into the system. A change of its construction after the system is established could prove to be very difficult if not impossible.

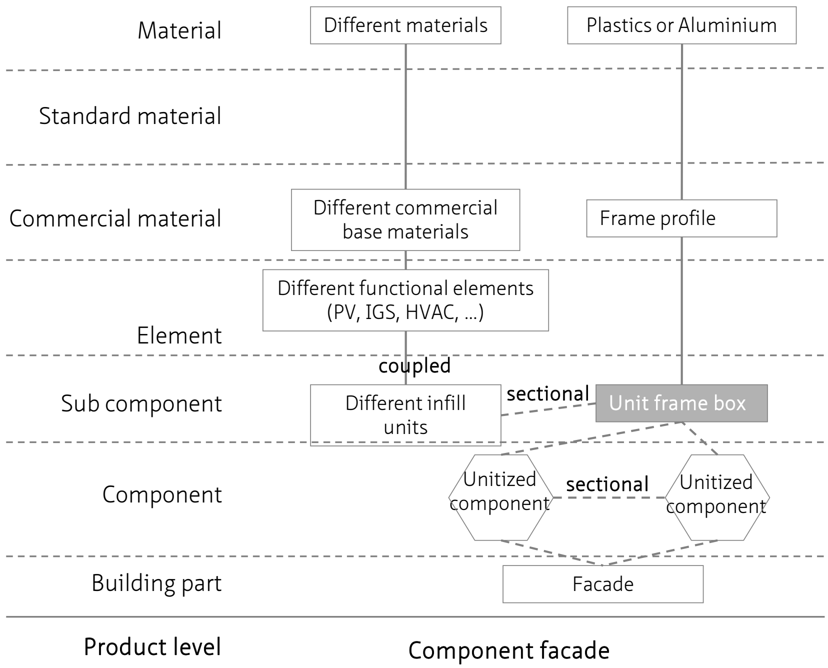


Figure 155
Product levels of Component facade

Step 3 – Design and construction process

The process profile shows that the entire system design and manufacturing is done project independently. Project related architectural design is limited to the arrangement of components. This way, the design as well as the production phases can be extremely short. Permanent decentralised innovation is part of the concept. The scenario allows an exchange and upgrade of the façade during use. This could be done for architectural as well as performance reasons. The end of life scenario includes reuse or resale of the components.

Figure 156

Spanish Pavilion, Expo 2005, Foreign Office Architects

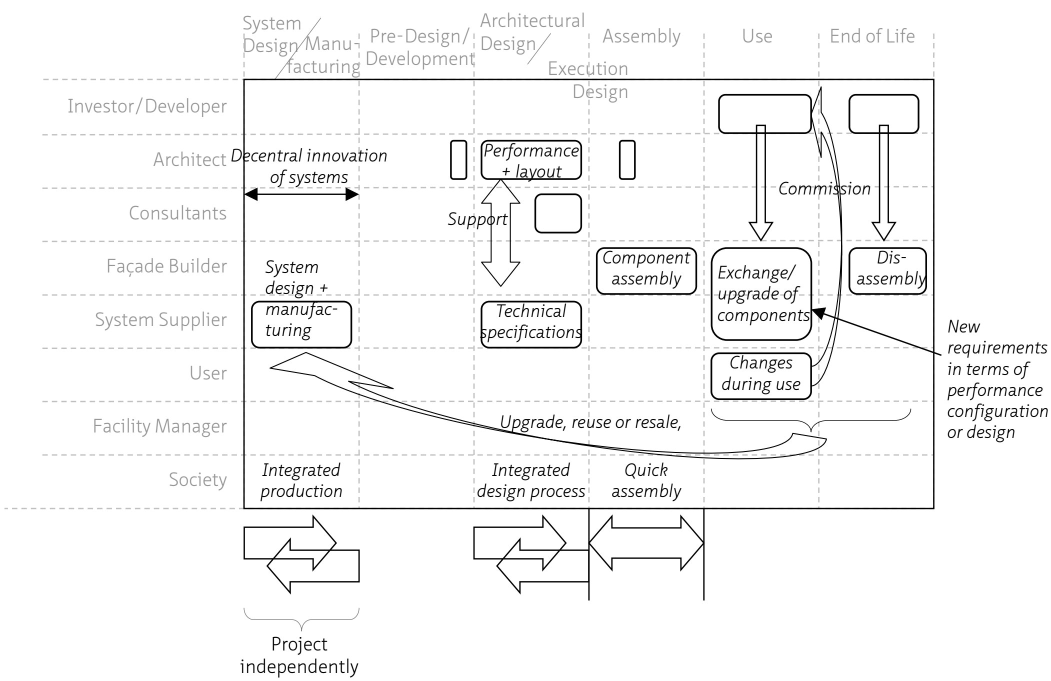


Figure 157

Process profile Component Facade.

Step 4 – Evaluation

The scenario offers a complete new approach to the way façades could be built and distributed. Countless functions could be integrated that do not have to be limited to the façade. Interior bookshelves, TV screens and other features are thinkable. Components could be treated like deposit bottles and come back to the manufacturer for reuse, resale or upgrade.
The façade is made from known, modular components which allows for founded performance predictions in terms of operational energy, embodied energy as well as comfort.
One cannot expect that the modular architecture performs very well in terms of the façade structure, since the unit frame means an extra constructional effort.
The component façade will offer much faster design and built processes, because most of the effort is shifted toward a phase prior to the actual project. Risks are very limited for all participating stakeholders. All parts can be elaborately tested before being sold.
The architectural design is reduced to façade performance specifications and the composition of the components. The limited design freedom is the major pitfall of this concept. An architect might not even be needed to compose the façade.
Different companies can independently develop and manufacture these components. As new, more powerful products become available, they can be seamlessly integrated into the system. A sufficiently high demand for such products guarantees continuous innovation. However, there is a disadvantage to the pre-defined interfaces, since it is difficult to modify them at a later stage, making them a possible innovation blocker for the entire system.

§ 6.6.2 Integral Façade – Charlotte Heesbeen

Involved parties	Charlotte Heesbeen, TU Delft Façade Master Program
Time span of development/implementation	2009-2010
Status	Experiment

Step 1 – Data collection

Charlotte Heesbeen explains her approach with the example of a tea cup (Figure 158). In the first cup, all primary functions are translated into one component. The second cup shows an integral architecture. The question is what a completely integral approach would mean for façade construction.

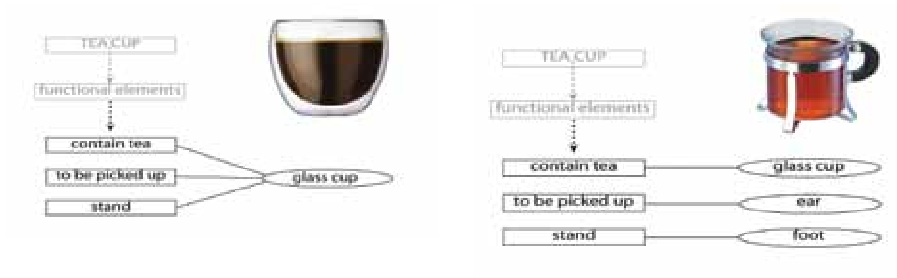


Figure 158
Integral vs. modular cup design

Heesbeen's inspiration came from bone structures (Figure 159). Basically, the entire bone is made from one material, but different zones embody different functional elements. The outer cartilage is soft and ductile and protects the actual bone structure. This is divided into a very massive and a sponge like structure to minimise weight.

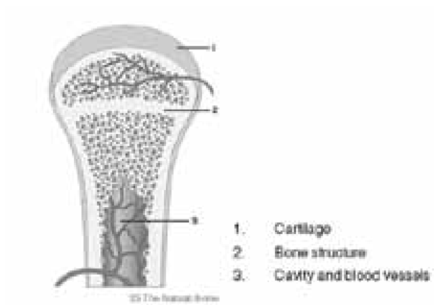


Figure 159
The structure of the bone as inspiration

The façade is made of concrete as a base material. Figure 160 shows how the concrete could be influenced in order to achieve different functionalities. Structure as well as insulation properties can be influenced by the mass and porosity of the material. For other functions, the shape can be adjusted or additives can be added, such as embedded reflective elements or glass fibres.

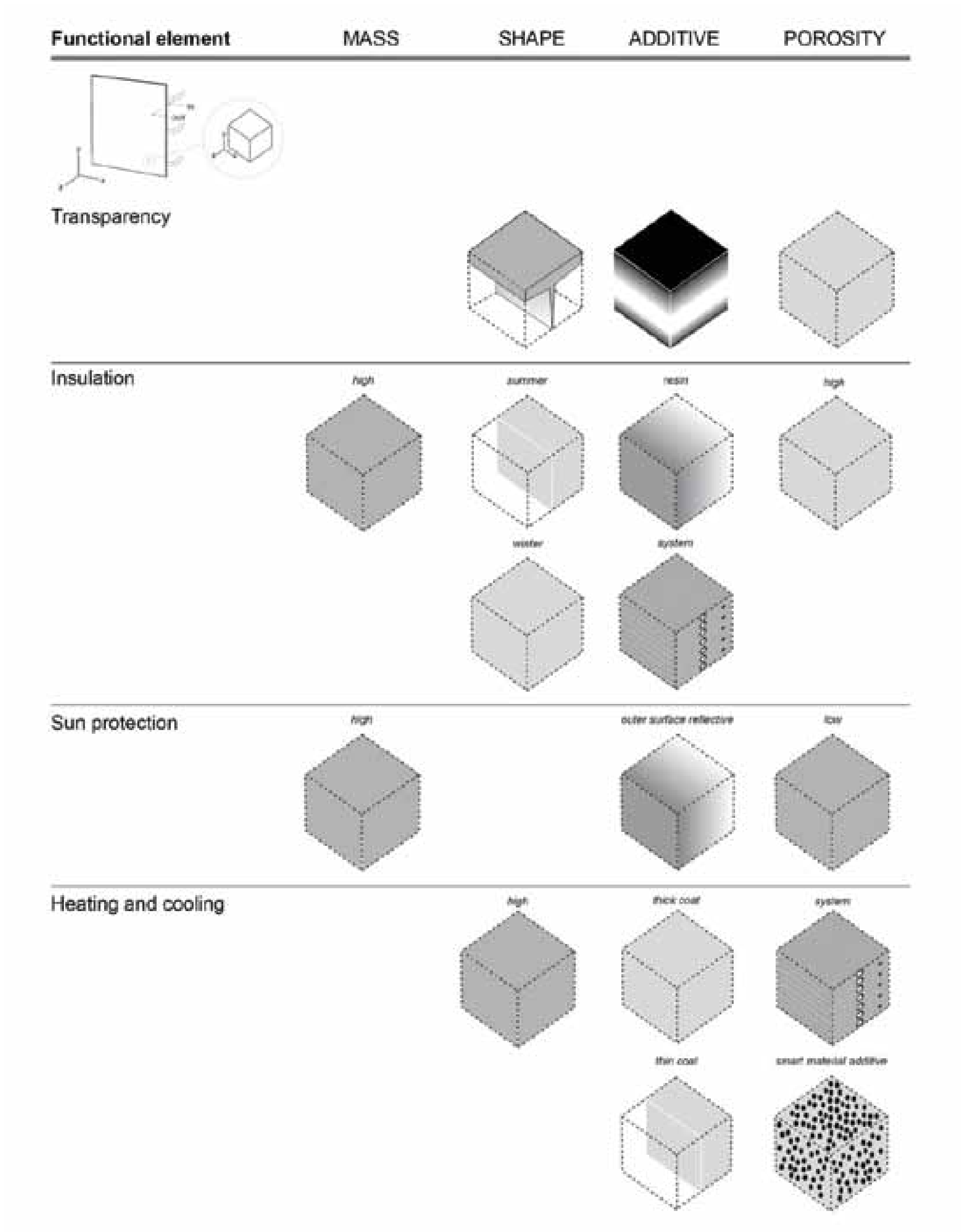
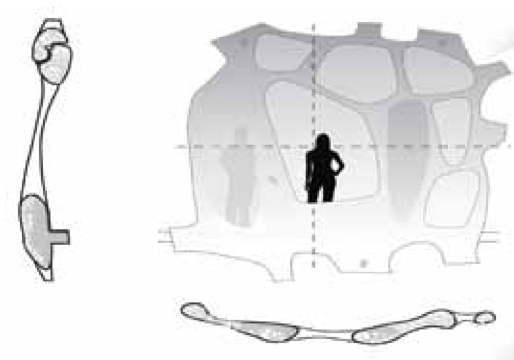
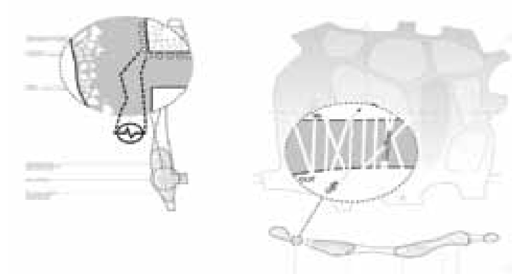


Figure 160
Means to influence a massive material to archive different functionalities

A façade design was made based on these aspects (Figure 161). Mass is accumulated where it is needed for structural reasons. For insulation purposes, the outer area is porous. Continuous pores in the inner area can transport warm and cold water for heating and cooling. Embedded glass fibres transport light.





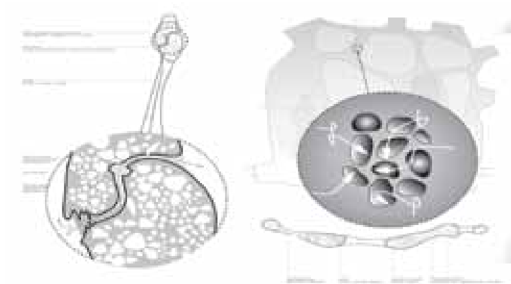


Figure 161
Elevation, section of the integral façade

Figure 162
Embedded heating components and light directing fibres

Figure 163
Ventilation through cavities in the material. The material has a higher porosity where less structural strength is needed

Step 2 –Product levels

The scheme shows the total integral product architecture. Even elements such as IGU´s or LED lights would be integrally connected to the façade structure.

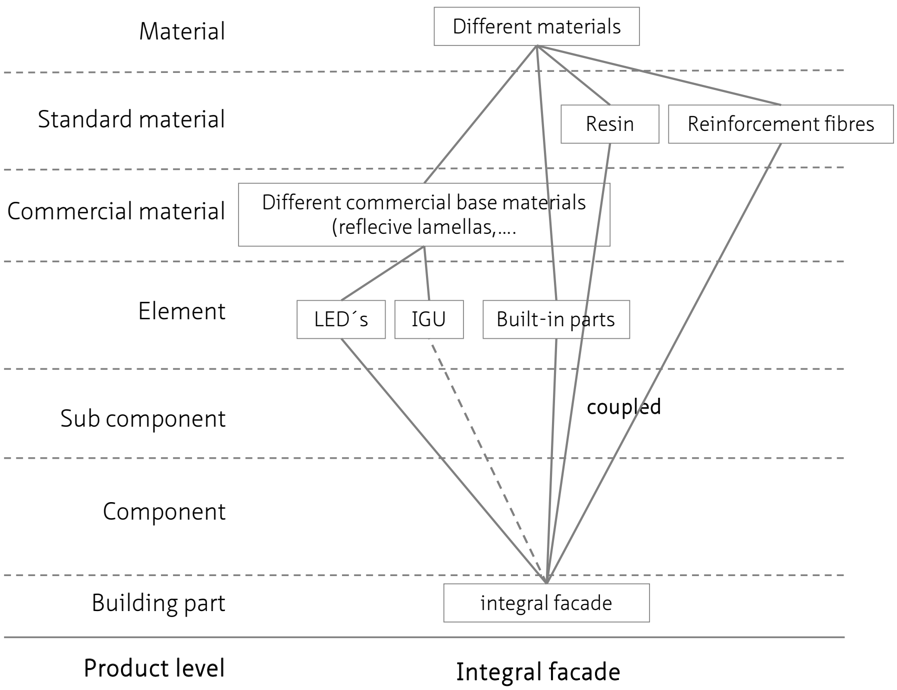


Figure 164
Product levels of the Integral façade

Step 3 –Design and construction process

The scenario does not rely on building systems (except possible IGU´s). This means the design team cannot fall back on given information to determine the future performance. It would require an intense cooperation of architect, consultants and builder throughout the entire process. And obviously this façade could hardly be built in an open tender process.

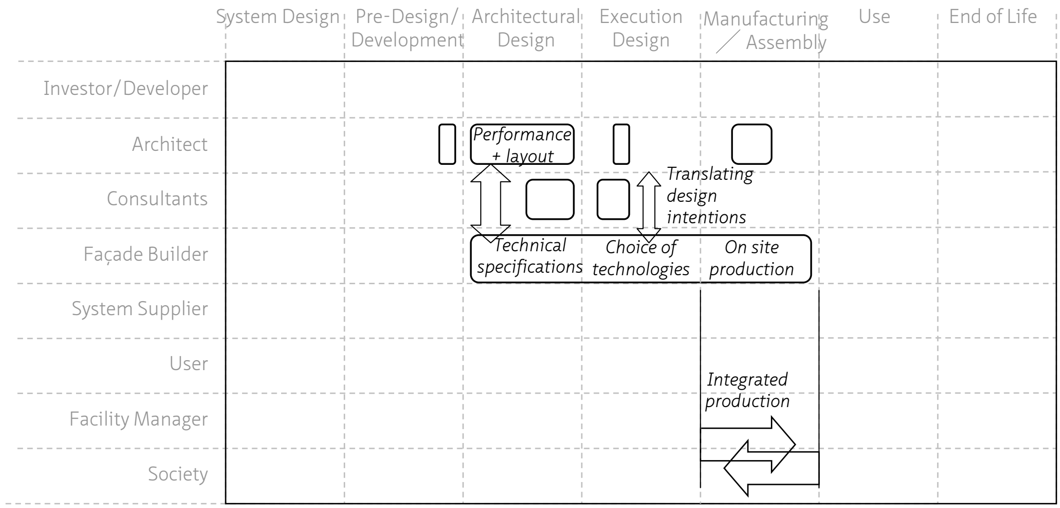


Figure 165
Process profile Integral Facade.

Step 4 – Evaluation

The benefit of an integral design is potentially higher structural and energetic performance, because the product can be adjusted according to its functionality. On the other hand, the façade cannot be adapted at a later stage and an end of life concept would strongly depend on the chosen material. In order to achieve some degree of adaptability, interfaces would finally have to be introduced to connect components that need to be exchanged.
A performance prediction can only be a rough estimate until the execution design is completed. The construction would most probably not lead to faster design and production processes unless automated onsite production technologies allow so (for example building with robots).
The architectural design possibilities are potentially very large but would depend strongly on the chosen building technology. On the other hand, risks for the entire project team would be great. There would be no possibility to correct planning mistakes or building failures once the façade is erected.
Every such integral façade would be built according to the latest design, material and production technologies; but upgrades at a later stage could not be accommodated.

