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International Conference
on Building Envelope Design and Technology

Organized by
Prof. Dr. Oliver Englhardt
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# Editorial

## advanced building skins - Building Envelope Design and Technology

Building skins have rarely been as fascinating and challenging as they are today. They are the most interesting field in contemporary architecture. Facades and building envelopes are determining the visual identity, character and expression of architecture. They are shaping the urban environment.
The facade of a building is the interface between inside and outside, between public and private realms. The skin affects both appearance and performance in such a way that these diverse constitutive features promote new design concepts and spur technical developments for the architecture of the future.

There are multiple demands on facade constructions and they are increasing continuously. First and foremost, performance criteria are driven by the need to reduce carbon emissions. Furthermore, technical requirements are aimed at all areas relevant to human comfort within the built environment, such as aspects relating to visuals, acoustics and safety.
Modern building envelope designs range from simple and flat ones to those containing extraordinary folds and curves. They rise up in a play on light, colours, surfaces and haptics. In conjunction with a huge number of traditional and exciting new materials and the availability of new production processes the design base for extraordinary building envelopes are broadening enormously.

Architects, structural and mechanical engineers, facade engineers, specialists in building physics and energy design, material developers, researchers and manufacturers: only full cooperation and interaction between all these professionals can provide successful and holistic concepts in the development, design and construction of advanced building skins.
With this international conference we will bring them together: creative and innovative professionals and researchers at the forefront of skin design. We will discuss tasks and issues in research, design and manufacturing of high-performance facades and building envelopes.

I would like to thank all the authors who have enriched this publication with their revealing and extraordinary contributions. Special thanks go to the staff of the Institute of Building Construction and all the sponsoring partners. Without their support this conference and this publication would not have been possible.

Oliver Englhardt

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# Construction Aware Design Thinking

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Benjamin Schneider
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## Summary

The rationalization of a mathematically described digital form into a discrete model and its further development towards a built structure assembled out of numerous components with material-immanent characteristics, confronts both architects and engineers and mathematicians and building firms with new challenges.
A close interdisciplinary collaboration, an exact understanding between the project involved parties and a consistent parametric data model are therefore the key to optimization potential and a successful project. It is necessary to constantly adapt the methods of design development to the upcoming challenges.

**Keywords:** Complex geometry, steel structures, digital design, design thinking

## 1 Introduction

For the past century, architects have been using cylinders, cones, rotational and ruled surfaces for their designs. Meanwhile digital design tools enable architects to use a very rich amount of different forms and computers and software are necessary for throughout the architectural design and planning of the construction industry. Whether it is the design or the draft of drawings of new complex building shapes, working with digital content has become the standard for the industry. There is a continuous tendency to give up linear forms with easily manageable numbers of the same elements. Free-form structures originated by the creativity of architects beginning in the last decade of the previous millennium have developed to symbols of elegance, grace, progress, and innovation. The construction of arbitrarily shaped building envelopes necessitates the computerized design and calculation of large number of unique elements. To transfer the architectural concept into built reality, an intense collaboration of geometrical and structural engineers combined with production and material management experience is necessary to standardize complexity and hence increase the feasibility of the design *(Figure 1)*.

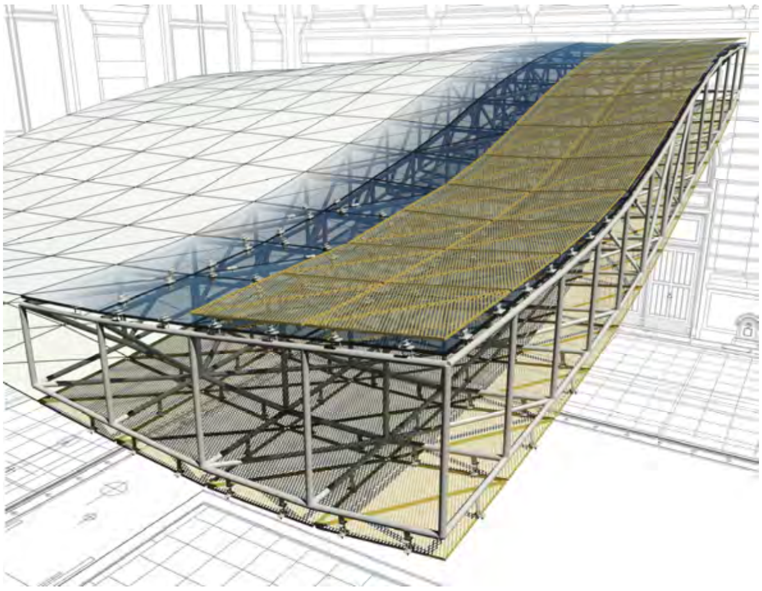


Figure 1: Multilayer freeform structure, Louvre Paris (Mario Bellini and Rudi Ricciotti)

## 2 Geometry as a Parameter in the Building Process

The interaction of design, construction, mathematics and an intensive cooperation between architect, engineer, geometer and client are essential and mandatory for successful projects and led to synergies of development and research. With the know-how of the participating architects and consultants, industrial enterprises and universities architectural visions became reality.
Mathematics and in particular geometry served for decades as inspiration in architectural design and many of the designs created by architects would not be realizable without deep geometrical knowledge (*Figure 2)*.

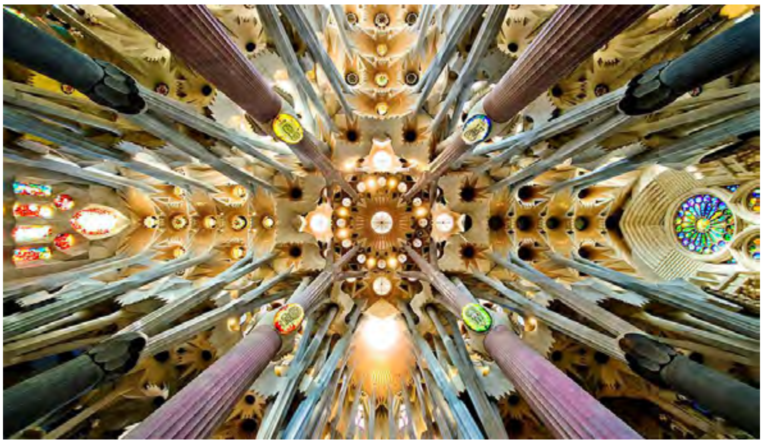


Figure 2: Sagrada Familia (Antonio Gaudi)

Dismantling surfaces into discrete parts and individual panels, so called *rationalization of surfaces*, is an important challenge for the building industry. The mathematical research supports the construction firms in setting up a digital model with the supply of the basic nets, smoothing of the curve networks over several nodes and the improvement of member orientation for the simplification node details. This development requires a consistent argument with the principles of the geometry of complex envelopes and further an adjustment and an improvement of the treatment and management of digital data sets. The integration of the *Advanced Geometry Engineering (Figure 3)* department in the planning process of Waagner-Biro was an important step towards the demanding market of freeform structures.

Figure 3: AGE integrated in the planning process

With the roofing of the Great Court of the British Museum in London *(Figure 4)* and the envelope of the Yas Marina Hotel in Abu Dhabi *(Figure 5)* the Waagner-Biro Stahlbau AG was able to show the viability of geometrically challenging steel glass structures in a competitive environment.

Figure 4: Great court at the British museum by Foster & Partners

Figure 5: Yas Marina Hotel by Asymptote

## 2.1 Rationalization of Complex Forms for Fabrication

The successful development of geometrically complex structures is an iterative process of analysis, modelling, calculation and modification. For conventional geometrically well determined designs like simple ruled surfaces, one may rely on many years of experience in structural design, the handling of building materials and methods for manufacturing.

The design geometry can be named to Ceccato [2] as follows: While *"pre-rationalised geometries"* are based on the outset of principles of feasibility, for *"post-rationalised geometries"* has at first to be developed a constructively logical approach which represents the original design in the best way possible and maintains at the same time the architectural intention.

Actually the basic layers of a building did not change within the last decades. We still have to deal with common space forming elements like supporting structure, walls, envelopes, and therefore cladding, joints, profiles and gaskets to ensure a structurally excellent building envelope. The approach of a construction firm didn't change so far, but we have to deal now with differing geometrical parameters and building forms. Del Campo and Manninger [3] stated that *additive systems formed the prevailing method of in the discipline of architecture when it comes to solve problems of transitions between interior and exterior, while another convention in architectural design is the usage of detail in the moments of transition between varying material conditions.* Constructive details are the minor part of the whole architectural conception. They are pushed back for the benefit of an almost *fluid* surface as an embodiment of a solid freeform shaped sculpture *(Figure 6)*.

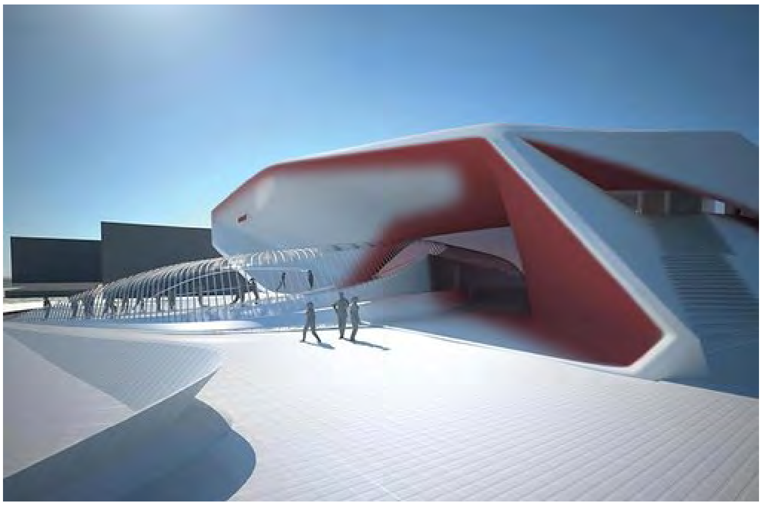


Figure 6: Shanghai Pavillion by SPAN Architects and Zeytinoglu

The geometrical properties of a double curved building envelope lead to a large number of elements and these will influence the following detailing process and, last but not least, will drive the costs. The goal of developing a rational steel structure which considers the immanent physical properties of the construction materials is an essential item within the building process. This includes tendering, aesthetics, structural calculations, detail design, manufacturing and installation on site in consideration of costs and economy.

Beside the feasibility one of the most influencing parameters are the costs. To maintain the given budget, quite often optimizations and changes of the original design are necessary, which is called *value engineering*. As part of the tendering process each component of the building is evaluated and assessed from a commercial point of view. The replacement of costly parts by reasonable alternatives is called value engineering. It is much more cost efficient to use proven standards instead of prototypes. A close partnership between the contractor and the manufacturer in the course of the years results in a vast knowledge and expertise in dealing with this process. Waagner-Biro's focus is to provide an economic and cost-effective solution which respects the design intent of the architect.