§ 6.6.3 Layered façade – Jasper Overkleeft

Involved parties	Jasper Overkleeft, TU Delft Façade Master Program
Time span of development/implementation	2009-2010
Status	Experiment

Step 1 – Data collection

Examples such as space suits or Gore-Tex jackets prove that the combination of layers with different properties can lead to remarkable performance. A space suit is only a few millimetres thick, but can protect against very low temperatures and dangerous radiation. Jasper Overkleeft uses this idea to specify the façade's main functionalities.

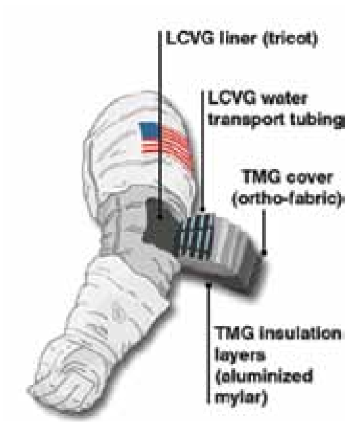


Figure 166
The space suit is made from multiple layers and is only about 7mm thick. (Source: NASA)

Unlike the other designs, in this system façade functions are created by combining different layers. Insulation properties are achieved by a combination of pneumatic cushions and reflective layers. The enveloping foil and the pneumatic cushions (working as a structural spacer) in combination with pre-stressing under-pressure is used to create stiffness. Flexible warm water capillary tubes are integrated for heating purposes (Figure 167).

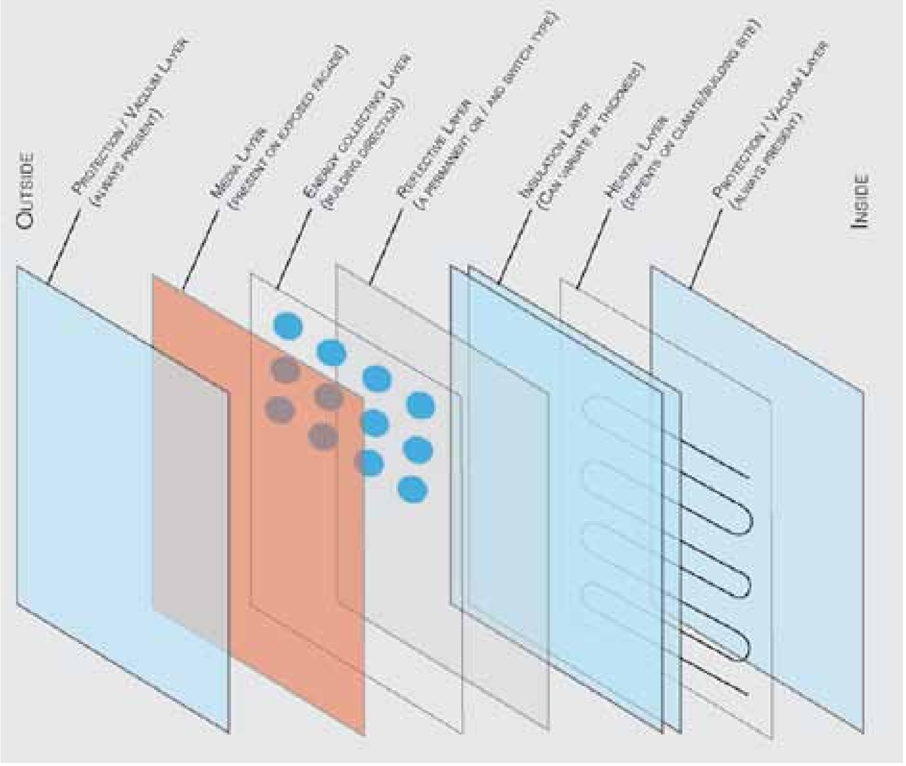


Figure 167
The combination of different layers determines the final façade functionality

All the layers are only temporarily held in place until the application of under pressure fixes them in place. This also means that there is no defined physical interface. The arrangement of the layers can be adjusted according to the user needs, the architectural idea and the direction of the building (Figure 168).

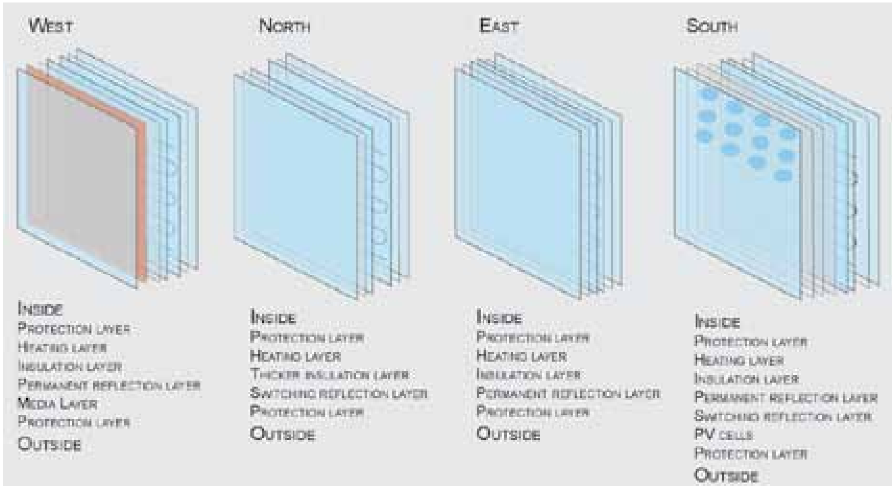


Figure 168
The layer arrangement can be adjusted according to building orientation, desired functionality or architectural idea.

Architecturally, all kinds of colours, light emitting foils, etc. could be integrated. The façade could be transparent, translucent or opaque. Layers can have different sizes and overlap each other. At a later stage, the layers could also be rearranged to adjust the façade properties or to add new technologies. This type of façade is lightweight and could be transported in a rolled-up manner. It could be tailored like a sail, or made into three-dimensional shapes.

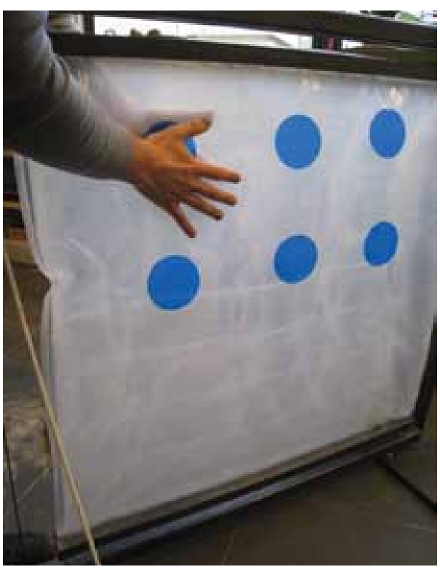


Figure 169
Façade mock-up

Step 2 –Product levels

The entire façade is made up of elements. They are fixed by a combination of ETFE foils and vacuum which means that no physical interface between the elements is needed. The layer elements have an integral product architecture. The façade itself is extremely modular.

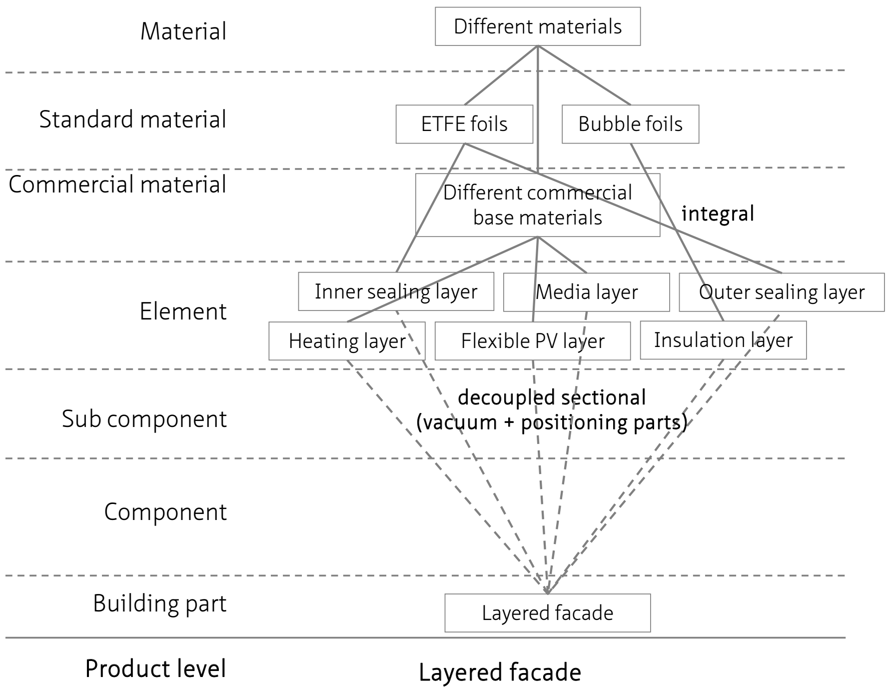


Figure 170
Product levels Layered facade

Step 3 –Design and construction process

All different layers can be prefabricated as yard ware, similar to textile bales. The façade design could be done just like sail design. The façade would be built in textile or sail makers workshops. The layer ware is cut to size and laid out to final façade parts which are rolled up and transported to site. Presumably, the design as well as the production process would be short.

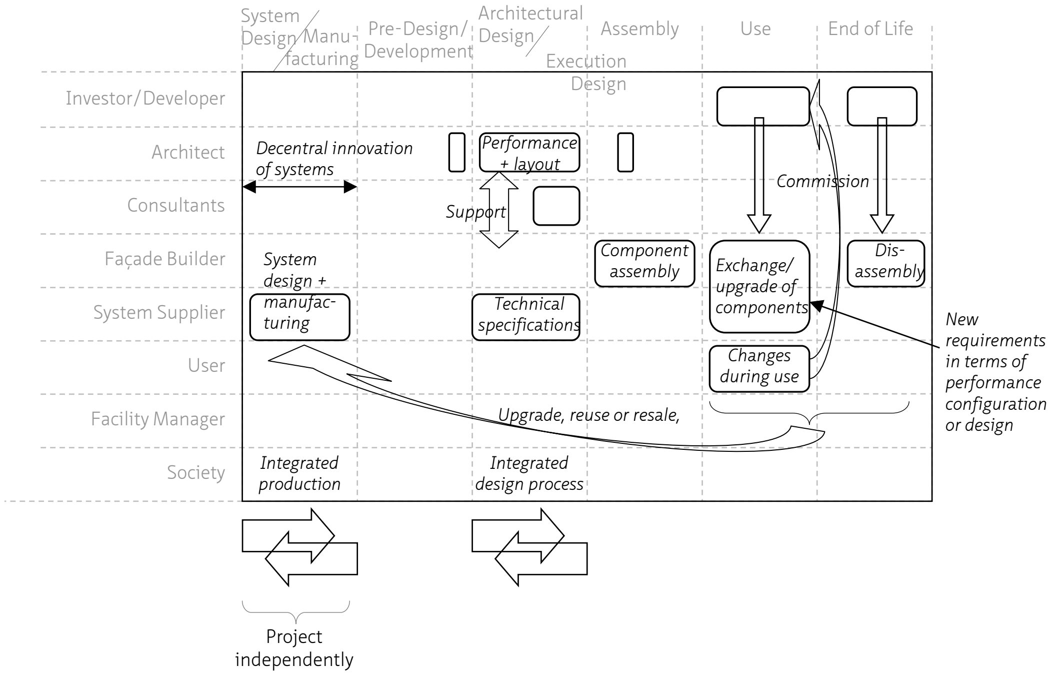


Figure 171
Process profile Layered Facade.

Step 4 – Evaluation

Due to its modular character and easily detachable layers, the façade can be completely reused. The lightweight textile construction potentially uses a minimal amount of material.
Insulation properties can be high, depending on the layer arrangement. This might be conflicting with a desire for transparency. Climate adaptability could only be achieved by layers that can switch their properties.
Design as well as production processes would be short and risks for the stakeholders low.
Architectural variety would be great, providing that a textile envelope is desired. Countless different materials for different functionalities or decoration reasons could be added. The architect becomes a fashion designer for houses.
New innovative layers could be added or upgraded at any given time.

§ 6.6.4 Layered Component Façade – Chenjie Wu, Bart van den Ende, Wouter Streefkerk

Involved parties	Chenjie Wu, Bart van den Ende, Wouter Streefker, TU Delft Façade Master Program
Time span of development/implementation	2009-2010
Status	Experiment

Step 1 – Data collection

As the name implies, the idea behind this façade is to combine the positive features of component façades and layered Façades. It is composed of three layers: A main structural layer, made of load-bearing components, is located in the middle. It is air tight and thermally insulated. The outside layer serves as rain screen, thus allowing a simpler construction of the component interface. PV cells or other energy generating components can be added here. The third, inner layer is used to attach additional translucent insulating panels, HVAC components, or anything that provides additional functionality for the interior. The entire system is stiffened by pretension cables in the inner and outer layers.

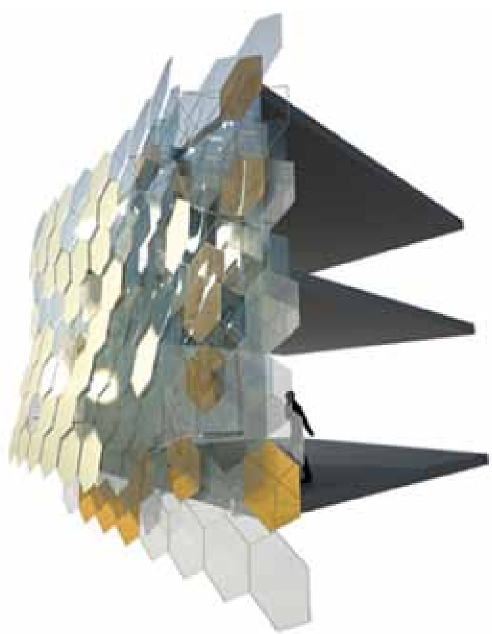


Figure 172
Vision of the Layered Component Facade

The component size of the different layers can be different, allowing a greater design flexibility, and to overcome the problem of the fixed resolution of the component façade.

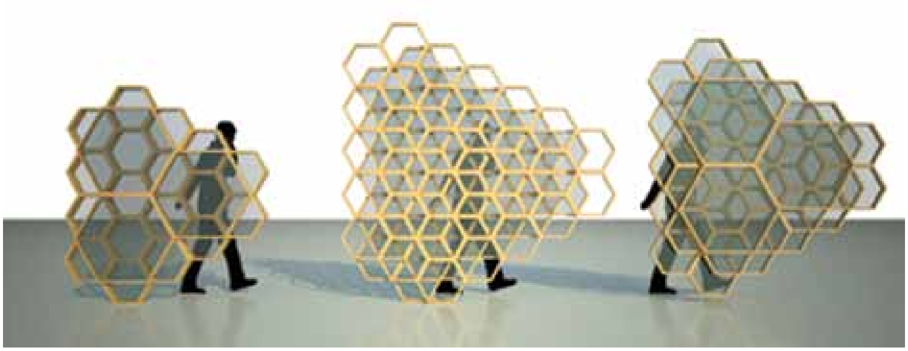


Figure 173

Different component sizes of the layers are possible

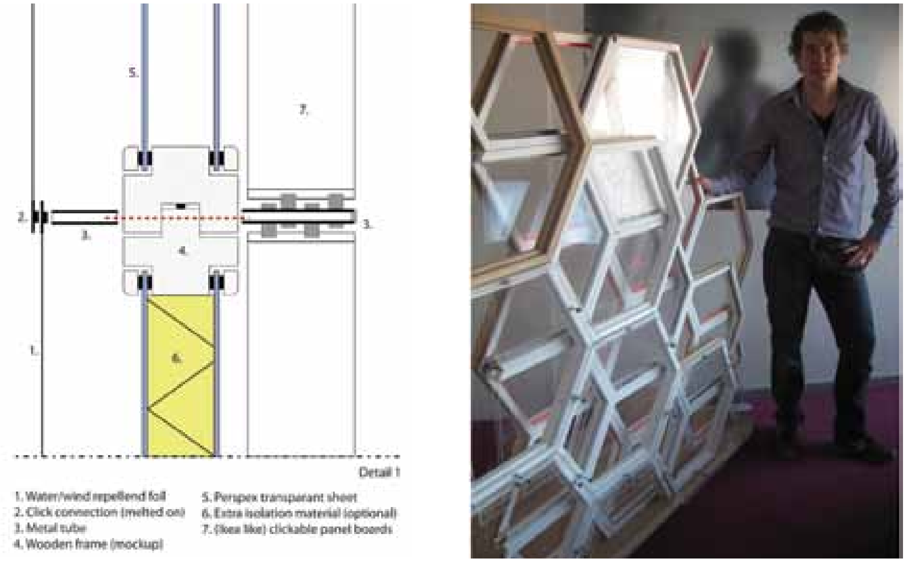


Figure 174

Sketch detail and first mock-up

Step 4 – Evaluation

The concept has many positive features such as disassembly and reuse, performance prediction, fast design process, and incorporated decentralised innovation.
The possibility to combine layers allows for a greater architectural design variety, although there are restrictions. In the same time, the combination of different layers also potentially allows for a higher functional resolution.

The four different student designs show integral as well as modular product architectures. They might be a step away from becoming real façade solutions. But they demonstrate how a completely different approach can have a big effect on façade performance in terms of the future challenges as defined in chapter 3.

Summary

This chapter discusses integral approaches to façade construction aimed at finding new strategies to the curtain wall. The cases have different constructive natures, but also differ in their motivation, meaning the problem they aim to solve. They range from full façade concepts to system products. The Inholland façade is a special construction, designed for an optimal structural performance. Next Active Façades and the Solarlux project are interesting because they aim at bridging problems that arise from the existing separated market structure by strategically linking different stakeholders groups. Also examined are two innovative production and assembly technologies. Finally, experimental façade designs are analysed based on defined constructional scenarios.

Whenever possible, function structures and product level schemes are used to analyse the different cases in a comparable manner. Individual process profiles are created for each case. They show how the different stakeholders interact during the project phases. At the end, each case is evaluated for its performance in terms of future challenges.

The following chapter 7 focuses on a final evaluation of the cases and draws conclusions about how integral and modular product architectures perform in terms of future challenges.

7 Case study evaluation

§ 7.1 Introduction

In the previous chapters, current curtain wall constructions as well as integral approaches to façade construction were analysed. It became obvious that the cases not only differ in terms of their product architecture but also in their particular design and construction process, decision making procedures and stakeholder roles.
In order to map out how a new approach to curtain wall construction can be made, this chapter focuses on the evaluation of the cases, and draws conclusions about how integral and modular product architectures perform in terms of future challenges.

The following schemes are used to graphically support the evaluation:
Product profiles show the level of modularity or integrity of the product architectures of the cases, composed over the different product levels. In a next step, the performance of the cases is compared in terms of future challenges. Finally, the results are displayed in the scheme of the design and production process.

The ultimate goal of this research is not to identify façade solutions, but rather to generalise the results and develop theoretical propositions that describe strategies for the future curtain wall.

§ 7.2 Comparing different product profiles

The product profiles of the different case studies are compared in Figure 175. On the horizontal axis, each product level is categorised as either integral or modular. Hereby it does not matter how far to the left or right a construction is located within one category. The interfaces are either coupled or de-coupled. The scheme allows a comparison of the different constructions, although they cover different product levels. Some cases have not been considered here. The Solarlux façade, for example, is not interesting in terms of its construction, because it is standard and not innovative. Rather, its process profile shows important characteristics. Obviously all constructions are based on materials and these are neither integral nor modular. This means all constructions have the same starting point.

The experimental integral façade, of course, comprises a completely integral construction; just as the Inholland Façade. Though it is not made of a single material, all commercial materials and elements a tightly nested to create the slender construction. The GRP sandwich construction of the Windesheim building is based on standard materials. The remaining cases have an integral construction; only showing a de-coupled interface between the large components. The X-frame is only a window product and thus does not cover all levels. It only has one de-coupled interface where the aluminium cover profiles can be attached to the profile. This was necessary to allow transportable unit sizes. De-coupled interfaces on the component level are a main feature of the Component Façade, whereas the component infill's (elements and subcomponents) can potentially have an integral architecture. The Next Active Façade is based on a standard curtain wall construction, and thus shows the same product profile as, for example, the E² Façade analysed in chapter 5.

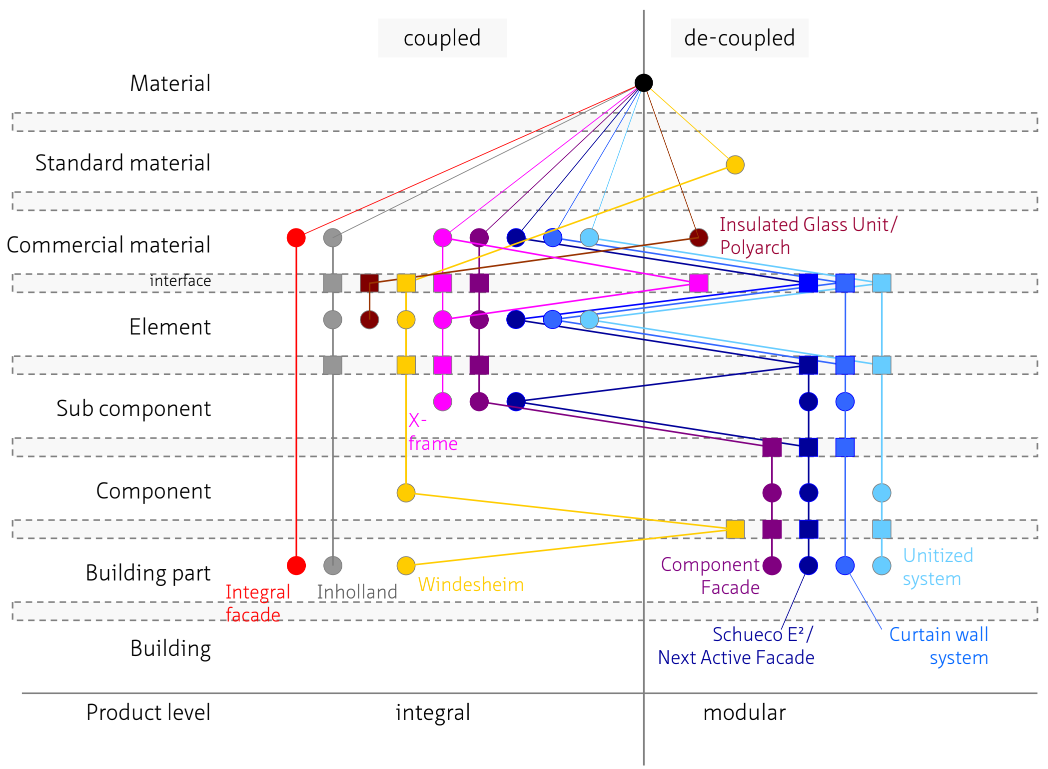


Figure 175

Comparison of the product profiles of the analysed cases. The interface between different product levels can be coupled or de-coupled. The degree to which a product has either a modular or an integral architecture is indicated by the horizontal location right or left of the vertical line.

Most cases exhibit a mix of both types of architecture but belong to one or the other side in terms of their performance behaviour. The Component Façade has an ambivalent nature. The elements and sub components can be highly integral, whereas its main characteristics are owed to its modular architecture on the component level, allowing easy assembly, change and upgrade.

§ 7.3 Evaluation of cases

By understanding the different product profiles, one can now summarise how the different cases perform in terms of the future challenges in form of a matrix (Figure 176). Again, relatively integral product profiles are located to the left, and those that comprise a relatively modular one are on the right. The extreme examples integral façade and curtain wall system are located at the far ends.

§ 7.3.1 How the cases perform in terms of future challenges

The analysed cases are of different quality: They include existing façades or systems, but also experimental designs. So it needs to be noted that this manner of comparing is partly based on assumptions. Rapid manufacturing, in fact, is an existing production technology; but the case study assumes that an entire façade is designed and built this way; which is actually not yet feasible. The same is true for the Polyarch case. Here, the assumption is that polymer technologies are applied to a façade in form of coatings and films. Some fields in the matrix have been left empty, because these cases did not permit a clean evaluation.
Whenever possible, a qualitative evaluation of each aspect of the cases was made. Plus (+) indicates a better performance, minus (-) a worse. The ´+´ fields are highlighted for better visibility. This allows seeing the pattern that indicates whether an integral or a modular architecture potentially scores best for each of the analysed cases. For better readability, the patterns are framed by a blue outline. However, the results are never ´black or white´, as this evaluation might implicate. Rather, different product architectures require different means to accomplish the performance goals - which in some cases might not be available yet. This will be specified more in the following paragraphs.

Future challenge	Function	Integral Facade	Inholland Facade	Rapid manufacturing Step 3 (complete façade)	Polyarch
Minimize embodied energy	Choose materials with low impact	- Concrete as a base material		+ Project oriented choice of materials	
	Reduced material quantities	+ Integrally structural optimized design	+ Structurally optimized	+ Integrally structural optimized design	+ Small amount of materials, large effects
	Offer recycle ability	- Not possible	- Experimental construction: Difficult	+ Possible by integrating modular interfaces	
Reduce operational energy	Improve level of insulation	+ Theoretical by porous concretes	Not the design target (special construction)	+ Possible by optimized construction with no thermal bridging	+ Potentially improving U-value
	Adapt to climate	- Not possible	- Not adaptable	Would need integration of adaptable component	+ Daylight management
Predict façade performance in terms of	Embodied energy	- Requires completed design		Requires completed design	+ Calculation of effect possible
	Operational energy; Comfort	- Requires completed design		Requires completed design	+ Calculation of effect possible
Create a faster process	Shorten design process	- Complex design. Needs development of knowledge base	- Experimental construction	- Needs development of knowledge base for RM technologies	+ Reduces constructional complexity
	Shorten production and assembly process	- Depends on Production technology. Pre-fabrication not possible	- Experimental construction	+ Calculable production time	+ Reduces construc-tional complexity. Integration in coating processes
	Reduce external risks	- High risks due to onsite building process	- High risks	- Requires integrated design	
Enable architectural possibilities	Bridge knowledge gap between stakeholders	- Requires integrated design process	+ Integrated design and engineering in co-operation with builder	+ Requires integrated designprocess	
	Allow architectural variety	+ Theoretical everything is possible, process flexibility need	+ Offers possibilities, but limited to constructional necessities	+ Theoretical everything is possible	+ Provides new design possibilities, reduces constr. complexity
	Support architectural design intentions throughout process	+ Integrated design throughout the process required		+ Integrated design throughout the process required	
Stimulate innovation	Control innovation centrally	+ All development is in one hand	+ By central development of Technology	+ All development is in one hand	+ Central innovation required
	Incorporate decentral innovation	- Design team needs to be informed in all areas		- Design team needs to be informed in all areas	
	Upgrade existing construction	- Not possible	- Not possible	+ By defining modular interfaces	- Not possible

Relatively integral profile

Figure 176

The figure shows in detail how the different cases perform in terms of future challenges. A potentially good performance is highlighted. Fields framed in blue indicate generally good performance of integral or modular architectures.

Windesheim X	X-frame	Component Facade	Smart Post	Next Active Facades	Curtain Wall
- Bound to technology	- Bound to technology	Possible for subcomponents but not main frame	- Difficult without fundamentally changing construction	- Difficult without fundamentally changing construction	- Difficult without fundamentally changing construction
+ Lightweight, structurally optimized	+ Lightweight, structurally optimized	- Fixed by frame design	- Already structurally optimized system	- Already structurally optimized system	- Already structurally optimized system
- Inseparable materials	- Downcycle	+ Very good. Reuse, recycle possible	+ Modular architecture	+ Modular architecture	+ Modular architecture
+ Minimized thermal bridging	+ Minimized thermal bridging	- Limited to frame properties	- Only marginal possible. Mature system	- Only marginal possible. Mature system	- Only marginal possible. Mature system
- Not adaptable	- Not adaptable	+ By choice of components	+ Potential good because of building services integration	+ Potential good because of building services integration	+ Modular architecture
- Assumptions first. Possible after execution design completion	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue
- Assumptions first. Possible after execution design completion	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue	+ possible prior to design process because of known catalogue
+ Is a must due to required early architectural design completion	- Difficult because of inherited decision making structure.	+ Composition of predefined modules	- Difficult because of inherited decision making structure.	+ Simplifies complex decision making process for services integration.	- Difficult because of inherited decision making structure.
+ Efficient due to technology	- Difficult. Results in less flexibility for design	+ Production process project independently. Quick assembly	+ Supports building services integration	+ Starting production of subcomponents before design completed	- Difficult. Results in less flexibility for design
+ Integrate engineering and building process	+ Known system and clear responsibilities	+ Low risks, defined responsibilities	+ Known system and clear responsibilities	+ Known system and clear responsibilities	+ Known system and clear responsibilities
+ Integrated design and engineering in co-operation with builder	+ Accepted technology	+ Accepted technology and defined interface structure	+ Aim of the concept	+ Aim of the concept	+ Accepted technology
+ Good, but bound to Sandwich technology	- Always limited to product catalogue	- Very limited to component shape	- Always limited to product catalogue. Large size of post	- Always limited to product catalogue.	- Always limited to product catalogue
- Early completion of architectural design required	+ Known architectural implications	+ Known architectural implications	+ Known architectural implications	+ Known architectural implications	+ Known architectural implications
+ By central development of Technology	+ Central upgrade of window system	- rethink interface structures difficult.	- rethink interface structures difficult.	- rethink interface structures difficult.	- rethink interface structures could mean complete change of characteristics.
	+ Possible for infill elements	+ All sub systems suppliers innovate separately	+ All sub systems suppliers innovate separately	+ All sub systems suppliers innovate separately	+ All sub systems suppliers innovate separately
- Not possible	+ Only architectural cover elements	+ All sub systems potentially exchanged separately	+ All sub systems potentially exchanged separately	+ All sub systems potentially exchanged separately	+ All sub systems potentially exchanged separately

Relatively modular product profile

- Lower material quantities are a prerequisite for a construction to exhibit low embodied energy. Integral constructions perform well in this area. With geometric nesting, a good structural performance can be achieved as demonstrated with the Inholland façade. The general problem of modular architecture is that a certain constructional effort is used for standardisation and interfaces. The standardised frame of the component façade, for example, must be designed to accommodate all structural eventualities, independently of whether the component is located in the upper or the lower part of the façade. Integral architecture potentially performs better to improve the level of insulation than modular architecture for the same reason as above. Chapter 3 showed that improving the U-value of curtain wall systems is only marginally possible without fundamentally changing the interface structure to the infill elements.
- Recyclability can be ensured by incorporating modular interfaces that allow easy disassembly. Contrary, an integral architecture does not allow a separation of parts. The only choice would be downcycling or using materials or technologies that biodegrade, for example.
- Adaptation to climate is usually done by the modular addition of adaptable elements and sub components such as sun shading systems. Adaptive materials or technologies such as polymer coatings will potentially enhance the performance of integral architectures.
- For the prediction of façade performance at an early design stage, modular product architecture offers an advantage, especially when working with façade systems: The performance of all elements from a system catalogue can be calculated before hand. Again an example: A window is composed of frame and infill elements. Their U-value is known and can be calculated for the entire window by accounting for a certain window/infill relation. This allows making predictions at an early project stage. For integral construction this would require a finished design or intensive calculation of different stakeholders such as architect (functional definition and layout), structural engineer (materials used) and building physics consultant (U-value performance of used materials).
- The situation is similar when external risks are to be reduced. Working with defined interfaces and responsibilities helps preventing misunderstandings and failures.
- Integral product architecture bears the possibility to incorporate special design wishes. The Windesheim façade is a good example. Almost any shape and colour is possible. Nevertheless, it is limited by the chosen technology. Architectural variety of modular systems is always bound to the system catalogue. On the other hand, the system catalogue helps to support architectural design intensions throughout the process. This is particularly true for system products such as the curtain wall. Product aesthetics are visible before and, and expectations are levelled. Just think of the Smart Post case, where deviation from the expected mullion size led to the denial of the concept.
- Integral product architecture generally supports central innovation. The prerequisite is, of course, that the design team is up to date with the latest developments. A modular architecture promotes decentralised innovation and, of course, is the only way to allow an upgrade of existing constructions.

§ 7.3.2 Future challenges allocated to the scheme of product levels

Those results that concern the product architecture of façade construction can be allocated to certain areas of the scheme of product levels (Figure 177).
In terms of the choice of materials, naturally both constructional strategies have the same point of departure. Integral constructions will potentially perform well in reducing material quantities and creating a high level of insulation. On the level of elements, subcomponents and components, a modular construction is likely to allow upgrading and good recycleability. The figure indicates which constructional area in the scheme of product levels can be targeted in order to improve certain product functions. Depending on specific goals, a more modular or integral constructions can be beneficial.

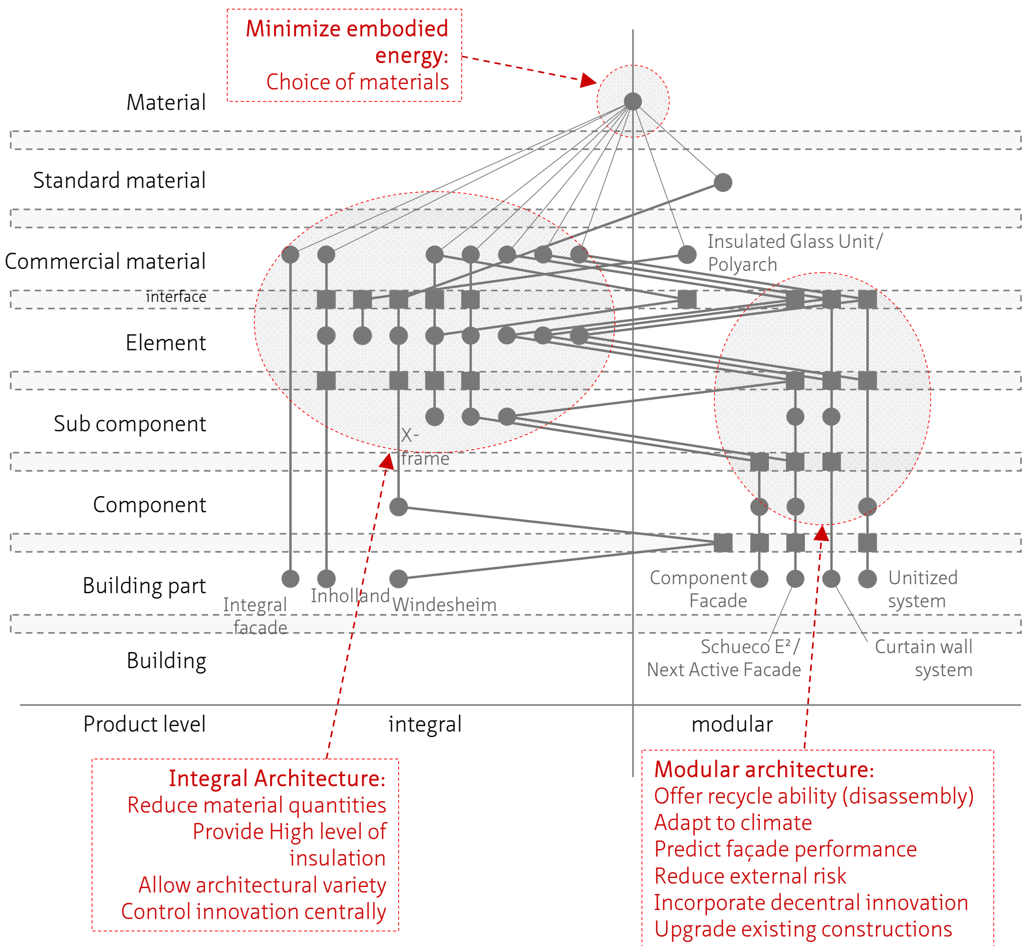


Figure 177
Future challenges allocated to the scheme of product levels.

§ 7.3.3 The façade design and construction process

The results of the case evaluation can also be allocated to particular areas of the scheme of the design and production process, which was developed in chapter 3 (see 3.4.6). The two different process strategies to address future challenges of integral and modular facade constructions become clear:
Integral construction (Figure 178) asks for technology development by the builder/ producer of the façade prior to the project itself. An integrated design process is required during the design phase in which all decision making parties have to participate. It is necessary to build up process knowledge in order to shorten design and construction processes. Flexible production processes will allow custom building and architectural variety. Integral constructions potentially exhibit a high performance.

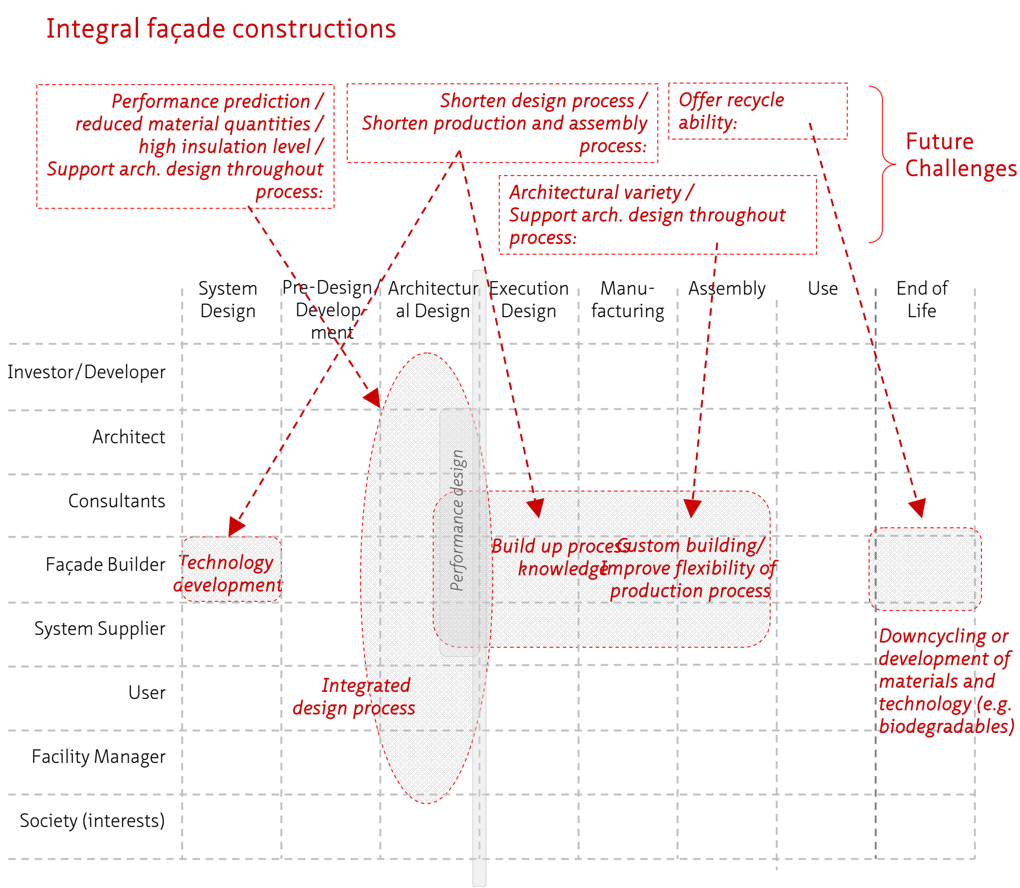


Figure 178
Integral façade construction requires a certain process strategy to address the future challenges.