## 2.2 Geometrical Processing

The representation of complex geometry with regular elements requires profound understanding of the surfaces properties. Therefore the recognition of repetitive topologies, patterns and components, as well as the exact analysis and modelling of the geometry are necessary skills to understand which possibilities exist to provide a competitive solution. Furthermore it is necessary to enhance the complete planning process including the development of new production technologies and new assembly concepts. Traditional conceptions of repeatability and standardisation of individual constructional components are replaced or adapted. Without further processing and optimisation of a double curved geometry, the process of rationalization will always lead to warped, twisted or non developable construction components, which may rule out the full functionality of a building envelope. The orientation of steel members, the relation of member angle to node orientation, the even distribution of panel sizes, minimizing gaps between neighbouring elements and improving the properties of offset are the main goals of the rationalization. Furthermore we deal with aspects of aesthetics like the fairness of lines, the equal distribution of element sizes and angles between faces, triangular or quadrangular grids and their orientation on the surface.

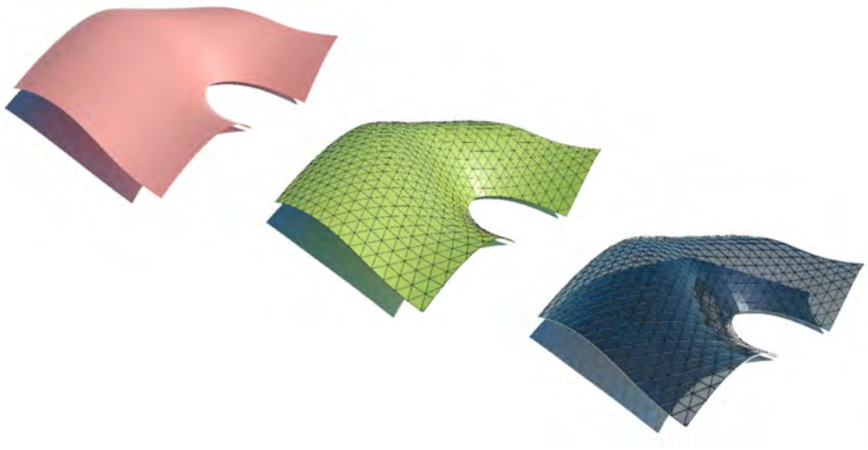


Figure 7: From a NURBS surface to a discrete mesh to a full digital model

All these factors of a panelised surface directly influence the properties of glass elements. While many designs may be approximated by triangular or in some cases flat quadrangular glass panes, there are cases where the original form and their smoothness have to be preserved either because a solution is only possible with a significant visual impact or the architect does not allow changes. Assuming there is a proper budget available for such a project this isn’t a problem at all.

A further approach is the use of cold or thermally bent glass. According to Eigensatz et al [5], pane types can be classified in flat, cylindrical, toroidal and spherical forms, which differ in material, fabrication method and costs. Various fabricators have developed proprietary methods and techniques for manufacturing spherical glass elements. An interesting method to decrease the costs of double curved glass structures is to simplify the geometry and breakdown the different types into a few manageable groups. To facilitate the workflow and enable important optimising techniques custom made software tools were developed by *Evolute*.

In the past years, researchers have solved various demanding tasks, like the panelisation of a double curved surface with a rectangular grid consisting of planar quadrangular faces. An additional approach in contrast to using an existing model is to perform a kind of reverse engineering and to remodel the complete compliant geometry. A big advantage of doing this is to be able to better understand the initial design and to create a clean model of the building which satisfies the needs for further processing. A disadvantage of this new model is that it is just an interpretation of the original geometry, including deviations and maybe misinterpretation, which we have to keep in mind while processing the project. The extracted curve network and the resulting mesh out of it is always an approximation of the original NURBS surface, whereby the nodes of the mesh ideally lie exactly on the compliant surface. For this reason there are many possible alternatives to interpret the base geometry, differing in number of members, panes size, aesthetics and costs.

Figure 8: Frankfurt MyZeil Shopping Centre by Massimiliano Fuksas (image courtesy of Frank Müller)

Figure 9: The Blob Eindhoven by Massimiliano Fuksas

# 3 Digital Data

Reduced use of conventional plans and drawings in the design phase is leading to an increase of the usage of 3D models, which are directly integrated into the design, assembly and manufacturing process. 3D models provide much more control than technical 2D drawings and a complete overview of the structure. Handling of a large amounts of different construction details and therefore the extraction of plans and drawings is only effective and economic with the full automation of creating 3D construction drawings and further drawing generation processes.
It is essential to manage data transfer between the main contractor and the manufacturer and not to allow any room for interpretation and ambiguity. Only an exact compliance and execution of the given data allows smooth assembly on site.

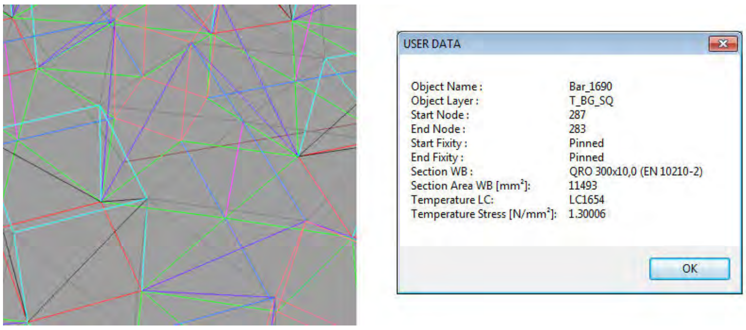
## 3.1 Consistent Data Model

Data models usually develop from different levels of detail from the conceptual model to the highly detailed parts for production. The 3d model is the base of all further derivate drawings like plans, sections, elevations, detailing, renderings, and CNC-data.

How to achieve a consistent data model? Generally known there are various file types to exchange data between certain software applications. Every exchange of data between applications inhibits the risk of loss of information. This information is addressed as meta-data. Examples of meta-data may be the name of a truss member, its cross-section area, overall surface area or assembly weight. Storing all your custom information to a specific object of your model, we would like to refer to this as a *rich-data-model*.

How to generate and obtain such “rich-data-models”? Each software application inherent means of storing meta-data, but the challenge is to export or re-import files. One suitable approach is to use the API (Application Programming Interface) of your software applications. Most applications offer a very good programmable interface, which are able to transport more data than the common existing exchange file-formats.

An example of data sharing is to import structural data from Dlubal RStab into the McNeel Rhinoceros environment. Rhinoceros with its strong geometrical capabilities (NURBS-based modeler) also offers possibilities to customize your own commands. It is also very often the start for the design geometry provided by the architect or by reengineering the system geometry out of other data formats, even 2d drawings. Rhinoceros is very capable of storing heaps of meta-data, this data can derive not only from a single, but from various software applications, to a single object which can be compared or altered between various stages in the progressive design. Also the existing meta-data can be “remapped” onto possible alterations of the architect’s geometry, which gives a huge advantage to not set up a new model in the structural application and apply all the various load cases again. This gives a high flexibility and therefore time and cost savings when handling different design variations.



Object Name : Bar_1690
Object Layer : T_BG_SQ
Start Node : 287
End Node : 283
Start Fixity : Pinned
End Fixity : Pinned
Section WB : QRO 300x10,0 (EN 10210-2)
Section Area WB [$mm^2$]: 11493
Temperature LC: LC1654
Temperature Stress [$N/mm^2$]: 1.30006

Figure 10: Meta-data stored to a single curve in Rhinoceros (“rich-data-model”)

## 3.2 Parametric Modelling

When using parametric modelling, as described by Zubin Kazabi [6] in his introduction of “Generative Algorithms using Grasshopper”, complex geometry usually starts from a very simple first level and then other layers are added. Usually the complex geometry consists of familiar but individual elements. So the same rules of the parametric algorithm apply to each individual element no matter if you are modeling a single geometry or hundreds of thousands. Even your multiple system geometries, which your elements are based on, can derive from a single base surface. In parametric modeling mostly a few geometric elements or even pure mathematical functions are the basic input of parametric modelling.

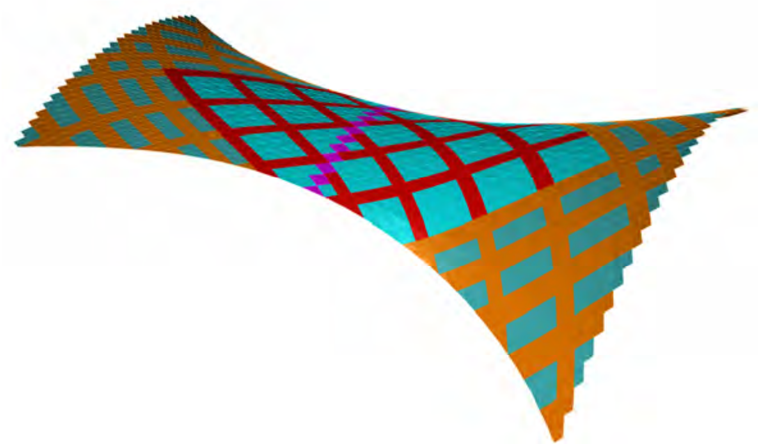


Figure 11: Base-Geometry, consisting of 3146 triangles

Especially in early stages of a design the parametric modeling has a huge advantage to study multiple solutions, therefore finding to optimum solution concerning the design. In later stages the design is often driven by other values like feasibility, costs, manufacturing limits and assembly issues. So it is necessary to alter certain parameters of the design to achieve the optimum solution, even going back to the very start and applying an altered (improved) basic geometry to the algorithm. Since the defined rules of the algorithm don’t change you can easily recalculate the total geometry.

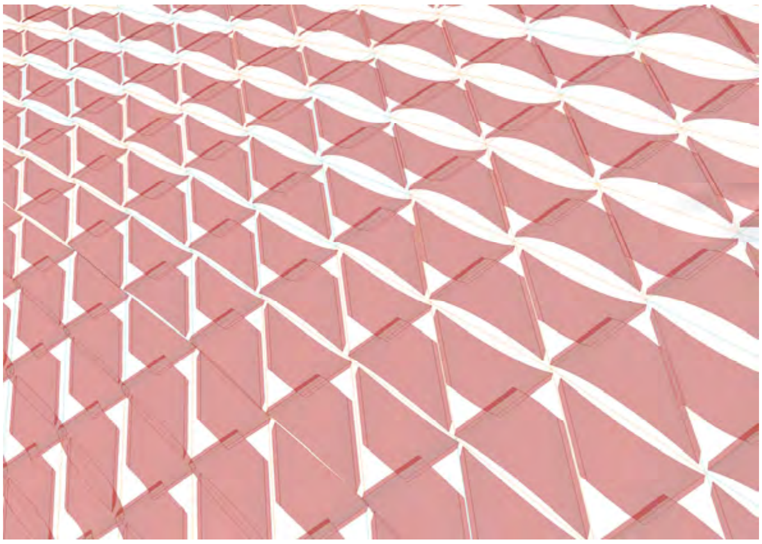


Figure 12: Result of parametric algorithm

This again gives a high flexibility and therefore time and cost savings when dealing with very late design changes, sometimes these are major (basic geometry), sometimes these are minor (detail geometry).