In contrast, modular façade constructions must rely on the development of standardised systems and its interfaces prior to the realisation of a project. The strength lies in using accepted technologies, the possibility for pre-manufacturing, and splitting up tasks.

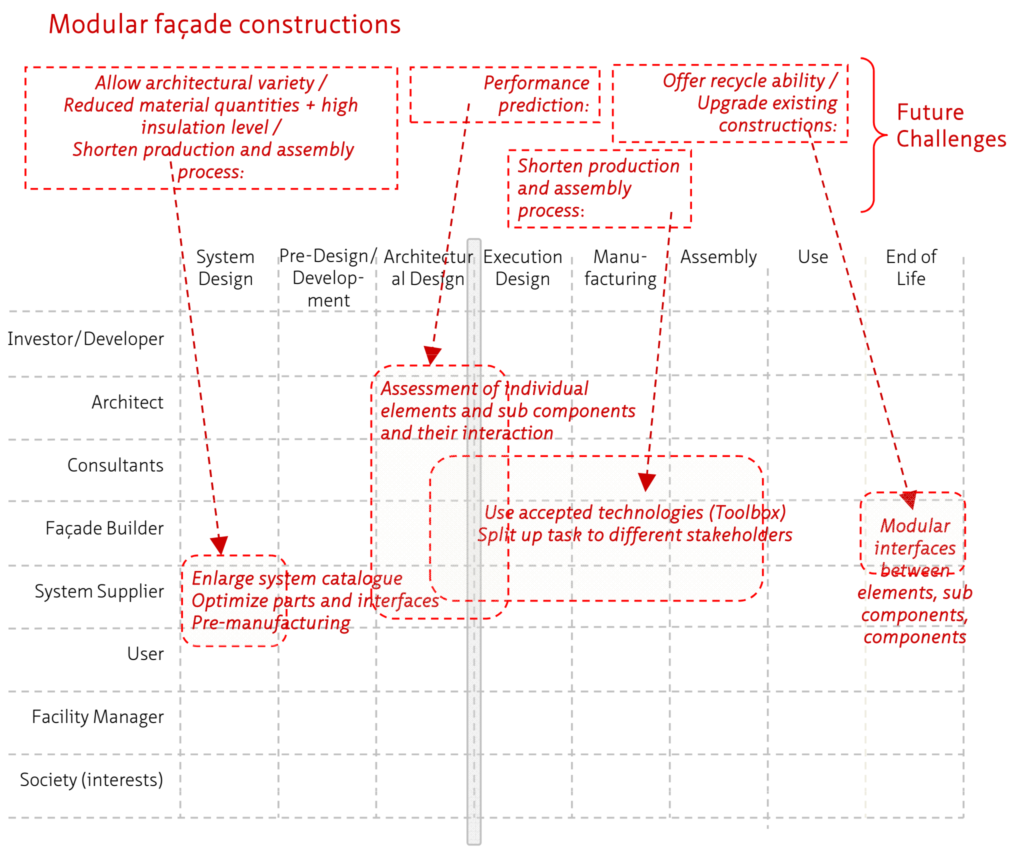


Figure 179

Modular façade construction requires a certain process strategy to address the future challenges.

§ 7.4 How modular and integral product architectures address future challenges

As mentioned above, both types of architecture must rely on different means to address future challenges. A summary is given in Figure 180. As shown above, these means relate to the type of construction as well as the design and construction process.

It is important to understand what consequences the choice for one of the constructional strategies has. Or the other way around: Depending on specific goals, a more modular or integral architecture might be beneficial.
Integral façade construction requires a certain process strategy to address the future challenges.

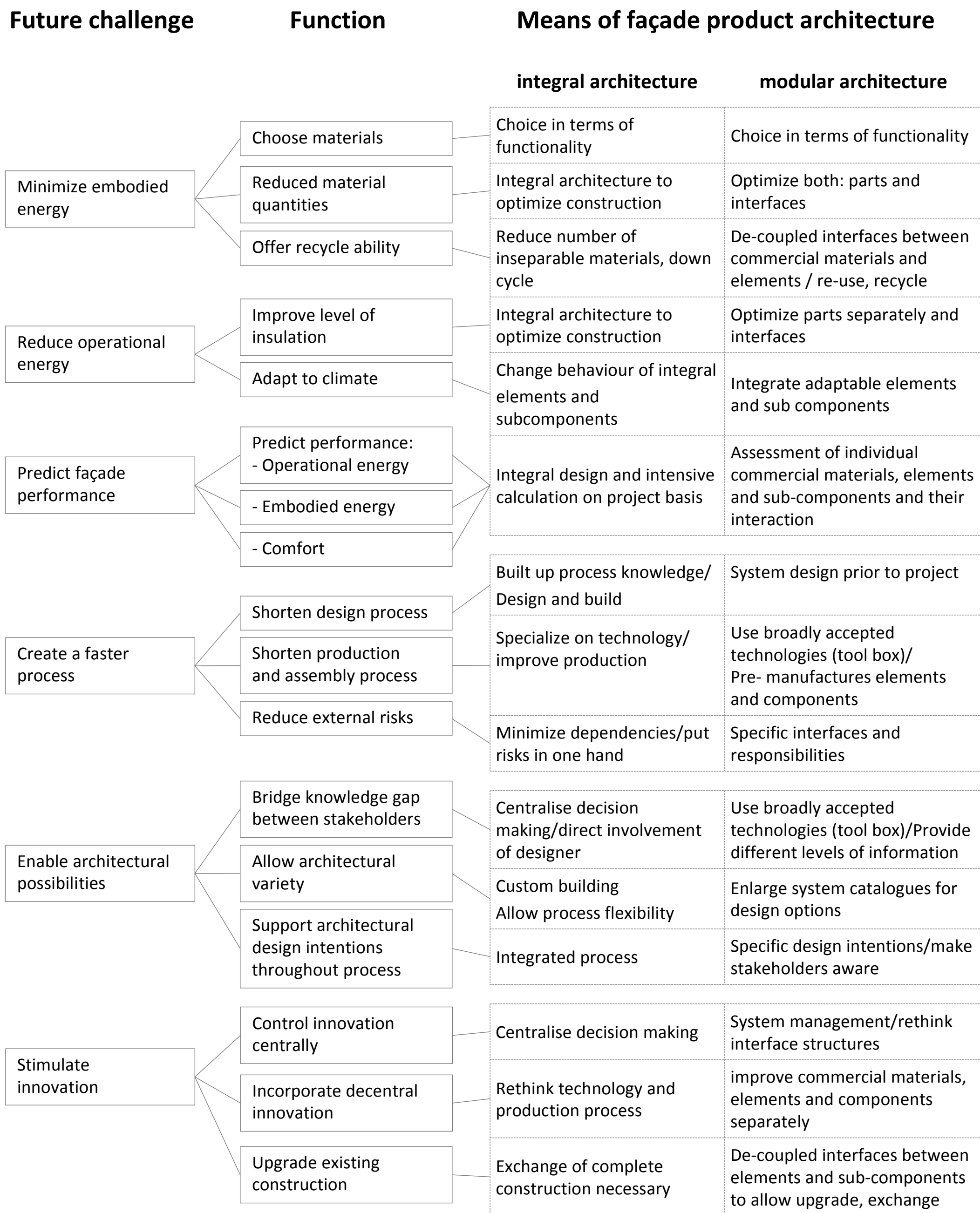


Figure 180

How different product architectures can address future challenges

One must be aware that the situation sketched is not a static picture. There are different factors that can have an influence on future façade product architectures.

1 Change of façade functions

The research has identified a catalogue of future functions as described in chapter 3. But this list might change due to unknown events. It might be possible that certain future challenges become more important than others. In chapters 4 and 5 ee have seen how crucial it is to specify the functions correctly when defining the façade construction. The reduction of embodied energy could be the decisive factor for buildings using almost zero operational energy. If a building is only designed for short time use, high U-values might not be an important factor, whereas smart disassembly strategies become more crucial.

2 New technologies and materials

When new technologies and materials become available (which will undoubtedly happen) it can turn out in favour for one or the other type of construction; most likely to integral architectures. Two examples have already been analysed in the previous chapter. The prospects of RM production technologies are breathtaking. Initially, they will be used to improve existing façade systems. At a later stage entire façades could be designed fully customised and on demand. Integrated and permanent design teams are needed, which have, project independently, developed a solid knowledge base to realise those façades. Polymer technologies can lead to more function integration and therefore to more integral but simpler constructions.

3 Changes in the market structure

The analysis shows cases that try to meet the existing market structure with separated stakeholder relations and decision making processes; others are niche constructions that develop their advantages by departing from the given structure, such as the Windesheim façade built by Holland Composites. With the development of technology, we will most likely see are greater diversity in this field. With a larger complexity of façades and new possible constructions, it might be that investors depart from a classical way of submitting a building and rather opt for functional specifications. Describing the functionality of a façade or a building can be more cost efficient and secure a better outcome than defining the type of construction to be built. But in general, tackling future challenges asks for a more integrated approach of stakeholders and decision makers in comparison to the separated market approach we see today.

Summary

Modular and integral cases are compared in terms of their performance related to future challenges. This allowed to draw general conclusions and to allocate the effect a) to certain product levels and b) to the design and construction process. The means of modular and integral architectures to tackle future challenges is summarised in a table. Both types rely on completely different strategies. Integral product architectures rely on technology development and require integrated design processes, whereas modular architectures rely on system development and match the current separated stakeholder approach. It is important to know the implications of the choice of one or the other type, or, the other way around: Depending on the desired functionality, a certain type of architecture can be beneficial. What can be concluded though is that rising requirements, represented by the defined future challenges or functions, will favour integral high performance solutions. A more integrated stakeholder approach will be required in the future.

Chapter 8 draws a conclusion by formulating generalised propositions on how a new approach to the curtain wall can be made.

8 Conclusions

§ 8.1 Introduction

There is a multitude of developments and requirements that demand new strategies for the future of the curtain wall. These can be found in the structure of the design and construction process as well as in curtain wall construction itself. Both have incrementally developed over a long period. The objective of this dissertation is threefold. First, it sets out to chart the particular structure of the façade market. Secondly, the state of the art of curtain wall construction is assessed. Both is necessary to scout for and evaluate new approaches to façade construction, which is the third objective of this research.
The first part of the conclusion provides answers to the research questions. The second part formulates a sequence of generalised propositions.

§ 8.2 Answers to the research questions

§ 8.2.1 How can the faced design and construction process be analysed?

The different steps of the design and construction process of curtain walls have been extensively discussed in previous research. The analysed literature provides a lot of detailed information here. However, it mostly focuses on managing the supply chain and does not include the phases after the installation of the façade. Yet they are crucial for this research because in the future a lot of attention will be paid to how façades behave during use and in terms of end of life scenarios. Eight phases of the design and construction process have been identified that serve as a backbone for expert interviews.
The interview covers a very wide range of aspects; it was therefore not possible to discover all aspects in depth within the scope of this research. However, the focus is laid on the principle understanding of the process, with more detailed information only

where it seems to be useful for this research's specific purpose. Therefore, qualitative rather than quantitative research was conducted.

§ 8.2.2 How does the façade construction process work and what are the driving factors and bottlenecks for innovation in façade construction?

This question is answered by addressing the following five sub-questions:

- *What are the process steps, what are the dependencies?*

The market analysis has revealed some interesting points about the façade design and construction process. First of all, it shows the fragmented entanglement of the stakeholder actions. It can be described as an utterly complex process, happening again and again with different stakeholders for different projects.
This whole process has developed incrementally parallel to the other crafts and is based on a craftsmanship driven concept of building. But unlike some of the other crafts, façade construction has long and extensively incorporated industrial processes.
This is also the reason why a complex combination of architectural design, execution design and system design is needed to create a curtain wall that on one hand needs to match craftsmanship driven procedures and on the other cope with the needs of industrialised products.
In the centre of the process is the tendering phase. This phase is the moment when design and engineering intensions are handed over to the executing parties. Four different methods have been defined, all with different impact on costs, innovation or architectural design. The main difference is to what degree the engineering team pre-defines the project and to what extent the builders are allowed to place their influence.

The proposition that processes become shorter can be confirmed without being able to extract clear figures. Most parties say that in principle they can work faster. This means that their internal processes are rather optimised. Most interviewed parties state that their internal risks are quite manageable and limited, which gives the images of a rather self confident and highly developed industry. The general opinion is that faster projects would lead to considerably higher risks, mostly because of the dependencies to other parties. It is thus not the ability of the individual stakeholders but the process itself that is the bottleneck for shorter project duration.

It is most interesting that the entire façade construction process ends with the assembly phase for all designing and building parties. Façade builders are sporadically involved with maintenance during the time of use of a building. Though all interviewed parties agreed that sustainable design and construction will be the task of the future, they do not seem to be clear on what terms such as embodied energy or end of life scenarios practically mean. This also shows in the fact that sustainability and end of life scenarios are not explicitly mentioned in the legal descriptions of architect's services in The Netherlands and Germany. No wonder that the holistic view on all aspects of sustainability is still missing.

The future demands buildings that will feature optimised energetic performance. This concerns operational energy as well as embodied energy in constructions. Façades will play an important role here. This energetic performance has to be predicted by the designing and building parties. The prediction has to be done on a project to project basis for phases that they are typically no longer involved in.

- *How is the aspect of architectural design geared into the façade construction process?*

All façade solutions need to be measured concerning their impact on the architectural design on different levels: on an urban, building and detail scale. It is important to understand that this is the fundamental nature of architecture as a discipline. In contrast to e.g. the product design or automotive industries, it is not about creating optimal products that anticipate a market, but finding answers for a specific task.
The interview showed that façade design actually happens on different levels. At first, there is architectural design. Secondly, an execution design phase by the façade builder is executed. The iterative architectural design procedure has to be linked to the linear procedure of the builder. This is not only very time consuming, but also burdened with conflicts. Symbolically, this is where the baton of architectural intentions gets handed over to the executing party.
Finally, façade design is influenced by the system design, which is done and completed before the project even starts. On one hand, systems help the architect to fulfil his or her intended goals. They are tested in terms of their thermal or structural performance. They come with knowledge about costs, etc. On the other hand they limit the design possibilities. The choice is limited to what is available. The products can be adapted to some extent, but in most cases there is neither the time nor the money to create fundamentally new systems.

- *What is the role of the different stakeholders in this process and how does the decision-making process take place?*

The following scheme characterises the relationship of stakeholders in the façade design and construction process:
The investor commissions architect and engineers to develop an execution plan to realise the business target. Architects and engineers are the ones who primarily determine the type of construction as well as the systems to be used. But the architects' knowledge of the systems and façade construction becomes increasingly insufficient as complexity increases. System providers depend on the decisions but ultimately have to

sell their products to the façade builder. The façade builder translates the architectural design into a physical construction, but has a business relation with the client. At the same time, the targeted user and the future facility manager are often excluded from the development process.

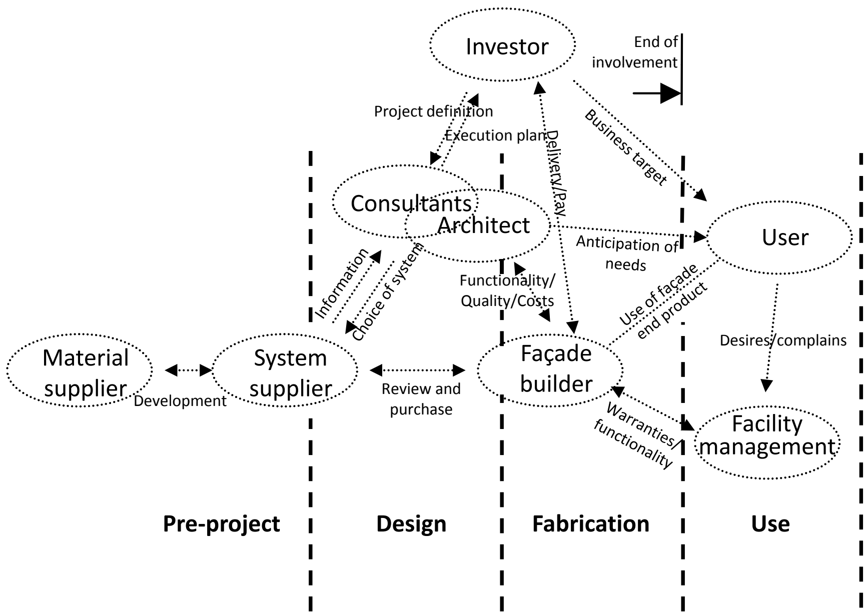


Figure 181

Scheme of the relationship of stakeholders

It is interesting to see what will need to happen to this stakeholder relationship anticipating, for example, a more sustainable approach. This could mean lower energy consumption of the building as well as lesser embodied energy in the façade construction or disassembly strategies. Whereas the latter will mostly concern the systems themselves and the way the façade builder assembles them, energy consumption and comfort must be seen in close relationship to the building as a whole, its construction typology, the type of use and the building services concept. More decisions will have to be taken in an early design phase and in a shorter amount of time.
This whole process relationship virtually cries out for a more integrated approach. Design and communication tools might help the situation but new or different alliances of different stakeholders are thinkable.
The question is how this can be done without compromising architectural design intentions. The role of the architect needs to be reinforced. The facility manager will become increasingly important to handle use and end of life issues.

- *What is the impact of the façade construction process on innovation?*

Architecture is a project oriented and competitive discipline. Different parties work together continuously, trying to create the best possible result for a specific task. Their success is measured on a project basis. They have all generated their own experience and knowledge which they are trying to introduce in the process.
It can be said that the entire façade construction discipline slowly and evolutionary innovates. Radical innovation cannot be introduced for standard buildings. It can only happen in exceptional projects where all involved parties mutually agree to take a leap forward.
The analysis does not show that the structure of the building market actually blocks innovation, but innovation definitely happens de-centrally and peripherally driven by the different stakeholders. Since it happens on a project by project basis and with differing teams, it has a highly accidental nature. The market structure with its inherited procedures works like a guiding structure, but at the same time, it is a straitjacket for fundamental innovation.

- *What are the future challenges for curtain wall construction?*

A number of challenges are defined resulting from the process analysis. They are not scientifically proven and have the character of propositions. These challenges are translated into functions, which is the first step in connecting them to physical façade components:

- **Minimise embodied energy**
  Functions:
  - *Choose materials with low impact*
  - *Reduce material quantity*
  - *Offer recyclability*

- **Minimise operational energy**
  Functions:
  - *Provide high level of insulation*
  - *Adapt to climate*

- **Predict façade performance:**
  Functions:
  - *Predict use of operational energy*
  - *Predict embodied energy*
  - *Predict comfort*

- **Create a faster process**
  Functions:
  - *Shorten design process*
  - *Shorten production and assembly process*
  - *Reduce external risks resulting from a faster process*

- **Enable architectural possibilities**
  Functions:
  - *Bridge knowledge gap between system, design architectural design and execution design*
  - *Allow a maximum of architectural variety*
  - *Support architectural design intentions throughout the process*

- **Stimulate innovation**
  Functions:
  - *Control level of innovation centrally and systematically*
    - *Incorporate decentralised innovation*
    - *Upgrade existing constructions*

§ 8.2.3 How can a systematic be defined to conduct a constructional façade analysis?

The developed systematic relates to the dependency between the material and immaterial side and it requires base vocabularies. A study of literature in the field of architecture as well as the field of product development provides a vocabulary that can be applied to define a systematic for a comparative analysis.

- *How are façade construction and its dependency on the building market described in literature?*

Building technology has incrementally developed over centuries. Literature on building construction can be seen as an attempt to deliver an overview of existing strategies, which obviously is a gigantic task in itself. The requirements, norms and regulations alone that have to be adhered to when designing a building (or a façade) are extensive. In this context, teaching material does not consider rethinking the inherited ways of building or even the creation of new technologies the architect's task.
In contrast, other disciplines such as product development offer a deeper understanding of the relationship between construction and market. The theory of product architecture explicitly discusses this relationship. Further, the literature analysis shows that functions are essential in understanding construction. In fact, the purpose of construction is a way of fulfilling one or more functions.

- *What vocabulary can be derived that is suitable for the analysis of façade construction?*

In order to analysis different façade constructions in a comparable manner, a systematic can be used that consists of three key components:

1. A façade function tree has been developed on the basis of the function related vocabulary. It does not claim to be all-inclusive but can serve as a guideline to understand which functions a certain construction aims to fulfil.
2. The above mentioned theory of product architecture can be used to describe the relationship between the construction and the structure of the design and construction process.
3. The hierarchical scheme of product levels can show how a construction is composed - from material to elements and components to building parts.

§ 8.2.4 What is the state of the art in of curtain wall constructions and how is it linked to the design and construction process?

Fifteen contemporary as well as historic examples are analysed to understand curtain wall construction as well as the developments that led to the status quo.
The process of how the standard curtain wall is designed can be described as a toolbox approach, meaning that a design problem is solved by applying proven constructions. It allows the distribution of tasks to different stakeholders and phases of the design process. This process has been described in detail in chapter 3. Whereas Mies van der Rohe is solely in control over the development of the Crown Hall façade, architects today need to rely on system products and the expertise of builders. Thus, the design process of curtain walls works in three steps: system design, architectural design, and execution design.
The modular product architecture perfectly corresponds to this standard way of designing façades. Many different stakeholders are involved in the design of such a system. It is built on a project to project basis and must fulfil many different functions and regulations. The modular architecture is a strategy to create highly standardised and exchangeable components, and still allow a certain amount of product variety. Increasing requirements (functions) have resulted in an increasing complexity of the construction. The modular product architecture provides the opportunity to extend the product development of different subcontracts such as metal construction and glass components. This certainly has its specific advantages. Standardised interfaces allow for independent developments of the individual components. For example, new insulated glass units can easily be incorporated.
But the separation of functions also leads to slowing down in terms of invention. All providers of sub-components concentrate only on the improvement of a particular

aspect. Therefore, components have grown more and more complex, rebate gaskets and insulators form the interface between them and the whole system has become less flexible. The analysis shows that its improvement could only be done by continuous complex nesting of parts. Radical new building methods or materials can hardly get incorporated. Curtain wall system technology focuses on a broad application. It has become the benchmark system for architects and builders.

§ 8.2.5 How can contemporary curtain wall construction tackle the challenges formulated in chapter 3?

A generalised evaluation can be done, based on the characteristics of curtain wall systems: They are established systems with known interface structures and responsibilities. Curtain wall constructions and their design and building procedure are evolutionary optimised constructions.

The modular product architecture of curtain walls scores high when it comes to functions that rely on the separation of commercial materials, elements and sub-components, such as: recycleability, climate adaptation, decentralised innovation and upgrade of constructions. The application of a well known façade system allows a good prediction of façade performance before the design process has actually started, bridges the knowledge gap between stakeholders, and supports architectural design intentions throughout the process. The split responsibilities on the immaterial side help to reduce external risks.

On the other hand, the system has reached a state of maturity and is structurally optimised. Reducing material quantity is therefore hardly possible. And neither is a simple exchange of materials with those of lesser embodied energy and equal functional properties. The entire construction including the interface standards would need to be adapted. The same is true if a higher level of insulation is required. It is difficult to shorten the design and building process, and only possible when existing decision making structures are bridged. Most likely it would lead to less design flexibility. Finally, architectural design possibilities are limited to what the product catalogue offers, and controlled centralised innovation is limited by inherited interface structure. Rethinking these interfaces will potentially lead to a complete change of the product characteristics.

§ 8.2.6 What strategies can be found to overcome the existing design and construction procedures and the mature construction concepts?

Modular and integral cases are compared in terms of their performance related to future challenges. This allows to draw general conclusions and to allocate the effect

a) to certain product levels and b) to the design and construction process. Both construction types rely on completely different strategies to tackle future challenges. Integral product architectures rely on project independent technology development and require integrated design and construction processes; modular architectures on system development. And they match the current separated stakeholder approach. It is important to know the implications of the choice of one or the other type, or the other way around: Depending on the desired functionality, a certain type of architecture or a mix can be beneficial.

One must be aware that the situation sketched is not a static picture. There are different factors that can have an influence on future façade product architectures.

1. Change of façade functions
2. New technologies and materials
3. Changes in the structure of the design and construction process

What can be concluded though is that rising requirements, represented by the defined future challenges or functions, will favour integral high performance solutions. A more integrated stakeholder approach will be asked for in the future.

§ 8.3 Generalised propositions

- *How can a new approach to curtain wall construction be made in order to deal with the rising performance demands, growing complexity and the new role that the building envelope has for the building as a whole?*

The answer to this research question can not be given in form of a new façade solution. Instead, a sequence of generalised propositions is formulated:

The project oriented and iterative architectural design process has a distinct influence on the way façades are constructed. Façade construction will thus always differ from other constructional disciplines such as the automotive industries or product design.

The ´Use´ phase and the ´End of life´ phase in the process of design and construction will rapidly gain importance. These phases will open up a new business field for designers, façade builders and those who are going to manage the use and end of life cycles of façades.

A new approach needs to include insights on how curtain wall construction corresponds to the design and construction process. Describing constructions in terms of modular and integral characteristics is a promising idea, because it clearly shows the process relation.

Graphic tools developed in this dissertation, such as the façade function tree, product and process profiles are valuable for evaluating as well as creating new constructional concepts.

Curtain wall systems are benchmark products today, but these mature constructions reach their limits in terms of certain functionalities. In the future, we will see a greater diversity of constructional façade types with more integral product architectures.

This greater diversity will widen the knowledge gap between architects and executing parties. Integrated design teams and procedures will be needed.

When designing façades in the future, instead of defining constructional solutions, the definition of façade functionalities will be the most important task.

A new way of educating architects or façade specialists is required in order to meet the needs of the future building market: Away from a purely application oriented towards a product architecture driven approach, which clearly includes the implications on the structure of the design and construction process.

Final remark:
The conclusion of this dissertation is dedicated to Mike Davies. His famous article from 1983 ´A Wall for All Seasons´ has been described in the side notes before. It is a technological vision that has yet to be realised. But considerable progress has been made, and we can expect new technical solutions for the concept in the near future (for example from the field of polymer technologies).

However, it is now possible to ask new questions for the promotion of the Polyvalent Wall:

Who will be involved in designing and building this highly complex construction? Because of its complexity, it is likely to be a system product. If so, how should system boundaries and interfaces be defined to allow maximum performance in terms of the future challenges? And even more importantly: What design variations will the concept leave to the architect and what will its impact be on the architectural quality of our environment?

I am sure that by answering these questions, the Polyvalent Wall might become a worthy successor of the contemporary curtain wall.

Summary

The curtain wall is one of the most successful types of façade construction and widely accepted amongst architects. Its development at the end of the 19th century is a direct result of innovations in the field of structural building. The introduction of frame construction made it possible to eliminate massive exterior wall constructions and therefore allowed for a completely new definition of the building envelope.
As the name implies the curtain wall is a construction independent of the load-bearing structure of the building. It protects the building's interior from weather and climate conditions. Its non-load-bearing property allows for expansive transparent areas. The result is a previously unknown freedom of architectural design possibilities for the façade with equally great new options for the interior space.
While the requirements on façades have slowly increased over the last decades, the curtain wall has evolved from craftsmanship oriented constructions to sophisticated façade systems. But its modular construction principle is still the same. With the latest requirements of almost energy neutral buildings, faster building processes and increasing technicalisation of the building envelope, this construction principle is reaching its limits. The curtain wall system has reached a state of maturity; it needs new and more integral constructional strategies to guaranty that this successful product will be able to fulfil future challenges.
These strategies can be found in the curtain wall construction itself as well as in the structure of the design and construction process, both of which have incrementally developed over a long period of time. The objective of this dissertation is threefold. First, it sets out to chart the particular structure of the façade market. Secondly, the state of the art of curtain wall construction is assessed. Both tasks are necessary to scout for and evaluate new approaches to façade construction, which is the third objective of this research.

Chapter 2. Methodology for the analysis of the façade design and construction process

One keystone of this dissertation is to analyse the impact of the design and construction process on façade construction itself. In a first step, the design and construction process is defined as the entire process from the initial idea to the end of life of a façade. Then, the different process phases are outlined. On that basis, an interview methodology and form is developed. It includes the interaction between stakeholders and its impact on the physical construction of curtain walls.

Chapter 3. Analysis of the design and construction process

The chapter focuses on the analysis and the interpretation of the interviews. It sketches the process steps and dependencies, the role of the different stakeholders and how architectural design is geared into façade construction. It becomes clear that the process is very fragmented as it relates to the project oriented architectural design process. Innovation is introduced de-centrally by different stakeholders.
The chapter is summarised by formulating a number of challenges, resulting from the process analysis. These challenges have a general nature and, in order to establish a connection to façade construction, they are translated into façade functions. In chapter 5 and 6 these challenges will be used to evaluate existing constructions as well as new constructional strategies.

Chapter 4. Systematic for a constructional façade analysis

The chapter provides a basis for the analysis of contemporary curtain wall constructions. The constructional strategies in use today have developed simultaneously with the building processes. Thus, a systematic is developed that allows insight into the relationship between construction details and the structure of the design and construction process.
A literature study is conducted for two reasons: Firstly to see how this relationship is reflected in educational and professional literature, and secondly to develop a useful vocabulary for the systematic. It shows that literature from the field of architecture and façade design is based on the application of given technologies and does not question whether particular constructions reflect current process strategies. Literature from the field of product development and product architecture offers more fundamental insight into this relationship and provides valuable vocabulary for the analysis of curtain wall construction.
The chapter concludes with the development of a systematic that is based on three key components:
A Façade Function Tree that serves as a guideline to understand which functions a certain construction aims to fulfil. The hierarchical Scheme of product levels shows how a construction is composed from material to elements and components to building parts and their interfaces. The Theory of product architecture is used to describe the relationship between the construction and the structure of the building market.

Chapter 5. Analysis of curtain wall product architecture

Fifteen different constructions are analysed, beginning with historic examples, to contemporary constructions to building services integrated concepts. Entire façades as well as individual elements are analysed. The difficulty is to create comparable results. The systematic developed in the previous chapter is applied for this purpose.

The analysis demonstrates how the curtain wall has historically developed from craftsmanship oriented constructions towards highly systemised products. With increasing functionality, the systems have grown more complex. Whereas early curtain walls show an integral construction, contemporary systems are highly modular with decoupled interfaces.
The analysis shows how curtain wall systems will potentially be able to address future challenges as defined in chapter 3; where curtain wall systems will presumably perform well and where they will fail. The curtain wall system has reached a state of maturity. The tight correlation of its modular construction to the fragmented structure of the design and construction process blocks further development of components and new interface structures. And it will make it more and more difficult to meet all of the challenges and requirements façades will face in the future.

Chapter 6. Case studies for a new approach

The chapter discusses new integral approaches to façade construction aimed at identifying new strategies for the curtain wall. The cases are of different constructive natures, but also differ in their motivation, meaning the problem they aim to solve. They range from full façade concepts to system products. Also examined are innovative production and assembly technologies. Finally, experimental façade designs are analysed based on defined constructional scenarios.
Function structures and product level schemes are used to analyse the different cases in a comparable manner. Individual process profiles are created for each case. They show how the different stakeholders interact during the project phases and that integral constructions demand a different and much more integrated design and construction process in comparison to the standard curtain wall construction.

Chapter 7. Case study evaluation

In chapter 7, the means of modular and integral product architecture employed to tackle future challenges are summarised/compared in a table. The two types are based on completely different strategies. Integral product architecture relies on technology development and requires integrated design processes, whereas modular architecture relies on system development and matches the current separated stakeholder approach. It is important to know the implications of the choice of one or the other type, or, the other way around: Depending on the desired functionality, a certain type of architecture can be beneficial.
This allows drawing general conclusions about which levels of a façade product (material, element, sub component or component) are suitable to address specific future challenges. This way a link is laid to construction details.

In addition, the results of the comparison are allocated in the scheme of the design and construction process. It shows how and at which moment in the process, a stakeholder group should deploy particular process strategies for both, integral as well as modular constructions.
A conclusion is that rising requirements, will favour integral high performance solutions; thus requiring a more integrated stakeholder approach in the future.

Chapter 8. Conclusion

Answers to the research questions are given in chapter 8. It concludes by formulating generalised propositions on how a new approach to the curtain wall can be made:

- The project oriented and iterative architectural design process has a distinct influence on the way façades are constructed. Façade construction will thus always differ from other constructional disciplines such as the automotive industries or product design.
- The ´Use´ phase and the ´End of life´ phase in the process of design and construction will rapidly gain importance. These phases will open up a new business field for designers, façade builders and those who are going to manage the use and end of life cycles of façades.
- When following the traditional fragmented design and construction process, the increasing complexity of façade constructions will inevitably lead to an exclusion of the architect from the materialisation of the façade.
- Curtain wall systems are benchmark products today, but these mature constructions reach their limits in terms of certain functionalities. In the future, we will see a greater diversity of constructional façade types with more integral product architectures.
- This greater diversity will widen the knowledge gap between architects and executing parties. Integrated design teams or procedures will be needed.
- When designing façades in the future, instead of defining constructional solutions, the definition of façade functionalities will be the most important task.
- A new approach also includes new insights on how curtain wall construction corresponds to the design and construction process. Graphic tools developed in this dissertation, such as the façade function tree, product and process profiles are valuable for evaluating as well as creating new constructional concepts.
- A new way of educating architects or façade specialists is required in order to meet the needs of the future building market: Away from a purely application oriented towards a product architecture driven approach, which clearly includes the implications of façade product architecture on the structure of the design and construction process.

Zusammenfassung

Die Vorhangfassade (Curtain wall) ist einer der erfolgreichsten Fassadenkonstruktionstypen und ist unter Architekten weltweit anerkannt. Ihre Entwicklung Ende des 19. Jahrhunderts ist eine direkte Folge von Innovationen im Bereich der Baukonstruktion. Die Einführung der Skelettbauweise ermöglichte es, massive Außenwandkonstruktionen zu eliminieren und erlaubte damit eine völlig neue Definition der Gebäudehülle.

Wie der Name sagt, ist die Vorhangfassade eine vom Gebäudetragwerk unabhängige Konstruktion. Sie schützt das Gebäudeinnere von Wetter- und Klimaeinflüssen. Ihre nicht tragenden Eigenschaften erlauben großflächige transparente Flächen. Die Folge ist eine bis dahin ungekannte Freiheit an architektonischen Möglichkeiten für die Fassade, einhergehend mit gleichsam weit reichenden neuen Möglichkeiten für den Innenraum.

Während die Anforderungen an die Fassade über die letzten Jahrzehnte immer größer wurden, hat sich die Vorhangfassade von einer Handwerk-orientierten Konstruktion zu einem technisch ausgefeilten Fassadensystem entwickelt. Das modulare Konstruktionsprinzip ist dabei aber gleich geblieben. Im Zuge der neuesten Entwicklungen hin zu beinahe Energie-neutralen Gebäuden, schnelleren Bauprozessen und einer ständig steigenden Technologisierung, steht dieses Konstruktionsprinzip allerdings kurz vor seinen Grenzen. Das Vorhangfassadensystem hat den höchsten Grad an Ausgereiftheit erreicht; es bedarf neuer und integralerer Konstruktionsstrategien, um zu garantieren, dass dieses erfolgreiche Produkt auch zukünftige Anforderungen erfüllt.

Solche Strategien sind in der Konstruktion der Vorhangfassade selbst zu finden sowie in der Struktur der Entwurfs- und Konstruktionsprozesse, die sich beide schrittweise über einen langen Zeitraum hinweg entwickelt haben. Diese Dissertation hat drei Ziele: Erstens soll die besondere Struktur des Fassadenmarktes aufgezeichnet werden. Zweitens wird der aktuelle Stand der Vorhangfassadenkonstruktion bewertet. Beides ist notwendig, um drittens, neue Ansätze für die Fassadenkonstruktion zu identifizieren und zu bewerten.

Kapitel 2. Methodologie zur Analyse des Fassadendesign- und Konstruktionsprozesses

Ein Grundpfeiler dieser Dissertation ist die Analyse der Auswirkung des Entwurfs und Konstruktionsprozesses auf die Fassadenkonstruktion selbst. In einem ersten Schritt wird der Entwurfs- und Konstruktionsprozess als Gesamtprozess von der ersten Idee bis zum Lebenszyklusende der Fassade definiert. Danach werden die unterschiedlichen Prozessphasen dargestellt. Auf dieser Grundlage wird eine Interview-Methodologie entwickelt, die die Interaktion zwischen den einzelnen Akteuren und deren Auswirkung auf die physische Konstruktion von Vorhangfassaden einschließt.

Kapitel 3. Analyse des Entwurfs- und Konstruktionsprozesses

Das Kapitel befasst sich mit der Analyse und der Interpretation der Interviews. Es zeichnet die Prozessschritte und Abhängigkeiten auf, die Rolle der unterschiedlichen Akteure und inwieweit der architektonische Entwurf sich auf die Fassadenkonstruktion auswirkt. Es wird deutlich, dass der Project orientierte Entwurfsprozess sehr fragmentiert ist. Innovation wird dezentral von unterschiedlichen Interessengruppen eingebracht.