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# Plastic Materials in Facade Applications The Oskar von Miller Tower

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## Summary

In the contemporary architecture formable materials get more and more important. Plastic materials are predestinated for modern architecture and its language of facades. The paper wants to analyze the creative potential of plastic materials in façade applications and tries to prove it by introducing a new contemporary project, the Oskar-von-Miller-Tower in Munich with its 42 m high façade made of a translucent plastic material. In the conclusion the paper wants to answer the question which are the characteristic and unique attitudes of plastic materials in façade applications by a short comparison of buildings like Olympic Stadium Munich (1972), Art House Graz (2003) and the Oskar-von-Miller-Tower (2010) also in relation to the possible change of exposure to the material and the structural design

**Keywords:** Plastic material, formability, transparency, Oskar-von-Miller, Plexiglas

## 1 Introduction

In the Nineties of the last century a new kind of architectural organic design developed more and more. This was not only ascribed to a new and special generation of architects, it is more caused by the digitalization of the planning offices since the beginning of the Nineties. Finding structures and forms with the help of digitalized mediums brought the architects and designer to a leaving of material reality, a leaving of conventional geometries. Now every form, every structure seems to be possible, can be simulated, and new complex geometries and new ideas of spaces and building designs are creaeted totally free. That is one of the important reasons why designs of Zaha Hadid or Ben van Berkel for example are existing and have been built in reality. Forms and structures becoming more free flowing, amorphous – it began a time of creating a new organic style of architecture with new materials suitable to the new development of designs. These materials must follow the simulated, flowing form, nearly jointless in their surfaces. As building is characterized by economics more and more the skin of the buildings become thinner and must include more and more technical functions. We can realize this development in the line of projects like the Eden Project by Nicolas Grimshaw, the art house Graz from Peter Cook and finally it cumulates in the skin of the Allianz Arena, Munich by Herzog & DeMeuron or the envelope of the Unilever Building, Hamburg, by Behnisch architects. This development and specification is characteristic for plastic materials with their attitudes and so you can realize digitalization of building is one of the main reasons for reinforced application of plastic materials in the building envelope after their “golden time” in the Sixties and Seventies.

## 2 The Creative Potential of Plastic Materials – The Oskar-von-Miller Tower

The creative potential of plastic materials is dominated by four significant items: individuality, formability, transparency or transmission and finally the size. All these items characterize the skin of a building and are completely responsible for the architectural design of the Oskar-von-Miller-Tower in Munich, the new sign of the Technical University Munich in Garching.

Figure 1: model Oskar-von-Miller-Tower

Figure 2: realized facade

As the existing tower had to be removed a new one was built in the entrance of the campus Garching. In the northern entrance to Munich it has the direct neighbourship to the second symbol of modern architecture with plastic materials in Munich the Allianz Arena and stands into the tradition to the Olympic stadium in Munich from 1972 as the used material was the same: PLEXIGLAS®. So for the material itself the building stands for the new generation of PLEXIGLAS® in the contemporary architecture. The tower as the new emblem of this innovative university site is 52m high up to the end of the cladding and the architectural demands for the façade material were very complex. It should be the translation of the idea of a dancing ballerina: You see the elegance and beauty of the form and the skin however in the same moment you see the strength, power and “making of” of the structural design under the shiny and mystical clothes of the façade. In detail in relation to the geometry of the building every façade element has another oval geometry and had to be so long as possible in order to create a nearless jointless façade. The material should be on the one hand translucent as possible for shining through the steel and concrete substructure in daylight and on the other hand nevertheless it had to be opaque as possible for LED projection and lighting by night. These architectural demands were only solved by the significant items of a plastic material.

Figure 3: façade view

**Project data:**
facade area: 1200 m²
facade height: 52 m
facade material: PLEXIGLAS XT, d= 25mm
element dimension: max. L = 6m, max. H = 1,52m
architect: Deubzer, König Rimmel, Munich
civil engineer: Barthel + Maus, Munich
building owner: Technical University Munich
building site: Helmut-Brandl-Straße, Garching (GER)

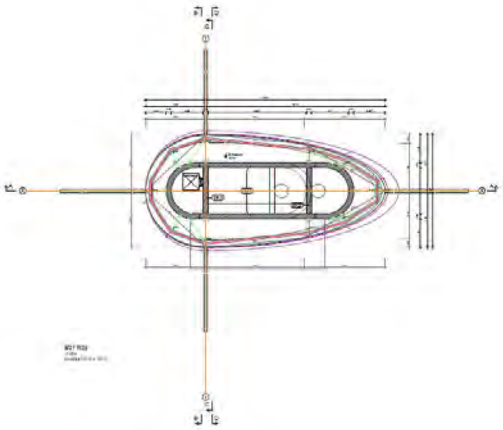

Figure 4: ground floor with oval geometry

Let us have a look to the item individuality which is the dominating attitude of the used cladding material. What is the meaning of this item for plastic materials? Individuality of a material is defined by reaching a high performance and variety in all points of construction and design with always using the same base material only changed in some few components. In order to reach a high flexibility of the attitudes of the material on a unmodified substance base you must have a suitable production process. Principally it is only possible for a synthesized material, which is controlling his attitudes with the special additives. It will be perfect if the additives are parts of the whole material and homogenous distributed in the profile as only covering of additives on the surface because this would be very vulnerable against mechanical damaging. The production process, cast and extrusion, of plastic materials perform this account very well. Mainly for design the production of many colours in combination with different qualities of surfaces is very interesting. Further each colour can be produced with different kinds of transmission. The game between transparent, translucent and opaque surfaces creates a lot of endless possibilities for our design ideas like no other material. Technical attitudes can be adjusted individually by mixing special additives with optical (UV, IR) or mechanical attitudes.

For the Oskar-von-Miller–Tower this mixing of special optical attitudes into the project specific formulation of the material was the translation of the design idea of a special translucency into the right grade of transmission. In the combination with the chosen kind of production as an extruded material the main characteristic attitudes of the skin could get true: very long elements, up to 6m long, made of a material with an individual and optimal translucency for the different lighting situation by day and night.

The second main item responsible for the design was the formability of the material. Regarding the geometric form of the tower each of the 251 elements had to have an individual radius. Therefore the material of the façade must be formable in a quick and economical way. The manufacturer used a negative form out of a high-pressured foam for the thermoforming process which could be milled into the next geometry after thermoforming an element which was the best and economic way to produce the individual geometries.

Figure 5: façade detail thermoformed element

Figure 6: entrance and box

One of the main problems was the structural design of the fixing. On the one hand the fixing should be minimized as possible on the other hand the landscape in the north of Munich is determined by large wind suction problems on tall buildings. Especially in the high levels there were an enormous wind suction so it would be necessary to use a material with high elasticity suitable to the substructure system. In order to get the substructure in a small dimension the weight of the elements had to be very low. The special pigmented PLEXIGLAS®, 25mm thick, was chosen for the façade elements drilled every 480 mm and fixed by consoles sitting on hanging steel frames. This kind of construction reduces disturbing horizontal joints and shows a very homogenous impression of the façade. An alternative solution with a glass façade would have been nearly impossible as first of all the self weight of the cladding material glass would have been to high for a the demanded small dimension of the steel frames and mainly second only a flexible material like a plastic material in combination with a point fixing was the ideal structure to take over the existing loads, which was approved by the necessary technical tests before starting installation of the façade. Especially the choose of a restoring construction by consoles in combination with the PLEXIGLAS® façade elements was the reason for the extremely high deflexion without any problems concerning the tension loads into the fixing points of the plastic material.

The Oskar-von-Miller-Tower in Munich shows the creative potential of plastic materials in façade applications very convincingly. Translucency, formability, weight and dimension as attitudes combined in one material and transferred into façade elements are the character of the architecture besides the typical geometry and they are responsible for the perfect translation of modern façade design into an innovative skin with an high architectural and technical performance

Figure 7: fixing console

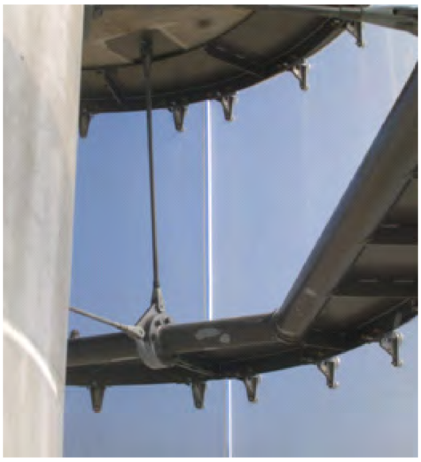

Figure 8: fixing detail steel frames

## 3 The Growing Idea of Structural Design with Plastic Materials - A Review and Outlook

Comparing the Oskar-von-Miller-Tower to other projects it is the youngest milestone on the way to develop the right symbiosis of structural design for building skins and plastic materials. The roof of the Olympic stadium in Munich from 1972 is characterized by using only flat sheets on a cable construction which is responsible for the geometric form. The fixing distances are very small and the fixing points are very dominating in the architectural design. The weight of the construction was the main technical feature why a plastic material was chosen in this application besides the protection against rain and the wish of high lightness of the architectural design.

If you have a look to the Art House Graz from 2003 the symbiosis of structural design and plastic material is getting stronger. The distances of the point fixing are higher as the stiffness of the thermoformed sheets is much higher than of the flat sheets in Munich. Further the development in this project is coming forward as the aspect of the translucency and the combination with light is realized in a façade project the first time. The geometric potential of the material is tapped completely and therefore in this project you can realize the transformation of a pure applied façade into a complete architectural skin of the building which characterize the architectural design.

Figure 9: Olympic stadium Munich 1972

Figure 10: Art House Graz 2003

Last of all the Oskar-von-Miller-Tower in Munich tries to go forward the next step by adding the plastic material as a necessary part of the structural design. The steel substructure, the kind of point fixing by consoles and the stiffness of the plastic material PLEXIGLAS® are one structural unit which is necessary for the structural design of this building on this site. In contrast to Munich here the plastic material is not only a cladding material, now it is getting an important part of the structural design.