Aus der Prozessanalyse ergeben sich eine Anzahl unterschiedlicher Anforderungen an zukünftige Fassadenkonstruktionen. Diese Anforderungen sind allgemeiner Natur und werden in Fassadenfunktionen übersetzt, um eine Verbindung zur Fassadenkonstruktion herzustellen. In Kapitel 5 und 6 werden diese Anforderungen verwendet, um vorhandene Konstruktionen sowie neue Konstruktionsstrategien zu evaluieren.

Kapitel 4. Systematik für die Analyse der Fassadenkonstruktion

Dieses Kapitel bietet die Grundlage für eine Analyse heutiger Vorhangfassadenkonstruktionen. Die heute angewandten Konstruktionsstrategien haben sich gleichzeitig mit den Bauprozessen entwickelt. Daher wurde eine Systematik aufgestellt, die einen Einblick in die Beziehung zwischen Konstruktionsdetails und der Struktur des Entwurfs- und Bauprozesses erlaubt.

Aus zwei Gründen wird eine Literaturstudie angefertigt: Erstens, um herauszufinden, wie sich diese Beziehung in Lehr- und Fachliteratur widerspiegelt, und zweitens, um eine hilfreiches Vokabular für die Systematik zu entwickeln. Die Studie zeigt, dass die Literatur aus den Bereichen Architektur und Fassadenkonstruktion auf der Anwendung bekannter Technologien basiert, und nicht hinterfragt, ob bestimmte Konstruktionen aktuelle Prozessstrategien widerspiegeln. Die Literatur aus den Bereichen Produktentwicklung und Produktarchitektur bietet eine grundlegendere Einsicht in diese wechselseitige Beziehung und außerdem ein wertvolles Vokabular für die Analyse von Vorhangfassadenkonstruktionen.

Das Kapitel wird mit der Entwicklung einer Systematik abgeschlossen, die auf den folgenden drei Schlüsselkomponenten beruht:

Ein Fassaden-Funktionsdiagramm (Façade Function Tree) als Hilfsmittel zum Verständnis, welche Funktionen ein bestimmter Konstruktionstyp erfüllen soll. Das hierarchische Produktebenen-Schema (Scheme of product levels) zeigt, wie eine Konstruktion von Material zu Elementen, von Komponenten zu Bauteilen und ihren Schnittstellen aufgebaut ist. Die Theorie der Produktarchitektur (Theory of product architecture) wird verwendet, um die Beziehung zwischen der Konstruktion und der Struktur des Baumarktes zu beschreiben.

Kapitel 5. Analyse der Produktarchitektur der Vorhangfassade

Dieses Kapitel zeigt die Analyse fünfzehn verschiedener Konstruktionen, beginnend mit historischen Beispielen über zeitgenössische Konstruktionen bis hin zu Konzepten mit integrierter Haustechnik. Es werden ganze Fassaden sowie einzelne Baukomponenten analysiert, wobei die Schwierigkeit darin liegt, vergleichbare Ergebnisse zu generieren. Dafür wird die im vorherigen Kapitel entwickelte Systematik angewendet.

Die Analyse zeigt, wie sich die Vorhangfassade von einer Handwerk-dominierten Konstruktionsart zu einem hoch systematisierten Produkt entwickelt hat. Im Zuge der steigenden Funktionalität sind die Systeme immer komplexer geworden. Während frühe Vorhangfassaden eine integrale Konstruktion aufweisen, sind heutige Systeme überaus modular mit entkoppelten Schnittstellen.

Die Analyse zeigt, inwieweit Vorhangfassadensysteme möglicherweise solche zukünftigen Herausforderungen erfüllen können, wie sie in Kapitel 3 beschrieben werden; wo sie voraussichtlich gut funktionieren werden und wo nicht. Das Vorhangfassadensystem hat seinen höchsten Reifegrad erreicht. Die enge Beziehung zwischen seiner modularen Konstruktion und der fragmentierten Struktur des Entwurfs- und Konstruktionsprozesses behindert die Weiterentwicklung von Komponenten und neue Schnittstellenstrukturen. Und sie macht es immer schwieriger, die zukünftigen Herausforderungen zu erfüllen.

Kapitel 6. Fallstudien für einen neuen Ansatz

In diesem Kapitel werden neue integrale Ansätze zur Fassadenkonstruktion diskutiert, mit dem Ziel, neue Strategien für die Vorhangfassade zu identifizieren. Die Fälle basieren auf unterschiedlichen Konstruktionstypen, unterscheiden sich aber auch in Motivation bzw. dem Problem, das mit ihnen gelöst werden soll. Sie reichen von Systemprodukten bis zu vollständigen Fassadenkonzepten. Außerdem werden innovative Produktions- und Montagetechnologien untersucht. Und schließlich wurden experimentelle Fassadenentwürfe anhand von definierten konstruktiven Szenarien analysiert.

Funktionsstrukturen (function structures) und Produktebenen-Schemen (product level schemes) werden für eine vergleichbare Analyse der unterschiedlichen Fallstudien verwendet. Individuelle Prozessprofile (process profiles) werden für jeden Fall erstellt. Sie zeigen, wie die unterschiedlichen Parteien während der Projektphase interagieren und, dass integrale Konstruktionen einen anderen und viel integrierteren Entwurfs- und Konstruktionsprozess erfordern als die standardmäßige Vorhangfassadenkonstruktion.

Kapitel 7. Bewertung der Fallstudien

In Kapitel 7 werden die konstruktiven, modularen und integralen Mittel, die dazu eingesetzt werden, zukünftige Herausforderungen zu erfüllen, in einer Tabelle zusammengefasst bzw. gegenüber gestellt. Die beiden Konstruktionsarten basieren auf völlig unterschiedlichen Strategien. Integrale Produktarchitektur ist von technologischen Entwicklungen abhängig und erfordert integrierte Entwurfsprozesse, während modulare Architektur von Systementwicklungen abhängt und dem aktuellen Ansatz der getrennt agierenden Akteure entspricht. Es ist wichtig, die Auswirkungen der Wahl für den einen oder den anderen Typ zu kennen, oder anders herum: Je nach gewünschter Funktionalität kann ein bestimmter Produktarchitekturtyp vorteilhaft sein.
Damit können allgemeine Schlüsse darüber gezogen werden, welche Ebene eines Fassadenproduktes (Material, Element, Sub-Bauteil oder Bauteil) geeignet ist, um bestimmte zukünftige Anforderungen zu erfüllen. Und das ergibt die Verknüpfung zu den Konstruktionsdetails.
Außerdem werden die Ergebnisse der Gegenüberstellung im Schema Entwurf- und Konstruktionsprozess zugeordnet. Das Schema zeigt, wie und zu welchem Zeitpunkt im Prozess eine Gruppe Akteure bestimmte Prozessstrategien für beide, sowohl integrale als auch modulare Konstruktionen, einsetzen sollte
Ein Fazit ist, dass steigende Anforderungen, integrale High-Performance Lösungen favorisieren; und damit ebenfalls zukünftig eine höhere Integration der einzelnen am Prozess Beteiligten erfordert.

Kapitel 8. Fazit

Kapitel 8 gibt Antwortungen auf die Forschungsfragen. Abgeschlossen wird es mit der Formulierung einer verallgemeinerten Aussage darüber, wie ein neuer Ansatz für die Vorhangfassade entwickelt werden kann:

- Der Projekt-orientierte und iterative Architektur-Entwurfsprozess hat eine deutliche Auswirkung auf die Art, wie Fassaden konstruiert werden. Daher wird die Fassadenkonstruktion sich immer von anderen konstruktiven Disziplinen, wie der Automobilindustrie oder dem Produktdesign, unterscheiden.
- Die Nutzungsphase und die ´End of life´ Phase werden im Entwurfs- und Konstruktion einen höheren Stellenwert einnehmen. Diese Phasen eröffnen neue Geschäftsfelder für Entwerfer, Fassadenbauer und diejenigen, die für die Nutzungs- und Nachnutzungsphase der Fassaden verantwortlich sind.
- Wird der traditionell fragmentierte Entwurfs- und Konstruktionsprozess aufrechterhalten, führt die steigende Komplexität der Fassadenkonstruktionen unweigerlich dazu, dass der Architekt von der eigentlichen Realisierung der Fassade ausgeschlossen ist.
- Heute sind Vorhangfassadensysteme Benchmark-Produkte, diese ausgereiften Konstruktionen haben allerdings in Bezug auf bestimmte Funktionalität ihre Grenzen erreicht. In der Zukunft werden wir eine größere Diversifikation der Fassaden-Konstruktionstypen mit einem höheren Grad an Integration sehen.
- Diese größere Diversifikation wird die Wissenslücke zwischen den Architekten und den ausführenden Parteien erweitern. Integrierte Design-Teams oder Prozeduren sind erforderlich.
- Wenn in der Zukunft Fassaden entworfen werden, ist das Definieren der Funktionalitäten der Fassade die wichtigste Aufgabe, und nicht das Bestimmen konstruktiver Lösungen
- Ein neuer Ansatz beinhaltet auch neue Erkenntnisse darüber, wie die Konstruktion der Vorhangfassade mit dem Entwurfs- und Konstruktionsprozess korrespondiert. Grafische Werkzeuge, die als Teil dieser Dissertation entwickelt wurden, wie das *Fassaden-Funktionsdiagramm*, *Produkt- und Prozessprofile* sind ein wertvolles Mittel, um neue Konstruktionskonzepte zu entwickeln und zu bewerten.
- Es bedarf einer neuen Methode Architekten oder Fassadenspezialisten auszubilden, wenn die Anforderungen des zukünftigen Baumarktes erfüllt werden sollen:
weg vom rein Anwendungs-orientierten und hin zu einem Produktarchitektur-orientierten Ansatz – was die Auswirkungen der Produktarchitektur Fassade auf den Entwurfs- und Konstruktionsprozess klar beinhaltet.

Samenvatting

De vliesgevel is één van de meest succesvolle geveltypen en wordt door veel architecten toegepast. De ontwikkeling ervan aan het einde van de negentiende eeuw is een direct gevolg van innovaties op het gebied van de gebouwconstructie. Door de komst van het draagconstructieve raamwerk kon de massieve dragende gevelmuur vervallen en werd een volledig nieuwe definitie van de gebouwschil mogelijk.
Zoals de naam al zegt, is de vliesgevel (in het Engels curtain wall, soms ook in het Nederlands vertaald als gordijngevel) een constructie die los staat van de krachtsafdracht in het gebouw. Het beschermt het interieur van het gebouw tegen het weer en de klimaatomstandigheden. Omdat het geen vloerbelasting hoeft af te dragen kunnen grote delen transparant blijven. Het gevolg is een, ten opzichte van vroeger, ongekende architectonische vrijheid voor de gevel met geweldige mogelijkheden voor de binnenruimte.
Doordat de eisen waar gevels aan moeten voldoen de laatste jaren steeds strenger zijn geworden, heeft de vliesgevel zich ontwikkeld van ambachtelijke constructies tot zeer geavanceerd gevelsystemen. Maar het modulaire constructieprincipe is nog steeds hetzelfde. Met de nieuwste eisen voor bijna energie-neutrale gebouwen, snellere bouwprocessen en het steeds technischer worden van de gebouwschil bereikt dit principe zo langzamerhand zijn grenzen. De vliesgevel raakt uitontwikkeld; het vereist een nieuwe en constructief meer integrale benadering om er voor te zorgen dat dit succesvolle product ook toekomstige uitdagingen aankan.
Die nieuwe benadering kan de de vliesgevelconstructie zelf betreffen, maar ook de structuur van het ontwerp en van het constructie proces, die zich beiden gedurende een langer periode stapsgewijs hebben ontwikkeld. Deze dissertatie heeft drie doelen op het oog. Allereerst wordt de bijzondere structuur van de gevelmarkt in kaart gebracht. Vervolgens wordt de beste stand van zaken met betrekking tot het vervaardigen van vliesgevels vastgesteld. Beide onderzoeken zijn noodzakelijk om nieuwe benaderingen voor het construeren van gevels op het spoor te komen en te evalueren, wat het derde doel is van dit onderzoek.

Hoofdstuk 2. Methodologie voor de analyse van het gevel ontwerp- en vervaardigingsproces

Een van de hoofdpunten van deze dissertatie is om de invloed van het ontwerp- en constructieproces op het vervaardigen van gevels te analyseren. Een eerste stap wordt gezet door het ontwerp- en vervaardigingsproces te definiëren als het volledige traject van het eerste idee tot het levenseinde van de gevel. Vervolgens worden de verschillende procesfasen omschreven. Daar op gebaseerd is een interviewmethodologie en vragenlijst ontwikkeld. De wisselwerking tussen de verschillende betrokken bouwpartijen en de invloed daarvan op de fysieke constructie van de vliesgevel is daarbij meegenomen.

Hoofdstuk 3. Analyse van het ontwerp- en vervaardigingsproces

Dit hoofdstuk richt zich op de analyse en de interpretatie van de vraaggesprekken. Het schetst de processtappen en -voorwaarden, de rol van de verschillende bouwpartijen en hoe het architectonisch ontwerp is afgestemd op het vervaardigen van de gevel. Duidelijk wordt dat het proces sterk gefragmenteerd is door de relatie met het sterk projectgerichte architectonisch ontwerpproces. Vernieuwingen worden aldus vanaf de zijlijn ingebracht door de verschillende bouwpartijen.
Het hoofdstuk sluit af met het op schrift stellen van een aantal uitdagende doelstellingen die voortkomen uit de procesanalyse. Deze doelstellingen hebben een generiek karakter en ze worden, om ze met het maken van gevels te verbinden, vertaald in functies van de gevel. In hoofdstuk 5 en 6 worden deze uitdagende doelstellingen gebruikt om zowel bestaande constructies als nieuwe constructiemethoden te evalueren.

Hoofdstuk 4. Systematiek voor een constructieve gevelanalyse

Het hoofdstuk vormt het fundament onder de analyse van hedendaagse vliesgevelconstructies. De vervaardigingsmethoden die momenteel worden gebruikt hebben zich gelijktijdig ontwikkeld met het bouwproces. Daarom is er een systematiek ontwikkeld waarbij inzicht wordt verkregen in de relatie tussen constructieve details en de structuur van het ontwerp- en vervaardigingsproces.
Om twee redenen is er een literatuurstudie gedaan. Allereerst om te bekijken hoe deze relatie is terug te vinden in lesmateriaal en vakliteratuur en daarnaast om te komen tot een bruikbaar vocabulaire voor de systematiek. Het blijkt dat de literatuur op het gebied van architectuur en gevelontwerp gebaseerd is op het toepassen van bestaande technieken en nooit de vraag opwerpt of bepaalde constructies een afspiegeling zijn van de huidige procesmethoden. Literatuur op het gebied van productontwikkeling of productontwerp bieden een veel wezenlijker inzicht in deze relatie en bieden een waardevol vocabulaire voor de analyse van het maken van vliesgevels.
Het hoofdstuk sluit af met de ontwikkeling van een systematiek die is gebaseerd op drie hoofdbestanddelen: Een ´Gevelfunctie-boomstructuur´ verschaft een leidraad om te begrijpen welke functies een bepaalde constructie beoogt te vervullen. Het hiërarchische ´Schema van Productniveaus´ toont hoe een constructie is samengesteld van materiaal naar element en van component naar bouwdeel en hun aansluitingen. En de Theorie van ´Product Architecture´ wordt gebruikt om de relatie te beschrijven tussen de vervaardiging en de processtructuur van de bouw.

Hoofdstuk 5. Analyse van de vliesgevel ´product architecture´

Er worden vijftien verschillende constructiesystemen geanalyseerd, van historische voorbeelden via hedendaagse constructies naar 'gebouw en techniek geïntegreerde' concepten. Zowel volledige gevels als individuele elementen worden ontleed. Daarbij is de grootste moeilijkheidsfactor om vergelijkbare resultaten te verkrijgen. Hiervoor wordt de in het voorgaande hoofdstuk ontwikkelde systematiek toegepast.
De analyse laat zien hoe de vliesgevels zich hebben ontwikkeld van ambachtelijke constructies tot sterk gesystematiseerd producten. Met het vergroten van de functionaliteit zijn de systemen steeds gecompliceerder geworden. Waar vroege vliesgevels een geïntegreerde constructie kenden, zijn hedendaagse systemen zeer modulair opgebouwd en uitgevoerd met loskoppelbare verbindingen (decoupled interfaces).
De analyse toont hoe vliesgevelsystemen waarschijnlijk in staat zullen zijn om op toekomstige uitdagingen in te spelen , zoals gedefinieerd in hoofsdtuk 3. Het geeft aan op welke gebieden vliesgevels waarschijnlijk goed zullen presteren en waar niet. De vliesgevel raakt uitontwikkeld. De nauwe samenhang tussen de modulaire opbouw en de gefragmenteerde structuur van het ontwerp- en vervaardigingsproces blokkeren de verdere ontwikkeling van componenten en nieuwe verbindingsconstructies (interfaces). Het wordt steeds moeilijker om aan alle doelstellingen en eisen te voldoen die gevels in de toekomst te wachten staan.

Hoofdstuk 6. Voorbeeldstudies voor een nieuwe aanpak

Het hoofdstuk bespreekt de nieuwe integrale benadering van gevelconstructies gericht op het opsporen van nieuwe methoden voor de vliesgevel. De voorbeeld gevels hebben verschillende constructieve eigenschappen, maar verschillen ook voor wat betreft hun reden van toepassing, dat wil zeggen het probleem waar zij een oplossing voor moeten zijn. Ze lopen uiteen van volledige gevelconcepten tot systeemproducten. Ook zijn vernieuwende productie- en assemblagetechniek onderzocht. En tenslotte zijn experimentele gevelontwerpen geanalyseerd op basis van omschreven constructie-scenario's.
Functie-boomstructuren en Productniveau-schema's zijn gebruikt om verschillende voorbeelden op een vergelijkbare manier te analyseren. Voor elk voorbeeld zijn individuele Procesprofielen gemaakt. Ze laten zien hoe de wisselwerking tussen de verschillende bouwpartijen verloopt tijdens de projectfasen en bovendien dat geïntegreerde constructies vragen om een andere en meer integraal ontwerp- en constructieproces vergeleken bij de huidige standaard vliesgevelconstructies.

Hoofdstuk 7. Voorbeeldstudie-evaluatie

In hoofdstuk 7 worden de middelen om met modulair en integraal ontwerp de toekomstige doelstellingen te behalen opgesomd en ze worden vergeleken in een tabel. Er komen twee typen voor, die zijn gebaseerd op totaal verschillende methoden. Integrale `product architecture` is afhankelijk van technologische ontwikkeling en vereist een geïntegreerd ontwerpprocces, terwijl het modulaire ontwerp afhankelijk is van systeemontwikkeling en overeenkomt met de huidige aanpak van de van elkaar gescheiden bouwpartijen. Het is belangrijk om te weten wat de implicaties zijn voor de keuze voor de ene of de andere soort of, andersom: Afhankelijk van de verlangde functionaliteit kan een bepaald type architectuur heilzaam zijn.
Dit maakt het mogelijk om algemene conclusies te trekken over de niveaus waarop een gevelproduct (materiaal, element, subcomponent of component) geschikt is om op toekomstige uitdagingen of doelstellingen in te spelen.
Op deze manier wordt een link gelegd naar constructiedetails.
Aanvullend krijgen de resultaten van deze vergelijking een plek in de planning van het ontwerp- en vervaardigingsproces. De vergelijking toont hoe en op welk moment in het proces de bouwpartijen specifieke procesmethoden moeten inzetten voor zowel integrale als modulaire constructies.
Een conclusie is dat strengere eisen integrale hoogwaardige oplossingen zullen bevorderen; dit vereist een meer geïntegreerde benadering van de betrokken bouwpartijen.