The next step into the future will be to reduce the substructure more and more and to go into the direction of a nearly self-bearing structure made of plastic materials in order to exploit besides the creative potential the complete structural potential of plastic materials in building applications like the attitude to glue the material with a high strength in combination with a high stiffness created by thermoforming. First steps in this direction were done in a cooperative project with the Bauhaus University Weimar and the Evonik Industries in 2010. The development of this complete transparent bearing structure (roof element span wide 6m) is the right step in direction to a nearly self bearing building skin and to come to the point to show the real potential of plastic materials in building applications in future.

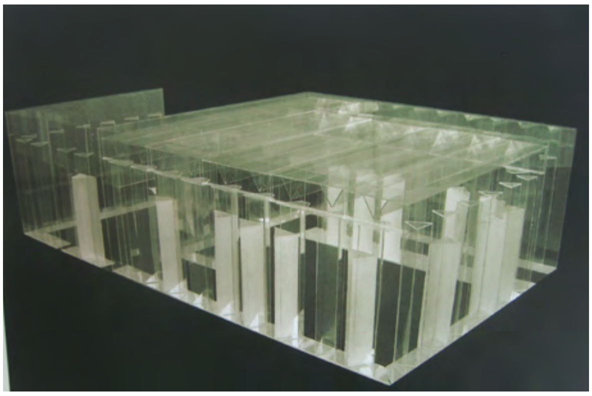

Figure 11: PLEXIGLAS pavilion, model

Figure 12: roof element, mock-up

# Waved Wooden Wall

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## Summary

This paper is a case-study on how a consortium consisting of a Norwegian and a Swiss timber contractor, a Norwegian boat builder, a Swiss timber engineer and designtoproduction as consultants and planners developed a modular timber façade system for the doubly curved waterfront façade of the KILDEN PERFORMING ARTS CENTER in Kristiansand, Norway. The whole project is based on tightly integrated teamwork between all involved parties, resulting in a continuously digital production chain from detail development until CNC-fabrication. The core of the process was a parametric CAD-model holding more than 14,000 individual building components and over 60,000 connection details.

**Keywords:** Geometries, Assembling/Mounting, Opaque, Materials, Curved, modular, digital pre-fabrication, CNC, timber

## 1 Introduction

Figure 1: The Kilden Performing Arts Center in Kristiansand (*ALA Architekter*)

The *Kilden Performing Arts Center* in Kristiansand, Norway, designed by Finnish architects ALA and opened in March 2012, provides facilities for the *Kristiansand Symphony Orchestra*, *Opera South* and a number of local theatre groups. The building volume is more or less a rectangular box – with one exception: a 100 m wide and 22 m high overhanging and undulating timber wall that looms over the foyer areas and defines the building's face towards the waterfront. The doubly curved wall cantilevers up to 35m and is bisected by a vertical steel/glass façade into both an exterior and an interior part. It is clad with oak boards that feature a continuous pattern of 10mm wide gaps along the whole façade, demanding a meticulous finish.

The original construction concept put out to tender consisted of curved steel tubes defining the shape of the façade and welded to straight steel beams suspended from the building's concrete structure. Several thin layers of timber substructure and finally the oak skin would be attached on site.

However, a mock-up of several square meters did not meet the high demands in terms of precision as well as visible and tangible quality. The on-site assembly of the cladding boards – which were straight, but twisted and had to be slightly tapered between the curved (longer) bottom edge and the straight (shorter) top edge of the façade – proved to be immensely laborious. But the most serious problem lay in the substructure: 3000 running meters of shape-defining steel tubes had to be bent with continuously changing radii in order to follow the wave form. As the only machines capable of bending tubes with the required cross sections were limited to fixed radii, the geometry had to be approximated by short arc segments, welded together on-site.

At this point, a consortium around the Norwegian timber contractor *Trebyggeriet* decided to suggest an alternative construction concept based on prefabricated façade elements.

## 2 Higher Precision through Prefabrication

Instead of building the façade as one continuous structure on-site, it is divided into 126 elements with rectangular footprints. The elements bring their own stiff substructure, which consists of two straight and a maximum of 13 single-curved glue-laminated timber beams, to which the cladding boards are then attached. These up to 50 sqm large elements can be pre-assembled off-site and hoisted directly into the primary steel structure, reducing on-site labor to an absolute minimum.

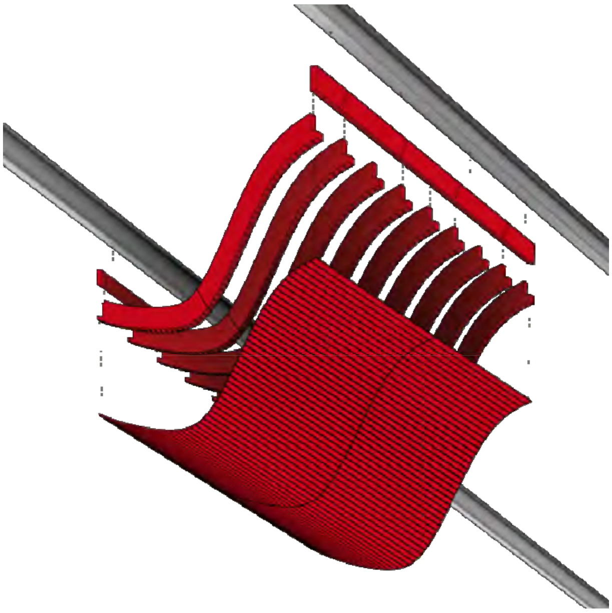

Figure 2: Explosion drawing of a façade element (*designtoproduction*)

With this approach, the critical part of the assembly – precise placement of the oak cladding boards – is brought away from the construction site to a much more controlled workshop environment. The substructure frame of each element can be laser-measured for quality control before and after attaching the boards. Moreover, the elementation as such prevents possible inaccuracies from adding up across the whole façade. The suspension detail between façade elements and primary steel girders allows for final adjustment during erection, which was one of the main challenges, since the building tolerance of the primary steel structure (±15mm) was ten times larger than the required precision for the outer façade layer (see also fig. 9).

Figure 3: The façade during erection (*Trebyggeriet*)

This way, the whole façade – consisting of more than 14,000 individual building components – could be produced with assembly gaps of as little as 10 mm between adjacent elements. This is no wider than the defined gap between oak boards, letting the elementation disappear completely in lateral direction.

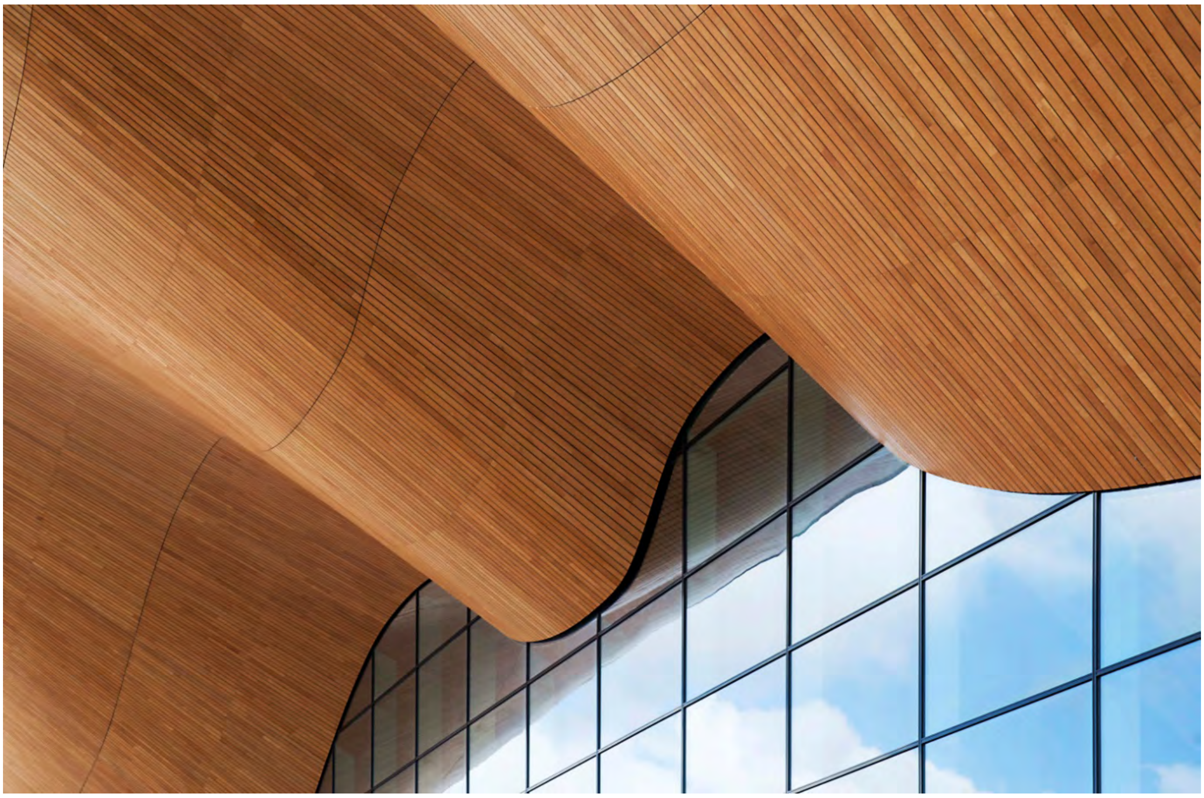

Figure 4: Gaps between elements are only visible in one direction (*Trebyggeriet*)

### 2.1 Maintenance

A panelized façade is generally easier to maintain than a façade assembled in place from individual components, because maintenance can – much like the assembly process in the first place – engage on a level of self-contained façade elements.

In the wave wall, the elements do not overlap at all. Thus, every element can be released and lowered individually, should it be necessary. The only exception are the lowermost elements, which stand on the ground. Here, the element above has to be taken away first.

## 3 Timber for the Shape-defining Layer

Critical advantage of the prefabrication system over the original approach is the replacement of the bent steel tubes by curved timber beams. When bending timber lamellas to produce curved glue-laminated beams, the springback leads to similar tolerance issues as when bending steel. But contrary to steel, pre-curved timber beams can then be machined in a CNC mill at high speed and a precision of some tenth of a millimeter, yielding very exact and completely strainless building components. On top of that, the shapes are not limited to (series of) arc segments but allow continuous changes in curvature.

Figure 5: CNC-milling a curved glue-laminated timber beam (*designtoproduction*)

### 3.1 Embedding Complexity in the Building Parts

But CNC-milling of timber not only allows for precisely curved building parts. It also allows for the parts to carry much more information about their placement and interconnection. In the Wave Wall production process, this was taken to extremes by not only cutting the secondary beams with the correct angle of bank at any point to guarantee a flush connection, but also by notching *seat cuts* for each and every cladding board into the beams (see fig. 6). With further seat cuts aiding the assembly of the substructure frame, the precise position of every part could be identified without measuring during element assembly – which would have been very difficult due to the curved geometry of the parts.

Through this concept, most of the geometric complexity of the façade is taken away from the assembly process and embedded into the individual components. This not only reduces the assembly effort drastically, but also minimizes (or nearly eliminates) the risk of incorrectly or imprecisely assembled elements. The oak cladding of the Kilden façade can act as proof of concept: The pin stripe pattern is nicely continuing across elements without disturbance (see fig. 4).

Figure 6: Curved secondary beams with embedded seat cuts for the oak cladding boards (*designtoproduction*)

## 4 Timber for Structural Elements

While – as shown in the previous section – geometrically timber performs much better than steel, structurally the comparison is more ambivalent. Timber generally requires larger cross-sections, while on the other hand it weighs much less. Letting aside the details of structural calculation, there are two main concerns when applying timber structurally – its anisotropic nature and its flammability.

### 4.1 Fiber Cutting Angle

Wood is an anisotropic material, meaning that its load bearing capabilities (or general properties) are depending on the load direction. It has by far the most strength in its fiber direction. This is – alongside the aim to minimize cutoff – the reason for using curved timber blanks (which are glue-laminated from thin lamellas in a bending mold) instead of milling curved beams out of much cheaper straight blocks.

From a structural point of view, the optimum would be a curved blank that exactly follows the direction of the beam it is supposed to become. But in most cases – including the Kilden Façade with its nearly 1,800 individual curved beams – it is not feasible to order blanks with batch size one, due to the time-consuming lamination process. So at this point a nonlinear optimization process is applied, weighing material cut-off against timber blank diversity to assign as many different but similar beam geometries to the same blank geometry. In the case of the Wave Wall, it was possible to mill up to 13 different curved beams out of identical blanks without exceeding acceptable cutting angles for timber fibers.

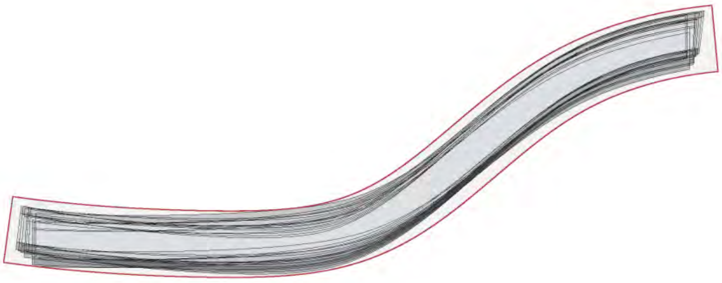

Figure 7: One common timber blank geometry for nine similar, but different beams (*designtoproduction*)

### 4.2 Fire Protection

The relevant difference of this façade system compared to the original one in terms of fire protection is the execution of the secondary structure in timber instead of steel. However, timber performs better as one would think: The façade achieved a rating of F30 (classification after DIN 4102, meaning fire resistance for 30 minutes) based on pure burn-off, i.e. without any additional coating or constructive protection.

The only part that needs dedicated fire protection are the steel bolts connecting the façade elements to the primary beams. They are covered with lids made from oak – in fact hard-wood is fire-protecting steel parts.

## 5 The Same Façade for Exterior and Interior Walls

One specific feature of the Wave Wall is that the upper part of the façade acts as an exterior wall while the lower part behind the vertical glass façade is the interior wall/ceiling of the main foyer. Thus, concerning building physics there are different demands to meet.

### 5.1 Thermal Insulation

Main thermal insulation perimeter of the wall is the glass façade with its vertical continuation through the back structure up to the roof (see fig. 1). So the façade elements below the glass façade only have to protect the foyer against the partly insulated roof volume. The space between the timber beams is filled with rock wool. On the outer side a layer of black fleece separates it from the oak cladding (also relevant for room acoustics, see 5.2) and two layers of plywood and gypsum plates terminate the elements on the inner side. The elements above the glass façade only separate exterior from non-climatized interior space. Still, they are partly insulated in a similar way, mainly to prevent condensation due to quick chilling.

Structurally, the timber elements are not directly connected to the glass façade to allow independent movement of both parts. The resulting shadow gap, which is filled with insulation, also meets the architectural design intent (see fig. 4).

### 5.2 Room Acoustics

The distance between the cladding boards had to be negotiated between the demands of the design (narrow gaps) and the room acoustics (wide gaps). Also, the gap width had to look the same everywhere despite changing angles between adjacent boards along the façade. All three demands were met by reducing the width of the boards towards their backside. Thus, the gaps widen from 10 mm at the visible side towards the connection to the frame, where the black textile membrane closes the element surface both optically and acoustically.

Figure 8: The cladding boards are individually tapered and numbered (*Risør Trebåtbyggeri*)

# 6 Parametric Modeling as Key to a Successful Process

A project like the one presented here, with exactly 14,309 individual components of which no two are the same, is only feasible with parametric modeling, i.e. abstracting the numerous different geometric conditions into a considerably smaller set of rules and rendering those into a set of tailor-made CAD tools. For this to succeed, a consistent design and construction principle is necessary in the first place, as each exception to the rule drives up complexity and effort by a high degree. Secondly, the digital process must not stop with the geometry model but extend into fabrication: Only with a continuous digital chain from design to production, the sheer amount of individual parts becomes manageable.

In case of the Kilden Façade, only two types of Timber/Steel connections exist that can adapt to the varying conditions throughout the wall by a set of defined rules. Furthermore, through the concept of *embedding complexity in the building parts* (see 3.1) the adaptation even takes part in the individually milled timber beams, so that the steel connectors and any other parts necessary can be "off the shelf". And this is where the material decision becomes key to success: 56,000 precise seat cuts could not have been milled into steel tubes.

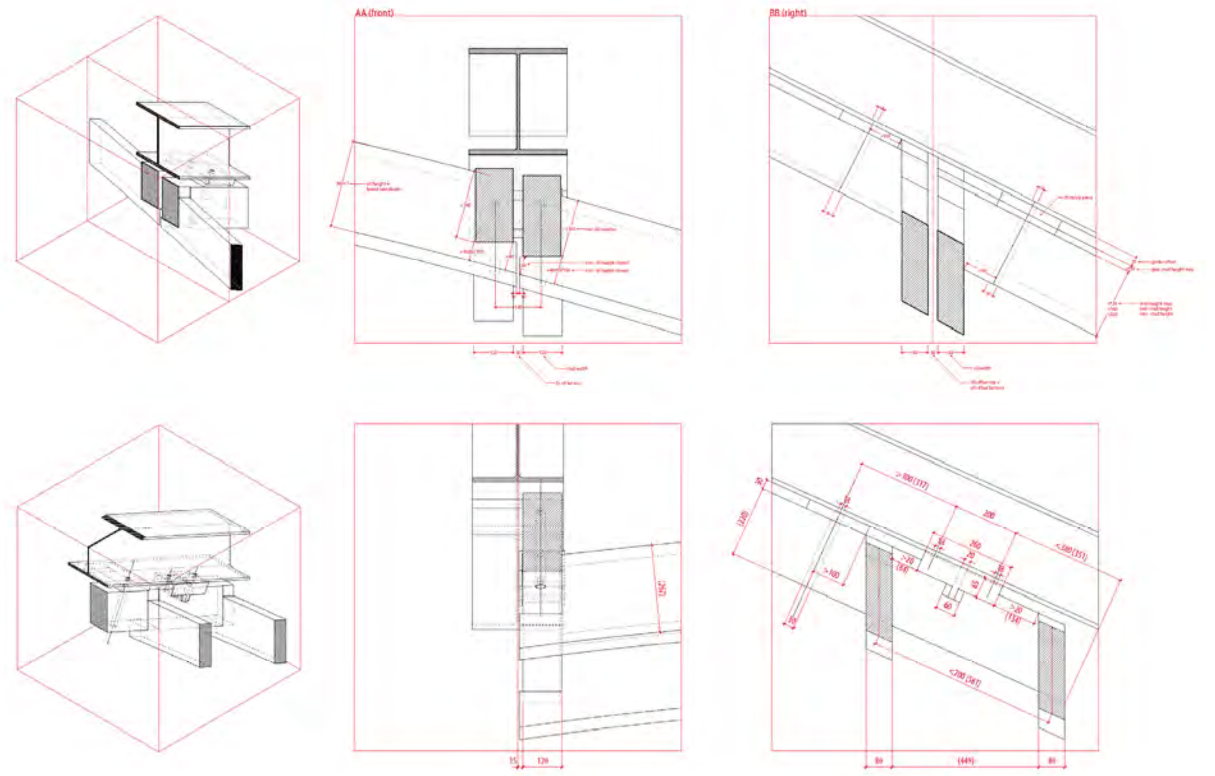

Figure 9: Two parametric connection details that adapt to different geometric conditions by individual cuttings in the timber beams (*designtoproduction*)

Thus, an elaborate prefabrication process that engages early in the building process – possibly even negotiating details of the design to ease fabrication while maintaining the design intent – combined with a continuous digital production chain from 3D model to CNC-fabrication can help to reduce cost and effort while ensuring a high quality of the result. Some of this money has to be spent earlier: When the first parts arrive on site – in fact, even when the first material is ordered – most of the work has already been done. While this should be most welcome, as it makes the building process much more predictable and not least highly reduces the work on site, it is antipodal to traditional processes. This seems to be one of the main obstacles for processes like the one presented here to be applied more frequently today.