Hoofdstuk 8. Conclusie

Antwoorden op de onderzoeksvragen worden gegeven in hoofdstuk 8. Het wordt afgesloten met het verwoorden van gegeneraliseerde voorstellen voor een nieuwe aanpak van de vliesgevel:

- Het Projectgerichte en iteratieve architectonische ontwerpproces heeft een duidelijke invloed op de manier waarop gevels worden gemaakt. Gevelconstructie zal daarom altijd verschillen van andere constructiedisciplines zoals bijvoorbeeld de autoindustrie of produktontwerp.
- De gebruiksfase en de levenseinde-fase zullen in het ontwerp- en vervaardigingsproces snel belangrijker worden. Deze fasen zullen een nieuw werkterrein openen voor ontwerpers, gevelbouwers en voor hen die zich bezig houden met het gebruik en de levenseinde-cyclus van gevels.
- Als het traditionele gefragmenteerde ontwerp- en vervaardigingsproces wordt voortgezet, zal de steeds grotere complexiteit van gevelconstructies er onvermijdelijk toe leiden dat de architect wordt uitgesloten van de materialisatie van de gevel.

- Vliesgevelsystemen zijn heden ten dage graadmeterproducten, maar deze uitontwikkelde constructies bereiken hun grenzen met betrekking tot bepaalde functionaliteiten. In de toekomst zullen we een grotere verscheidenheid zien aan gevelconstructie-typen met en meer integrale `product architecture´.
- Deze grotere verscheidenheid zal de kenniskloof tussen architect en uitvoerende partij vergroten. Geïntegreerde ontwerpteams of -procedures zullen nodig zijn.
- Bij het ontwerpen van gevels in de toekomst zal, in plaats van het bepalen van de constructieve oplossingen, het bepalen van de gevelfunctionaliteiten de belangrijkste taak worden.
- Een nieuwe benadering zal ook nieuwe inzichten geven over de wijze waarop het maken van vliesgevels overeenkomt met het ontwerp- en vervaardigingsproces. Grafische hulpmiddelen die zijn ontwikkeld voor deze dissertatie, zoals de gevelfunctie-boomstructuur en de product- en procesprofielen zijn zowel waardevol voor het evalueren als ook voor het scheppen van nieuwe constructieconcepten.
- Een nieuwe manier om architecten of gevelspecialisten op te leiden is nodig om te voldoen aan de behoeften van de bouw in de toekomst: Het zal verschuiven van een puur op toepassing gerichte aanpak naar een door het produktontwerp gedreven benadering, die sterk de invloed zal tonen van de gevel`product architecture` op het ontwerp- en vervaardigingsproces.

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Chapter 1

- Figure 8: Arne Künstler

Chapter 4

- Figure 34: www.cepolonia.com
- Figure 35: www.auna-multimedia.de

Chapter 5

- Figure 62: Raico Bautechnik GmbH
- Figure 63 : Kawneer Alcoa Architectural Systems
- Figure 67,68 : Kawneer Alcoa Architectural Systems
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- Figure 92: LeCorbusier, © VG Bild Kunst, Bonn 2007
- Figure 95: WikiArquitectura
- Figure 99-102: www.wicona-int.com/en/Product/Facade/TEmotion-Intelligent-facade-concept
- Figure 103, 104: www.smartfacade.nl
- Figure 106 : Marc Datthijn
- Figure 107-110 : www.schueco.comProfil, (Magazin über Architektur 05)

Chapter 6

- Figure 105,106: Holland Composites Industrials B.V.
- Figure 121, 122: Octatube
- Figure 128, 129: Joep Hoevels
- Figure 131, 132: www.xframe.dk
- Figure 137, 138: Holger Strauß
- Figure 140, 142: ©Gramazio & Kohler, ETH Zurich

- Figure 144: cepezed architects
- Figure 146: Emile Willems
- Figure 147: Thea van den Heuvel
- Figure153, 154, 156: Leonie van Ginkel
- Figure 160, 161, 163: Charlotte Heesbeen
- Figure x: NASA
- Figure167-169: Jasper Overkleeft
- Figure172: Chenjie Wu
- Figure173, 174: Chenjie Wu, Bart van den Ende, Wouter Streefkerk

Side notes

USB Story

- www.gravis.de
- www.wikimedia.org

Cloud gate

- www.architectureartdesigns.com/cloud-gate-in-millennium-park-chicago/
- www.zaha-hadid.com

Sony Walkman

- www.boom973.com
- www.sony.net

A Wall for All Seasons

- Mike Davies, Richard Rogers Partnership, London

References

Addington, M., & Schodek, D. (2005). *Smart materials and new technologies for architecture and design professions*. Oxford: Elsevier.

Richtlijnen voor de Aluminium Constructeur, (2010).

Ashby, M. F. *Materials selection in mechanical design Online resource* (4th ed.). Burlington: Butterworth-Heinemann.

Ashby, M. F., & Johnson, K. (2009). *Materials and design the art and science of material selection in product design* (2nd ed.). Oxford: Butterworth-Heinemann.

Baldwin, C. Y., & Clark, K. B. (2000). *Design rules. Vol. I. The power of modularity*. Cambridge, Mass.: MIT Press.

Beim, A., & Jensen, K. V. (2007). Forming Core Elements for Strategic Design Management: How to Define and Direct Architectural Value in an Industrial Context. *Architectural Engineering and Design Management*, 3, 29-38.

Beim, A., Nielsen, J., & Sánchez Vibaek, K. (2010). *Three Ways of Assembling a House*. Copenhagen: The Royal Danish Academy of Fine Arts, School of Architecture Publishers.

Beim, A., & Royal Danish Academy of Fine Arts School of Architecture. (1999). *Tectonic visions in architecture investigations into practices and theories of building construction; six case studies from the 20th century by Anne Beim*. Copenhagen: Royal Danish Academy of Fine Arts.

Bilow, M. (2012). *International facades: CROFT climate related optimized facade technologies*. Delft: Delft University of Technology.

BNA. (2008). *DNR-STB 2009 Standaardtaakbeschrijving*. Amsterdam: IMAGO Printing.

Brookes, A. J. (2002). *The turning point of building*. Delft: Technische Universiteit Delft.

Brookes, A. J., & Grech, C. (1992). *Connections; studies in building assembly*. Oxford: Butterworth.

Brookes, A. J., & Grech, C. (1997). *The building envelope and Connections*. Oxford: Architectural Press.

Brookes, A. J., & Meijs, M. (2008). *Cladding of buildings* (4th ed.). Abingdon: Taylor and Francis.

Brookes, A. J., & Poole, D. (2004). *Innovation in architecture*. London: Spon.

Canzler, B. (2005). *Dezentrale /Zentrale Klimatisierung in Bürogebäuden: Betrachtungen aus Sicht von Investoren, Mietern und Nutzern am Beispiel eines Großprojektes*. Neukirchen-Vluyn: TroxTechniko. Document Number)

Ching, F. D. K., & Adams, C. (2001). *Building Construction Illustrated* (3rd edition ed.). New York: John Wiley & Sons.

Compagno, A. (1999). *Intelligente Glasfassaden Material, Anwendung, Gestaltung* (4th ed.). Basel: Birkhäuser.

Corbusier, L. (1930). *Précisions sur un état présent de l'architecture et de l'urbanisme*. Paris: Crès.

Cross, N. (2008). *Engineering design methods: strategies for product design* (Fourth edition ed.). Chichester: John Wiley & Sons Ltd.

Danner, D., Dassler, F. H., Krause. Jan, R., & K*hler, G. (1999). *Die klima-aktive Fassade*. Leinfelden-Echterdingen: Koch.

Davies, M. (1981). A Wall For All Seasons. *RIBA Journal*(February 1981), pp. 55-57.

De Jonge, T. M., & Van der Voordt, D. J. M. (2002). *Ways to study research urban, architectural and technical design*. Delft: DUP Science.

Deplazes, A. (2005). *Architektur Konstruieren*. Basel: Birkhäuser.

DNR. (2005). The New Rules 2005, *Legal relationship client–architect, engineer and consultant*. Ouderkerk a/d Amstel: Royal Institute of Dutch Architects BNA and Organization of consulting engineers ONRI.

Du, Q. (2009). *Integrated Decision-Making in the Cladding Supply Chain*. University of Bath, Bath.

Durmisevic, E. (2006). *Transformable building structures. Design for dissassembly as a way to introduce sustainable engineering to building design & construction*. S.l.: S.n.

Ebbert, T. (2010). *Re-Face: Refurbishment Strategies for the Technical Improvement of Office Façades* Unpublished Dissertation, Delft University of Technology, Delft.

Eekhout, M. (2008). *Methodology for product development in architecture*. Amsterdam: IOS Press.

Eekhout, M., Verheijen, F., & Visser, R. (2008a). *Cardboard in Architecture*. IOS Press ; Amsterdam,.

Eekhout, M., Verheijen, F., & Visser, R. (2008b). *Cardboard in architecture elektronisk materiale*. Amsterdam: IOS Press.

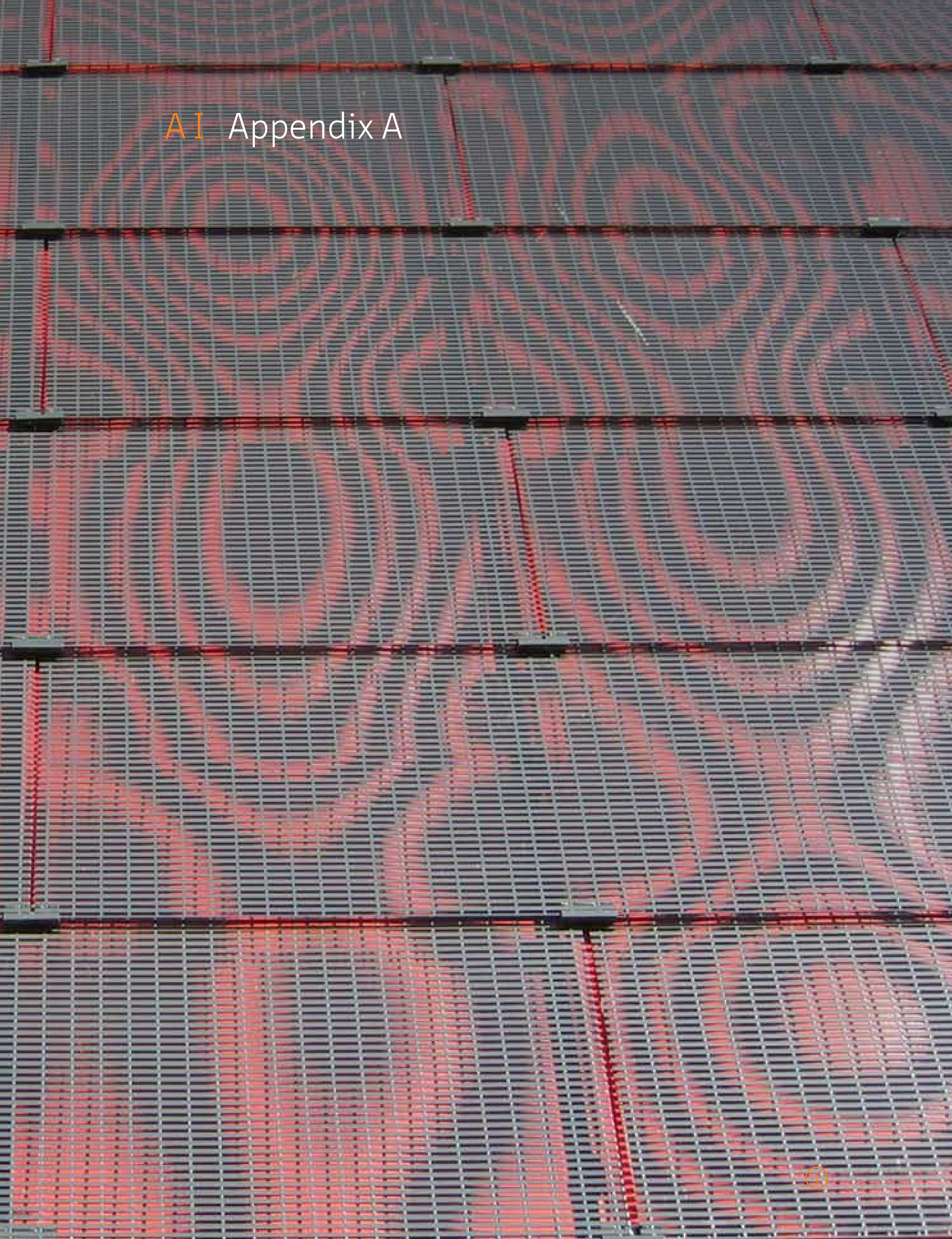
Egan, J. (1998). *Rethinking construction*. London: Department of Environment.

EU. (2010). Directive 2010/31/EU on the energy performance of buildings. *Official Journal of the European Union*.

Fisch, M. N., & Plesser, S. (2005). *Evaluation of Energyconcepts for Office Buildings*. Paper presented at the Fifth International Conference for Enhanced Building Operations.
Franzke, U., Heidenreich, R., Ehle, A., & Ziller, F. (2003). *Comparison between Decentralised and Centralised Air Conditioning Systems*. Dresden: ILK Dresdeno. Document Number)
Gaetano, S. D., & Zammit, K. (2011). *The structure and facade interface and the challanges of engineering tall building facades*. Paper presented at the IABSE-IASS Symposium: Taller, Longer, Lighter.
Gay, P. d., Hall, S., Janes, L., Mackay, H., & Negus, K. (1997). *Doing cultural studies - The story of the Sony Walkman*. London Sage.
Giera, M. (2011). *Additive processes in robot-based brick manufacturing*. Paper presented at the The Future Envelope 4 - Next Generation, Delft.
Gramazio, F., & Kohler, M. (2012). Architektur und Digitale Fabrikation. Available at: http://www.dfab.arch.ethz.ch/.
Grennberg, T. (1993). Project types in building and construction. *International Journal of Project Management, 11*(2), 68-71.
Habraken, N. J., Massachusetts Institute of Technology Laboratory of Architecture and Planning, Boekholt, J. T., Dinjens, P. J. M., & Gibbons, S. (1976). *Variations: the systematic design of supports*. Cambridge, Mass.: MIT Press.
Halman, J. I. M., Voordijk, J. T., & Reymen, I. M. M. J. (2008). Modular approaches in dutch house building: An exploratory survey. *Housing Studies, 23*(5), 781-799.
Hansen. (2011). X-frame. Available at: http://www.xframe.dk. from www.xframe.dk
Herzog, T., Krippner, R., & Lang, W. (2004). *Facade construction manual*. Basel: Birkh*user.
HOAI. (2010). *HOAI-TEXTAUSGABE; Verordnung ueber die Honorare fuer Leistungen der Architekten und der Ingenieure (Honorarordnung fuer Architekten und Ingenieure - HOAI -)* (2. Aufl. ed.). Wiesbaden: Bauverlag.
Hofer, A. P., & Halman, J. I. M. (2004). Complex products and systems: Potential from using layout platforms. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM, 18*(1), 55-69.
Hofer, A. P., & Halman, J. I. M. (2005). The potential of layout platforms for modular complex products and systems. *Journal of Engineering Design, 16*(2), 237-258.
Hofman, E., Voordijk, H., & Halman, J. (2009). Matching supply networks to a modular product architecture in the house-building industry. *Building Research and Information, 37*(1), 31-42.
Hunt, W. D. (1958). *The contemporary curtain wall; its design, fabrication and erection*. New York: Dodge.
Kalian, A., Watson, A., Agbasi, E., Anumba, C.J. and Gibb, A.G.F. (2001). *ICT Usage: Current and Future, Computer-Integrated*
Manufacture of Cladding Systems (CIMclad) Report 2. Leeds: University of Leedso. Document Number)
Kawneer. (2012). Kawneer Alcoa AA100 curtain wall system: Available at: http://www.kawneer.com/kawneer/germany/en/info_page/home.asp.
Kieran, S., & Timberlake, J. (2004). Refabricating architecture how manufacturing methodologies are poised to transform building construction (pp. 175 blz.). New York: McGraw-Hill.
Kilaire, A. (2012). *Design of an Integrated Passive and Active Double Facade System for UK Offices*. University of Nottingham, Nottingham.
Knaack, U. (2006). *Design of construction. Imagine! introduction lecture; held at TU Delft on 23. of July 2006 by Prof. Dr.-Ing.Ulrich Knaack and a collection of Future Fa*ade Principles by The Fa*ade Research Group, Chair Desgin of Construction, Faculty of Architecture*. Delft: Publikatieburo Bouwkunde.
Knaack, U., & Klein, T. (2009a). *The Future Envelope 2 Architecture-Climate-Skin*. Amsterdam: IOS.
Knaack, U., & Klein, T. (Eds.). (2009b). *The Future Envelope 2 Architecture - Climate - Skin*. Amsterdam: IOS Press.
Knaack, U., & Klein, T. (Eds.). (2010). *The Future Envelope 3, Facade - The Making Of* (Vol. 10). Amsterdam: IOS Press.
Knaack, U., Klein, T., & Bilow, M. (2008a). *Imagine - Deflateables*. Rotterdam: 010 Publishers.
Knaack, U., Klein, T., & Bilow, M. (2008b). *Imagine - Facades*. Rotterdam: 010 Publishers.
Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007). *Facades principles of construction* Basel: Birkhäuser.
Knaack, U., Strauss, H., & Bilow, M. (2010). *Rapids*. Rotterdam: 010 Publishers.
Kohlmaier, G., & Sartory, B. v. (1981). *Das Glashaus; ein Bautypus des 19. Jahrhunderts*. München: Prestel.
Lambert, A. J. D., & Gupta, S. M. (2005). *Disassembly modeling for assembly, maintenance, reuse, and recycling*. Boca Raton: CRC Press.
Ledbetter, S. (2003). *Communication Down the Cladding Supply Chain*. Paper presented at the Proceedings of Façade Design and Procurement.