## 7 Acknowledgements

Kilden Performing Arts Center, Kristiansand, Norway

| | |
|---|---|
| Architect: | ALA Arkitekter, Helsinki, Finland |
| General Contractor: | AF Gruppen, Oslo, Norway |
| Timber Façade Contractor: | Trebyggeriet, Hornnes, Norway |
| Façade Cladding, CNC-Fabrication: | Risør Trebåtbyggeri, Risør, Norway |
| Façade Structure, CNC-Fabrication: | Blumer-Lehmann, Gossau, Switzerland |
| Façade engineering: | SJB Kempter-Fitze, Eschenbach, Switzerland |
| Consulting, Digital Planning: | designtoproduction, Erlenbach/Zurich, Switzerland |

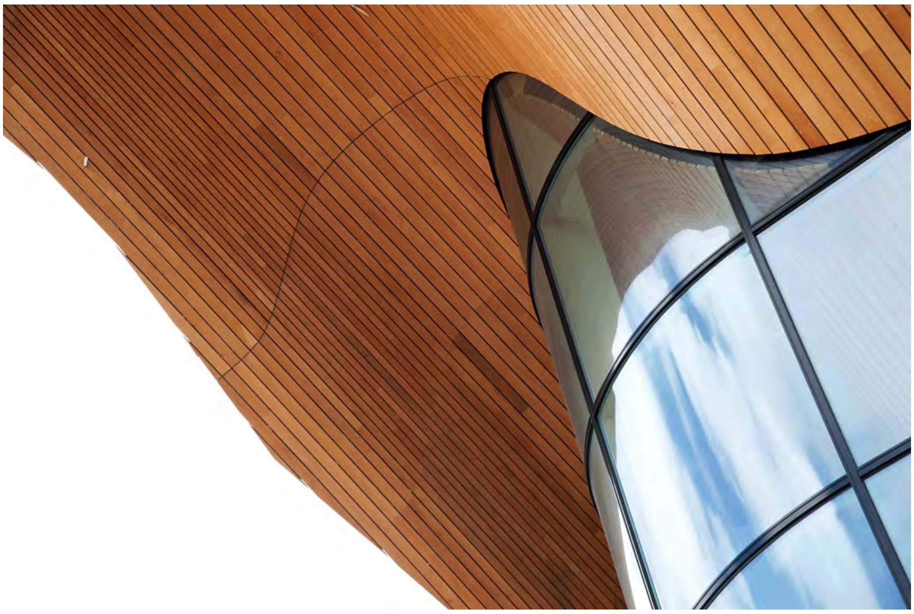

Figure 10: Corner detail (*Trebyggeriet*)

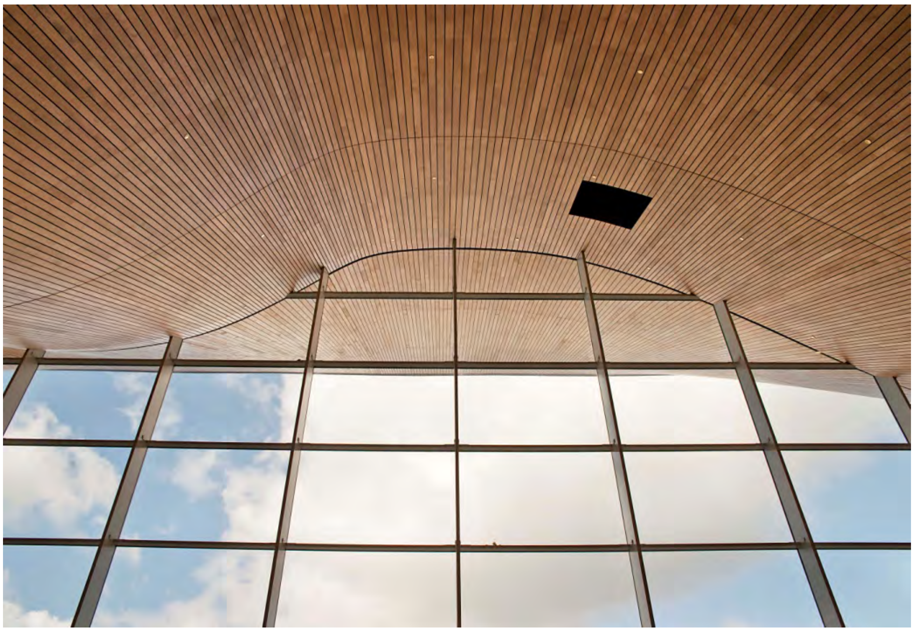

Figure 11: View from inside the foyer (*Trebyggeriet*)

# The Enzo Ferrari Museum, Modena
# Engineering a Freeform Skin

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## Summary

The exhibition gallery of the Enzo Ferrari Museum in Modena has been designed by Future Systems London referring to iconic free form elements of the sport car design. The gallery façade is composed of a curved glass envelope facing Enzo Ferrari's birth house as well as of a free-form yellow aluminum roof. This paper focuses on the customized solutions developed to engineer both the glass and the aluminum façade.

**Keywords:** Free Form, Cable-stayed facade, Aluminum roof

## 1 Introduction

The recently opened Museum dedicated to Enzo Ferrari in Modena plays with the duality between the renovated historical building where Ferrari was born in 1898 and a futuristic exhibition gallery designed by Jan Kaplicky  (Future Systems, London), shortly before his death. The gallery embraces the masonry building and relates to it, whereas its sculptural form is clearly inspired by sport car design. However, while in the car industry complex geometries are realized by moulding presses to produce numerous identical elements, in architecture the specificity of each work, the difference in scale and costs requires a different approach to deal with such forms. The philosophy chosen in engineering the façade for the Enzo Ferrari Museum in Modena was to maintain a relative simple geometry for the façade panels which have to be assembled and to adapt to the different geometrical situations by means of complex customized detailing.

Figure 1: Enzo Ferrari Museum (Werner Sobek Stuttgart)

## 2 Cable-Stayed Glass Façade

The 11 m high cable-stayed inclined glass façade is geometrically defined by two intersecting conical surfaces. A set of 32 mm vertical stainless steel cables supports the flat insulated glass units, made of a 10 mm fully tempered glass pane outside and two 6 mm heat strengthened glass panes laminated with a SentryGlas®Plus interlayer inside. The sinuous form of the façade was accomplished using straight cables and planar glass units. These had to be cut with certain specific angles to match the conical geometry.

Figure 2: Enzo Ferrari Museum during the opening – View from outside (Werner Sobek Stuttgart)

Figure 3: Enzo Ferrari Museum during the opening – View from inside (Werner Sobek Stuttgart)

Special attention was paid to control the deflections of the whole façade as well as the warping of the most critical insulated glass units by optimizing every single cable pretension force. These vary from 80 to 330 kN. Black coated curved aluminum shading devices further characterize the façade design and mitigate the museums heat gain.

Figure 4: Glass fixing and cable clamp. Rendering (left); Assembled cast piece (right) - (Werner Sobek Stuttgart)

The cable clamp and glass fixing has been designed specifically for this museum with the aim of reducing the material to a minimum and to match the specific architectural language. The 3D-Model for the pieces has been precisely defined in collaboration with a small casting factory specialized in Italian design objects.

## 3 Aluminium Roof

The 77 m long and 43 m wide freeform aluminum roof has to withstand wind, rain and snow while still being able to freely deform due to temperature variations and the absence of any expansion joints. A sophisticated detailing which allows for controlled movements and a parametric approach were the keys to address this task.

Figure 5: View of the aluminium roof (Teleya)

The outer skin is made of a system of coated extruded aluminum profiles, developed by Pinical. It adopts solutions typically used in the ship building industry. The profiles are joined through a male-gasket-female system and are connected to a steel secondary structure through adjustable screwed connections. The profile curvature was mainly achieved by bending the profiles on site along their longitudinal axis. The width has been set to 125 mm and therefore suitable for site-warping without visually detectable tessellation. Double curved roof elements showing small bending radii were pre-bended in longitudinal direction and additionally warped on site. This system allows to generate advanced double curved skins without prior thinning the material through plastic deformation. The analysis of the Gaussian curvature on a 3D surface model helped identifying the critical zones around the skylights and at the backside of the roof.

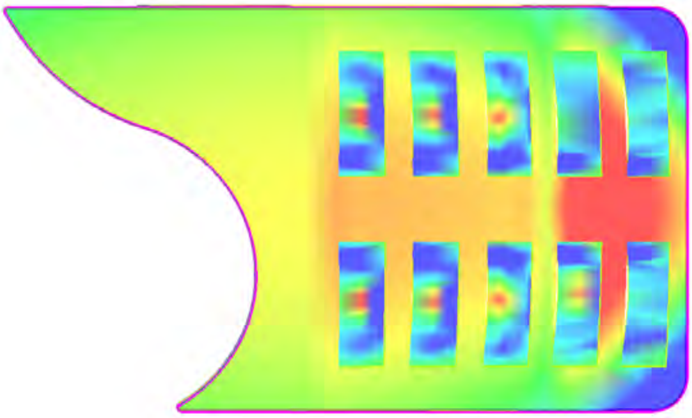

Figure 6: Analysis of Gaussian curvature on the 3D surface model. (Werner Sobek Stuttgart)

The roof has been designed to withstand high temperatures without any expansion joints through a system of movable and adaptable supports. It is fully floating but fixed at certain points along two axes, thus allowing thermal expansion in all directions. The roof temperature was assumed to reach up to 80°C on a sunny summer day and -20°C in winter. Taking a temperature difference of 100 K into consideration, the maximum thermal movement will be 3 cm at the roof edges. The node details therefore have to allow the roof surface to slide up to 6 cm in longitudinal and transversal direction. It was indispensable during installation to constantly measure the temperature and fix the roof to the nodes according to the surface temperature. Beside the sliding ability, the node detail can adapt to the different roof inclinations and is adjustable in height. This allowed utilizing only one typical detail to bridge the different heights arising between the segmented support surface (steel structure, insulation and waterproofing layer) and the smooth outer surface.

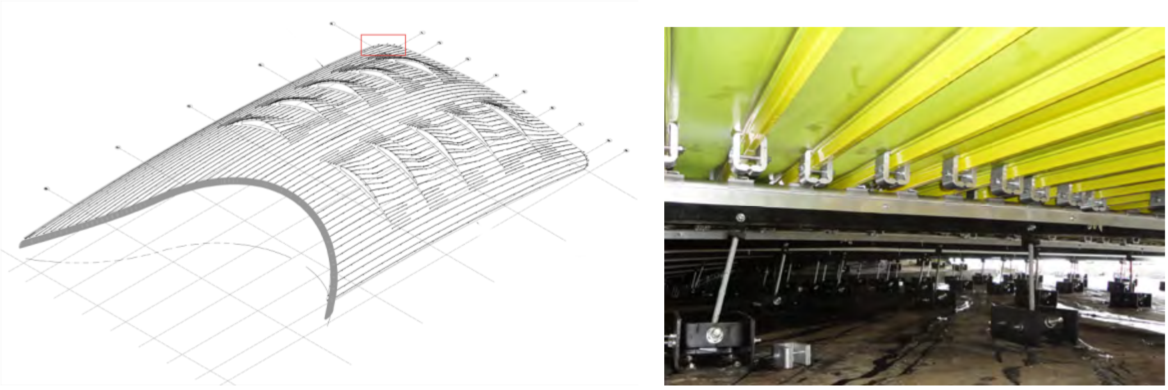

Figure 7: L-profile sub-structure (left). Node point with attached L-profiles and aluminum surface (right) (Werner Sobek Stuttgart)

In order to trace the roof curvature, 2.500 laser-cut steel plates were bended into L-shaped profiles to generate a unidirectional substructure. Around 62.500 boreholes were positioned using parametric modelling tools to match the node points. This way more than 95% of the roof surface could be quite easily engineered. The Pareto principle (also known as the 80–20 rule) states that, for many events, roughly 80% of the effects come from 20% of the causes; hence the utilized time follows the same principle. The required time to detail the remaining last 5% of the roof (edges and skylights) was definitively more than 80% of the detailing time. The comparatively small surface area of the ten skylights was constructed by laser-cutting 400 individually metal sheets with 25.200 individually positioned bolts. Furthermore edge lines were extracted from the 3D model to laser-cut rubber foils, which could be utilized as cutting gauges for the aluminum profiles along the skylight edges.

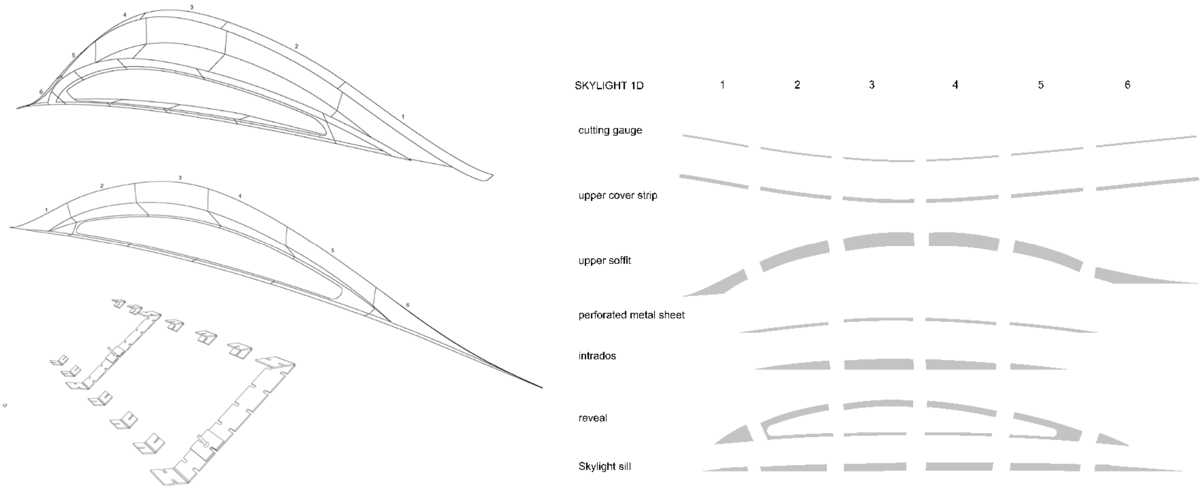

Figure 8: Individual laser-cut metal sheets of one skylight (Werner Sobek Stuttgart)

One of the main challenges in detailing the cladding metal sheets, was the definition of non-standard fixation points to be compatible with the roofs movement. Thanks to parametric design tools, the skylight cladding surfaces and the relative fixings were automatically generated. Especially the positioning of the bolts played a major role in the detail design of the skylights. Since the local curvature in the skylights is higher than elsewhere in the roof, bolts welded on the rear side of the metal sheets forces the sheets in position along the edges without any material preforming process.  A Gaussian curvature analysis was performed to identify the areas with small curvature radii in both directions.

Figure 9: Metal cladding at the skylights. The red arrows indicate zones of strong double curvature. (Teleya)

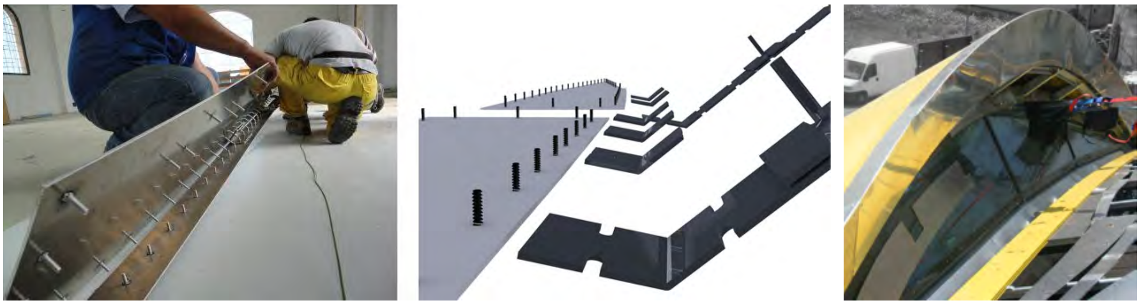

Figure 10: Metal cladding at the skylights. Partial assembling next to the site (left); visualization of the main components (middle). Pre-assembling on site (right). (Werner Sobek Stuttgart)

## 4 Conclusions

Building highly complex freeform buildings skins calls for a change in planning process from 2D drawings to 3D digital models. Nowadays standard planning tools support a quick architectural design of highly complex surfaces. However, the detailing, production and erection of such envelopes remains a very complex and challenging task. Several aspects (building physics, thermal behaviour, load bearing capacity, production processes, etc.) need to be synthesized during the overall engineering process. The first step is the definition of detailing and production principles which could be adapted to different geometrical and loading conditions. The second step is the implementation of the information into a 3D model and the finding of suitable interfaces to transfer data. Parametric rules have to be identified to match all the different conditions, so that the process could be automated as much as possible by means of scripted tools. Such a process allow for complex surfaces to be materialized with an impressive end quality, while still keeping the costs within a reasonable range.

## 5 Acknowledgements

The authors wish to thank the Foundation “Casa Natale Enzo Ferrari” for having made this museum possible. A special thanks is also due to the architect Andrea Morgante (Shiro Studio), to the structural engineer Fabio Camorani (Politenica) and all the contractors involved in the façade work (Teleya, Pinical, etc.) and in the site coordination (CdC) for the very good collaboration.

# A Transparent Facade Concept for the Redesign of an Existing Office Building

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## Summary

In this paper a case study is presented relating to the redesign of an office building dating from the 1960s. Especially the detailing and the structural complexity of designing the new double skin façade are described.

The building consists of a two-storey podium topped by a nine-storey tower, the overall height is 40m above ground level. In order to optimise the building's energy efficiency and present the public a modern appearance the whole building is completely renovated. The existing building envelope which mainly consisted of prefabricated concrete elements was dismantled and is now replaced by a transparent floor to floor double skin façade. Within the renovation two new storeys (12th and 13th floor) are added.

**Keywords:** glass; redesign; structural complexity; double skin façade; transparent floor to floor glazing

## 1 Introduction

Rising energy costs and amendments to regulations have strengthened the society's awareness of energy saving measures. In order to reduce $CO_2$ emissions many buildings dating from the 1960s and 1970s are being now refurbished. They scarcely comply with the stricter building standards introduced in recent years and very often need to be renovated not only in terms of energy efficiency but also in terms of fire protection and functionality.

Retrofitting existing buildings is very often even more complex than designing new ones as the remaining structure has to be included in the design concept and in many cases compromises have to be made to meet standards and requirements.

In this paper a case study is presented relating to the redesign of an office building dating from the 1960s. This example shows the creative potential but also the complexity that lies in the renewal of older buildings. Especially the detailing and the structural complexity of designing the new double skin façade are described.

Built in 1969 the building complex accommodating a bank company sets an important accent within the city centre of Rosenheim, which is a medium size town in Germany. The building consists of a two-storey podium topped by a nine-storey tower, the overall height is 40m above ground level. In order to optimise the building's energy efficiency and present the public a modern appearance the whole building is completely renovated. The existing building envelope which mainly consisted of prefabricated concrete elements was dismantled (Figure 1a & b) and is now replaced by a transparent floor to floor double skin façade Within the renovation two new storeys (12th and 13th floor) are added. The overall office area is 4000m$^2$. The energy consumption will be reduced from 400 kWh/m$^2$ to 100 kWh/m$^2$ which is a reduction of 75%.

Figure 1 a & b: Dismantling of the Concrete Façade Elements

The design of the office building dating from the 1960s as well as the redesign was planned by Schleburg Architects, Rosenheim.

The floor plan of the nine-storey tower has a rectangular shape having a size of approximately 22.5m x 13m.

The outer façade is suspended from steel fins which are mounted on the concrete floors. The dominating glazing parts of the secondary façade have a size of 2.5m x 2.5m, in the 11th floor the glazing height increases to 4.3m. The inner part of the facade consists of an insulated wooden cladding with linear supported floor to floor double glazed systems. Whereas the outer screen consists of glass panels which are locally supported by clamps along their edges.

## 2 Design of the Double Skin Façade

### 2.1 Glazing

The dominating glazing parts of the secondary façade have a size of 2.5m x 2.5m, in the 11th floor the glazing height increases to 4.3m. The glass panels are supported by clamps along their edges. The glass set-up consists of 2 x 10mm laminated heat strengthened glass and in the corner areas of 2 x 12mm laminated heat strengthened glass.

The glass panels are visually broken up by openable louvres which are 0.55m high and 1.25m wide, they are linearly supported along their short edges and have a glass set-up of 2 x 8mm laminated annealed glass. The louvers are used for natural ventilation and will also open in case of any smoke emission. Figure 2 shows the elevation of the façade.

The wind loads were determined based on a wind study which was carried out for the double skin façade.

As the gap between outer and inner façade is to be accessible for cleaning and maintenance the outer façade has to resist also impact loads. Therefore besides the structural analysis impact tests had to be carried out (see section 3).

For the louvers also additional requirements regarding remaining load carrying capacity after glass breakage had to be taken into consideration. This was necessary as the open louvers having an inclination more than 10° are classified as an overhead glazing. The testing is described in section 3.

For the secondary glazing of the façade a special permit from the authorities was needed.

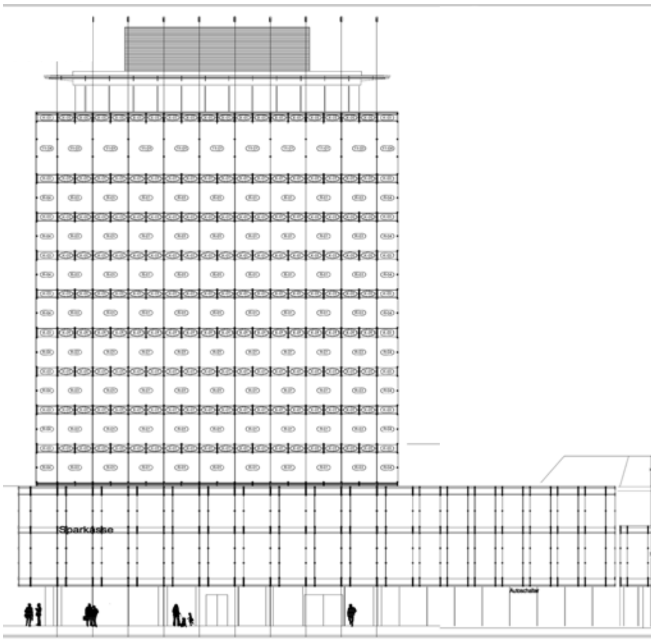

Figure 2: Elevation of the Façade

## 2.2 Supporting Structure and Detailing

The outer façade is suspended from steel fins which are fixed to the concrete slabs by anchors (Figure 3). The steel fin itself consists of welded flat steel plates (Figure 4).