Lichtenberg, J. J. N. (2002). *Ontwikkelen van projectongebonden bouwproducten door Josephus Joannes Norbertus Lichtenberg Online resource*. S.l.: S.n.
Lichtenberg, J. J. N., Stichting Bouwresearch, & Steenhoff, J. M. F. (1996). *Productontwikkeling voor de bouwmarkt; de tien belangrijkste succesfactoren*. Rotterdam: Stichting Bouwresearch.
Mahler, B., Himmler, R., Silberberger, C., & Matt, C. (2008). *DeAL Evaluierung dezentraler außenwandintegrierter Lüftungssysteme, Abschlussbericht*. Stuttgart: Steinbeiss-Transferzentrum und Steinbeis Forschungszentrum Energie-, Gebäude-, und Solartechnik. (B. f. W. u. Arbeit o. Document Number)
Murray, S. (2009). *Contemporary Curtain Wall Architecture*. New York: Princeton Architectural Press.
Nijs, J. C., Durmisevic, E., & Halman, J. I. M. Interface design for open systems building. *Open House International, 36*(1), 35-43.
Oesterle, E., Lieb, R.-D., Lutz, M., & Heusler, W. (2001). *Double-Skin Facades: Integrated Planning*. München: Prestel.
Poelman, W., & Keyson, D. (2008a). *Design processes what architects and industrial designers can teach each other about managing the design process*. Amsterdam: IOS.
Poelman, W., & Keyson, D. (Eds.). (2008b). *Design Processes*. Amsterdam: IOS Press.
Poelman, W. A. (2005). *Technology Diffusion in Product Design - Towards Integration of Technology Diffusion in the Design Process*. Unpublished Doctoral dissertation, Delft University of Technology, Delft.
Raico. (2008). Cross joint of curtain wall. Available at: http://www.raico.de.
Leitfaden zur Planung und Ausfuehrung der Montage von Fenstern und Haustueren, (2006).
Renckens, J. (1996). *Gevels en architectuur; facades in glas en aluminium*. Nieuwegein: Vereniging Metalen Ramen en Gevelbranche.
Rentier, C., Reymers, J., & Salden, M. (2005). *Omhulling 4B gevels* (eerste oplage ed.). Utrecht/Zytphen: ThiemeMeulenhoff.
RIBA. (2007). Outline Plan of Work. Available at: http://www.architecture.com/Files/RIBAProfessionalServices/Practice/OutlinePlanofWork%28revised%29.pdf. from http://www.architecture.com/Files/RIBAProfessionalServices/Practice/OutlinePlanofWork%28revised%29.pdf
Schueco. (2012). FW50 curtain wall system. Available at: http://www.schueco.com/web/uk/architekten/fassaden/products/facades/aluminium.
Smartfacade. (2006). Smart Box Energy Facade. Available at: http://www.smartfacade.nl/.
Solla, I. F. (2012). Le Corbusier: A French Lesson on 'Mur Neutralisant'. Available at: http://facadesconfidential.blogspot.nl/2012/04/le-corbusier-mur-neutralisant-and.html.
Sony. (2012). The Walkman. available at: http://www.sony.net/SonyInfo/CorporateInfo/History/SonyHistory/2-06.html.
TEmotion facade. Available at: http://www.wicona-int.com/en/Product/Facade/TEmotion-Intelligent-facade-concept/.
TroxTechnik. (2010). Post Tower. Available at: http://www.trox.de/de/company/references/showcases/office_building/bonn_tower/index.html.
UBF. (2008). *Leistungsbild und Honorargrundlagen - Fachingenieurleistungen für die Gebäudehülle*. Retrieved. from.
van Diepen, B. (2010). *Vergelijking tussen decentrale klimaatinstallatie systemen*. Unpublished Master Thesis, Delft Technical University, Delft.
Veenstra, V. S., Halman, J. I. M., & Voordijk, J. T. (2006). A methodology for developing product platforms in the specific setting of the housebuilding industry. *Research in Engineering Design, 17*(3), 157-173.
Vijverberg, G. (2012). *Handboek prestatiegericht samenwerken bij investeren en onderhoud*. Rotterdam: SBR.
Wiggington, M., & Harris, J. (2002). *Intelligent Skins*. Oxford: utterworth-Heinemann.
WikiArquitectura. (2010). Lloyd´s Building. Available at: http://en.wikiarquitectura.com/index.php/Lloyd27s_Building.
Yin, R. K. (1994). *Case study research: design and methods* (Second Edition ed.). Thousand Oaks: SAGE Publications.
Zeiler, W., & Quanjel, E. (2008a). Flexible Sustainable Proces Innovation: Integral Building Design Methodology. *10th International Design Conference - Design 2008, Vols 1 and 2*(48), 553-560.
Zeiler, W., & Quanjel, E. (2008b). Integral design for starting a cultural change in dutch building design practice. *Detc2007: Proceedings of the Asme International Design Engineering Technology Conference and Computers and Information in Engineering Conference, Vol 4*, 609-615.
Zeiler, W., & Quanjel, E. (2008c). Integral design methodology within industrial collaboration. *Detc2007: Proceedings of the Asme International Design Engineering Technology Conference and Computers and Information in Engineering Conference, Vol 4*, 633-641.

A I Appendix A



List of interviewed experts

The following experts have been interviewed. They contributed to the development of the analyses of the façade design and construction process in chapter 3:

A=Architect
Robert Platje, building technology expert/project manager, Mei Architecten en Stedebouwer, NL
Joost. M. Heijnis, projectmanager, architectenbureau cepezed b.v., NL
Christian Heuchel, Gesellschafter, Geschäftsführer (partner, director), Ortner & Ortner Architekten, D
Remigiusz Otrzonsek, Gesellschafter (Partner), HPP Architekten, D

C=Consultant
Patrick Teuffel, director, Teuffel Engineering Consultants, D
Marcel Bilow, director imagine envelope Façade Consulting, NL

S= System Supplier
Rogier Cremer, technical sales advisor, Alcoa Architectural Systems (Aluminum facade system provider), NL
Piet Brosens, manager techniek, Merford/Trox (Provider of decentralized building services systems), NL

D=Developer
Jan van´t Westeinde, senior adviseur installaties and duurzamheid (building services and sustainability), MAB Development Nederland BV (Project developer), NL

F= Façade Builder
Anco Bakker, adjunct director techniek, De Groot & Visser (Facade Builder), NL
Reinoud de Kroon, sales director, Holland Composites Industrials (Facade Builder), NL
Nico Kremers jr., sales and acquisition, Kremers Aluminium (Facade Builder), NL
Nils Eekhout, director, Octatube (Builder special metal glass facade), NL
Ralph Domenicus, manager engineering, Oskomera (Facade builder), NL

B= Branch organization
Bert Lieverse, Directeur, VMRG Vereniging Metalen Ramen en Gevelbranche (Association of the Dutch Façade Industry), NL

Interview Form - Architecture

The interview is conduction as part of the PhD project "Integrated Façade Constructions" at the Façade Research Group/ TU Delft. The project investigates the chances for new façade product architecture. Different Stakeholders from façade design and construction are interviewed (about 30 interviews).
It is not the purpose to assess the individual company or stakeholder, but to gain general knowledge about how façade construction is carried out today.

The interview has 3 parts:

1. Specific questions concerning the company
2. Processes in façade construction
3. General questions

Part 1

Name	
Name of company	
Position within the company	
Date of interview	

- What does your company do? (Description of the business activities):
- Description of company (Number of employees, turn over, organization):
- Compared to your competitors, how would you describe your profile? (Size, portfolio, target market or country, specifications, goal,...)
- A1. In what phase are you working in the field of building envelopes?

Pre-design (Client develops project)	Design	Manufacturing	Assembly	Use	End of life

- A2. Are you concerned with end of life scenarios?
- A3. Who guarantees the energetic performance of your building and is that measured afterwards?
- A4. How many design phases do you execute? Please name them. Please assign them to the phases above.

	1	2	3	4	5	6	7	...
%								

- A5. Compared to the volume of your whole contract, what is the turnover of the different activities?

	1	2	3	4	5	6	7	...
= 100%								

- A6. In what phase do you make the biggest win?

	1	2	3	4	5	6	7	...
%								

- A7. How big is your risk, failure potential?

	1	2	3	4	5	6	7	...
%								

- A8. What are the biggest risks?

Part 2 Processes in façade construction

A9. If 4 contracting concepts are considered, can you give a rough estimation (percentage of how often you are involved with them?

1	
Open tender. The façade is tendered on the basic of extensive specifications. (The façade builder has basically no influence on the design.)	%

2	
The builder gets involved in the architectural design (he is perhaps even paid for this). After that he is competing with other companies that are also asked to make a price.	%

3	
Direct contract. The façade builder is involved from the beginning and than negotiates a price and gets the job.	%

4	
Functional specifications: You are creating only functional specifications. (Can you make a façade that can do this and that and how much does it cost?)	%

- A10. Do you see a tendency here?

- A11. Which of these concepts assures:

a the best control over the final build result (Quality and architectural design)?
b the best chances for innovation?
c the lowest price of the façade?
d the most economic way of working for your company?

- A12. How many of your projects are executed with general contractors?
- A13. When a general contractor is involved, what is your relation with him?
- A14. What does that mean for the project (e.g. architectural quality, ...)?

- (Please see process sheet 1)
  Looking at the table of façade construction phases, what your interests are in cooperating with the different stakeholders?

- (Please see process sheet 2)
  Where do you see risks and conflicts in cooperating with the different stakeholders?

- (Please see process sheet 3)
  What decisions are made by whom in what phase?

- A15. Do you work with fixed partnerships/ subcontracts or are they differing from project to project? (Can you qualify and quantify?)
- A16. Has the time of your involvement in a project (from the assignment to finishing) become short in the last years? Can you quantify?)
- A17. Can you work faster?

Part 3 General questions

- A18. Who decides over the use of façade concepts and systems and products?
- A19. What are the decisive arguments for façade products?

	low	middle	high	comments
Architectural quality				
Design openess/flexibility)				
Cost				
Performance				
Other ...				

- A20. Do you have a good overview over the technical aspects of façade products e.g. curtain walls or window systems? Do you now how they differ?
- A21. Do façade products rather help or limit your work?
- A22. How big are the façade costs in comparison to the total building costs?
- A23. Do façades become relatively more expensive?
- A24. Do you have experience with building service integration? (Please describe project)
- A25. Do you have a good picture of the possible performance of this approach (Why it should be done)?
- A26. What is your opinion about building service integration? (Chances and bottlenecks)
- A27. Which are your current fields of research? Do you develop new products?
- A28. Generally, what would be the role of the Architect in innovation?
- A29. What are the limiting factors for you in terms of innovation? (Knowledge about the market, costs, the market structure itself, sales)
- A30. How do you transfer knowledge within your firm?
- A31. Do you generally see a development in the discipline of building envelopes? (New requirements, challenges?)
- A32. Where is the potential for your company, your discipline?
- A33. Other comments?
- A34. Do you have any objection against publishing the content of this interview?

Interview Form - Façade Builder

The interview is conduction as part of the PhD project "Integrated Façade Constructions" at the Façade Research Group/ TU Delft. The project investigates the chances for new façade product architecture. Different Stakeholders from façade design and construction are interviewed (about 30 interviews).
It is not the purpose to assess the individual company or stakeholder, but to gain general knowledge about how façade construction is carried out today.

The interview has 3 parts:

1. Specific questions concerning the company
2. Processes in façade construction
3. General questions

Part 1

Name	
Name of company	
Position within the company	
Date of interview	

- What does your company do? (Description of the business activities):
- Description of company (Number of employees, turn over, organization):
- Compared to your competitors, how would you describe your profile? (Size, portfolio, target market or country, specifications, goal,...)
- I1. In which phase are you working in the field of building envelopes?

	Development (Everything before design phase)	Design	Material/ Supply	Production	Transport	Assembly on site	During use of building	End of life
= 100%								

- I2. Are you concerned with end of life scenarios?
- I3. Compared to the volume of your whole contract, how big is the turn over of your different activities?

	Development (Everything before design phase)	Design	Material/ Supply	Production	Transport	Assembly on site	During use of building	End of life
= 100%								

- I4. In which phase do you make the biggest win?

	Development (Everything before design phase)	Design	Material/ Supply	Production	Transport	Assembly on site	During use of building	End of life
= 100%								

- I5. How big is your risk, failure potential?

	Development (Everything before design phase)	Design	Material/ Supply	Production	Transport	Assembly on site	During use of building	End of life
= 100%								

- I5b. How big is the influence of the following aspects on the risks and failures potential?

Design				
	low	middle	high	comments
Dependencies to other disciplines				
Planning mistakes				
Time				
Other ...				

Management/ logistics				
	low	middle	high	comments
External communication				
Internal communication				
Cost calculation				
Wrong evaluation of require-ments, complexity and volume				
Workflow				
Other ...				

Material/ supply				
	low	middle	high	comments
Material failures				
Quality of subcomponents				
Delivery times				
Other ...				

Production				
	low	middle	high	comments
Physical interfaces to other disciplines				
Time				
Other ...				

Transport				
	low	middle	high	comments
Timing				
Damage				
Other ...				

Assembly				
	low	middle	high	comments
Dependencies to other disciplines				
Physical dependencies to other disciplines (tolerance, mistakes)				
Parts that do not fit				
Weather				
Other ...				

During use	low	middle	high	comments
Failures				
Claims				
Wrong or missing maintenance				
Other ...				

- General, other remarks:
- I6. What do you do to prevent failures?

Part 2 Processes in façade construction

- I7. Considering four different contracting concepts, please give a rough estimation of how often you are involved with them?

1	
Open tender. The façade is tendered on the basic of extensive specifications. (The façade builder has basically no influence on the design.)	%

2	
The builder gets involved in the architectural design (he is perhaps even paid for this). After that he is competing with other companies that are also asked to make a price.	%

3	
Direct contract. The façade builder is involved from the beginning and than negotiates a price and gets the job.	%

4	
Functional specifications: You are creating only functional specifications. (Can you make a façade that can do this and that and how much does it cost?)	%

- I8. Do you see a tendency here?

- I9. Which of these four concepts assures:

a the best control over the final build result (Quality and architectural design)?
b the best chances for innovation?
c the lowest price of the facade?
d the most economic way of working for your company?

- (Please see process sheet 1)
  Looking at the table of façade construction phases, what your interests are in cooperating with the different stakeholders?

- (Please see process sheet 2)
  Where do you see risks and conflicts in cooperating with the different stakeholders?

- (Please see process sheet 3)
  What decisions are made by whom in what phase?

- I10. How many internal design steps do you have and how do you name them (after the architectural design)?
- I10b. To what extend do you prefabricate your products?
- I11. Has the time of your involvement in a project (from the assignment to finishing) become short in the last years and if can you quantify?
- I12. Can you work faster?

Part 3 General questions

- I13. Are you concerned with architectural design and what value does it have for you?
- I14. Does architectural design sometimes conflict with you work?
- I15. What does sustainability mean for your discipline?
- I16. Who decides over the use of façade concepts and systems and products?
- I17. What are the decisive arguments for façade products?

	low	middle	high	comments
Architectural quality				
Design openess/flexibility)				
Cost				
Performance				
Other ...				

- I18. How do you market your products?
- I19. To what extend are facades prefabricated today and do you see a tendency here?
- I20. Do you have experience with building service integration? (Please describe project)
- I21. Do you have a good picture of the possible performance of this approach (Why it should be done)?
- I22. What is your opinion about building service integration? (Chances and bottlenecks)
- I23. Which are your current fields of research? Do you develop new products?
- I24. Generally, what would be the role of the façade builder/system provider in innovation?
- I25. What are the limiting factors for you in terms of innovation? (Knowledge about the market, costs, the market structure itself, sales)
- I26. How big is the portion of theses categories for the whole façade product?

Design	Material	Production	Transport	Assembly	
					100%

- I27. Do you see a change here? (For example a raise in design costs)
- I28. How big are the façade costs in comparison to the total building costs?
- I29. Do façades become relatively more expensive?
- I30. Do you work with fixed partnerships/ subcontracts or are they differing from project to project? (Can you qualify and quantify?)
- I 31. Do you have to guarantee the performance of your product and is that I32. measured? (energetic performance, U-values, water tightness, noise protection,....)
- Do you work for general contractors?
- I33. Can you imagine taking the role as a general contractor for example for the discipline facades and installations?
- I34. How do you transfer knowledge within your firm?
- I35. What kind of employees are you looking for?
- I36. Do you generally see a development in the discipline? (New requirements, challenges?)
- I37. Where is the potential for your company, your discipline?
- I38. Do you have any objection against publishing the content of this interview?

A II Appendix B

Curriculum Vitae

Dipl.-Ing. Tillmann Klein

1967	Born in Wesel, Germany
1991-1992	DAAD scholarship University of Washington, USA
1994	Degree in architecture, Faculty of Architecture, RWTH Aachen, Germany
Since 1994	Professional occupation as architect and facade consultant
1999	Co-founder of the architecture firm rheinflügel baukunst
2000	Degree at the Kunstakademie Düsseldorf as „Meisterschüler“
2005	Art award for young artists from Nordrhein-Westfalen
Since 2005	Head of Facade Research Group, TU Delft, The Netherlands
2008	Co-founder imagine envelope b.v. facade consulting
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Bibliography

Klein, T. (2005). Fassadengestaltung mit Systemen. Deutsches Architektenblatt 12/2005, p.63-65.

Klein, T. (2007a). The Deflated Bridge – building with the existence of nothing. The Architectural Annual 2006-2007, p.32-35.

Klein, T. (2007b). Evolution or Revolution in of Systems in Façade Technology. The Future Envelope 1, p85-95.

Klein, T. (2008). Die Klimaorientierte Fassade. Glaswelt, 10/2008, p.20/21.

Klein, T. (2010a). De Gevel van de toekomst is klimaactief. Stedenbouw & Architectuur, 7/2010, 7.

Klein, T. (2010b). Wetenschap performance design. Een nieuwe beweging in onderzoek en ontwerp. Cobouw, 89, 11.

Klein, T. (2012a). De gevel als integraal onderdeel van gebouwen DeArchitect, 01/2012, p.60-67.

Klein, T. (2012b). Integrale Konstruktion als Antwort. Glaswelt, 12/2012, p.36/37.

Klein, T., & Bilow, M. (2012). Top 10 Innovatieve Gevels. Stedenbouw & Architectuur, 07/2012, p.30-31.

Klein, T., Bilow, M., & Zaag, E. v. d. (2012). Doorzonwoning. XIA Intelligente Architektur, 04-06/12, p.72-73.

Knaack, U., & Klein, T. (2009a). Facade Technology. Inspiring Emerging Developments. DAX, 4/2009, p.48-53.

Knaack, U., & Klein, T. (Eds.). (2008). The Future Envelope 1 - A Multidisciplinary Approach. Amsterdam: IOS Press.

Knaack, U., & Klein, T. (Eds.). (2009b). The Future Envelope 2 Architecture - Climate - Skin. Amsterdam: IOS Press.

Knaack, U., & Klein, T. (Eds.). (2010). The Future Envelope 3, Facade - The Making Of (Vol. 10). Amsterdam: IOS Press.

Knaack, U., Klein, T., & Bilow, M. (2008a). Imagine - Deflateables. Rotterdam: 010 Publishers.

Knaack, U., Klein, T., & Bilow, M. (2008b). Imagine - Facades. Rotterdam: 010 Publishers.

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007a). Facades principles of construction Basel: Birkhäuser.

Knaack, U., Klein, T., Bilow, M., & Auer, T. (2007b). Prinzipien der Konstruktion - Fassaden. Basel: Birkhaeuser.

Knaack, U., Klein, T., Bilow, M., & Techen, H. (2011). Imagine - Performance driven envelopes. Rotterdam: 010 Publishers.

Knaack, U., Klein, T., Bilow, M., & Techen, H. (2012). Total Concrete – Die nächste Generation massiver Fassaden. In E. DBZ (Ed.), Beton Bauteile (pp. p.106-116). Gütersloh: Bauverlag GmbH.

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