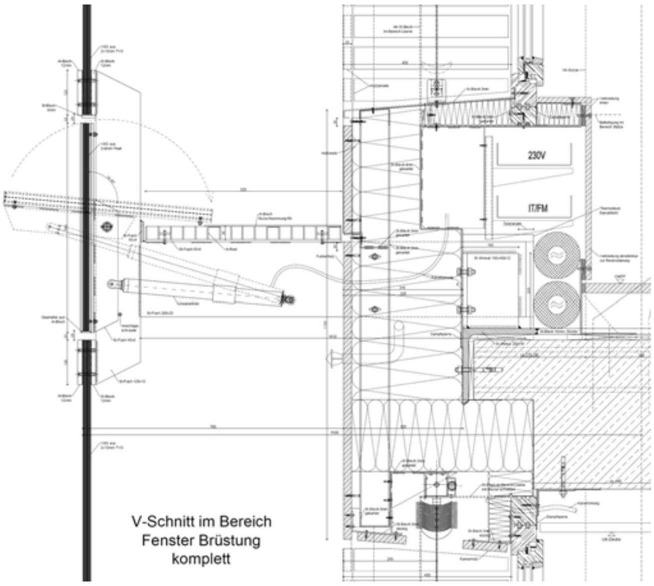

Figure 3: Vertical Section Steel Fin

Figure 4: Installed Steel Fin

When designing the supporting elements the main problem was the connection to the concrete structure. Due to the poor concrete quality dating from the 1960s and insufficient reinforcement at the slab edges it was necessary to fix the anchors at defined locations which were able to resist these additional loads (Figure 5). The gap between anchor and drill hole was filled with a suitable mortar to avoid any slip.

Figure 5: Steel Fins are fixed to the Concrete Floor by Anchors

Furthermore complex supporting details had to be developed to transfer the compressive forces locally into a defined area of the concrete edge (Figure 6a). To guarantee a uniform load distribution additionally the gaps between the steel sections and the concrete were filled with a high strength grout (Figure 6b).

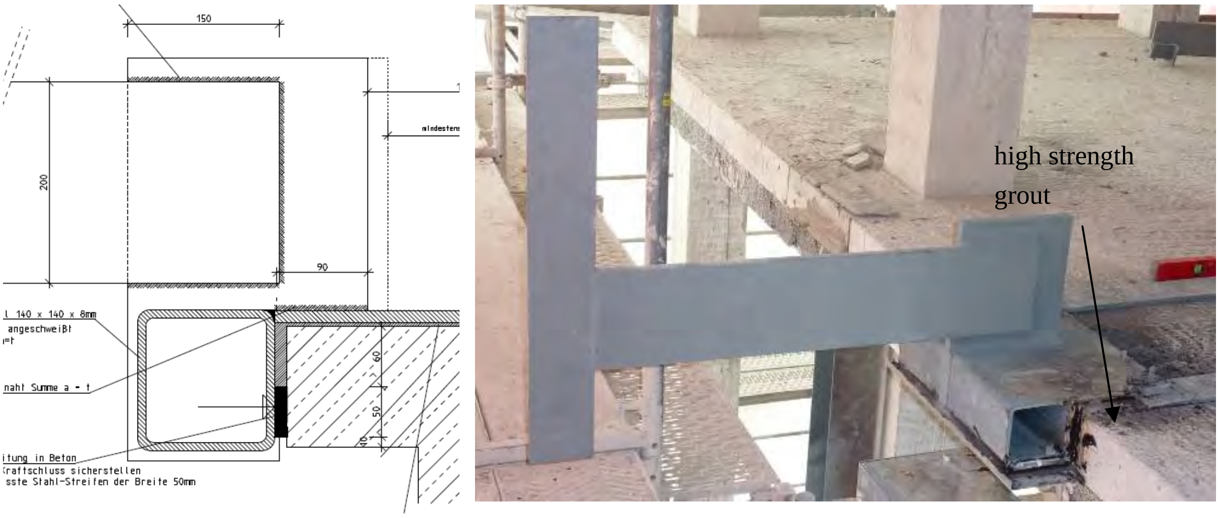

Figure 6 a & b: Load Application into the Slab Edge

The supporting elements were modeled by means of finite element analysis (Figure 7, Figure 8).

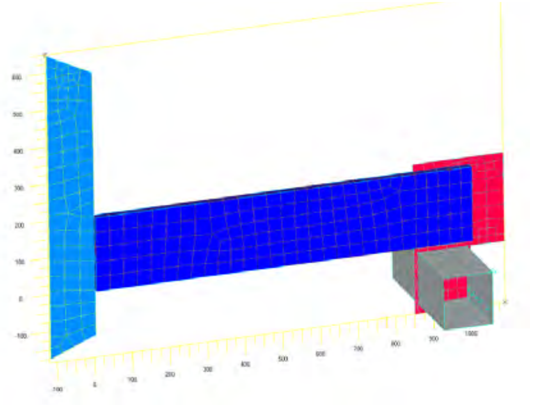

Figure 7: FEA model

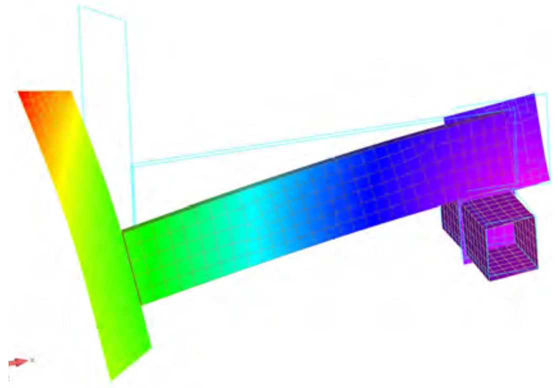

Figure 8: Max. deformation

# 3 Testing

## 3.1 Introduction

The design of this complex façade structure should not only be based on numerical simulation therefore full scale tests of the supporting elements were carried out to be able to evaluate the FEA-model in a qualified way (section 3.2).
As the gap between outer and inner façade is to be accessible for cleaning and maintenance the outer façade functions as a barrier and has to resist also impact loads. Therefore for the glazing of the outer skin impact tests were required according to TRAV [7] (section 3.3).

Finally the post-breakage performance of the openable louvres was determined (section 3.4). This was necessary as the open louvers having an inclination more than 10° are classified as an overhead glazing and a safe post-failure behaviour in the event of breakage for people beneath has to be guaranteed.

## 3.2 Deformation of the Outer Skin

Goal of these tests was to verify that there are no significant deformations or any slip of the façade supporting elements induced by dead, wind and traffic loads. The tests were carried out in full scale on site.
The loads where applied step by step starting with the characteristic values. Finally the design values were applied. For each load step the horizontal and vertical deformation was determined (Figure 9).

Figure 9: Test set-up

Figure 10: Load application

The loads were simulated by cement bags (Figure 10) and fixed to the location of load application by steel cables and deflection pulleys. The exact load value was determined by force transducers.
The following maximum deformations were determined: horizontal direction 1.3mm and vertical direction 5.0mm. These values matched very well with the calculated values of the structural analysis. In the tests no slip of the supporting structure was determined.

## 3.3 Impact Resistance

For the glazing of the secondary façade impact tests according to German TRAV [7] were performed using a standard pendulum according to EN 12600. A drop height of 900mm was used. The tests were carried out in full scale in the laboratory (Figure 11). The impact body hit the specimen on points that caused maximum glass and support damage. After an impact at the corner of the specimen the laminated glass broke (Figure 12), but as the impact body did not penetrate the laminated glass and no dangerous glass fragments fell down the test was passed.

Figure 11: Test set-up

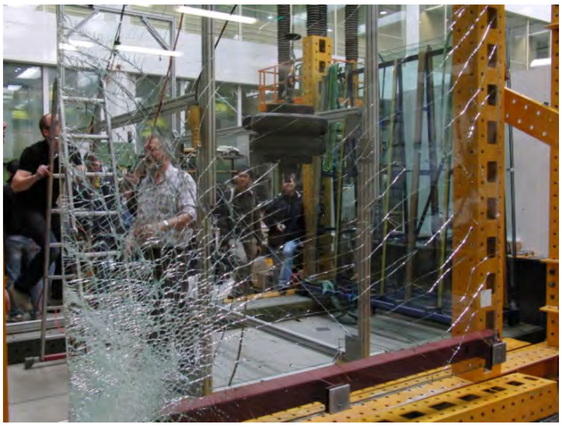

Figure 12: Damaged glass specimen

## 3.4 Post-breakage Performance

To determine the post-breakage performance of the louvres the laminated glass specimen were placed horizontally and loaded by half of the service load (Figure 13). With the load still applied all the sheets of the laminated glass panel were fractured at several locations by means of a hole punch and a hammer. The tests were carried out successfully: Within 24 hours the specimen did not slide from the supports and no dangerous glass fragments fell down (Figure 14).

Figure 13 :Test set-up with loading

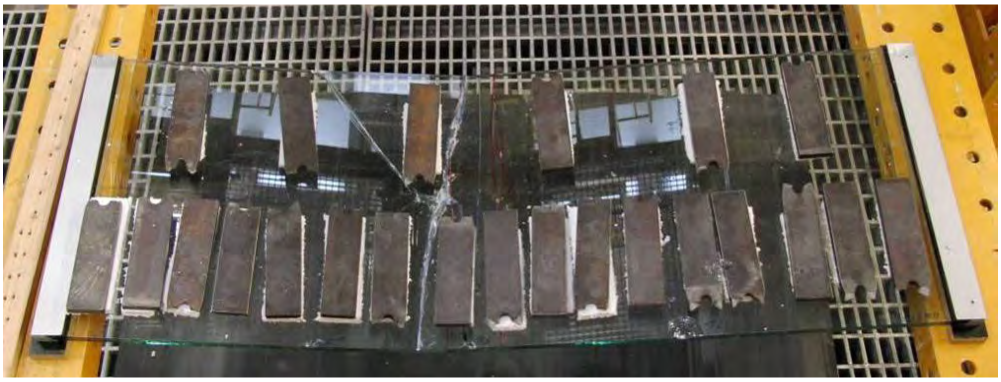

Figure 14: Specimen after testing

## 4 Conclusion

Retrofitting existing buildings is very often even more complex than designing new ones as the remaining structure has to be included in the design concept and in many cases compromises have to be made to meet standards and requirements.

Redesigning this office building the main problem was the connection of the façade supporting elements to the existing concrete structure. Due to the poor concrete quality dating from the 1960s and insufficient reinforcement at the slab edges it was necessary to design special joints and fix the anchors at defined locations which were able to resist these additional loads.

Moreover for the outer glass skin besides the structural analysis additional requirements such as resistance against human impact and post-breakage performance were demanded from the building authorities.

Although redesigning the building was very complex, by improving the energy efficiency and present the public a modern appearance the renovation of the building was very successfully (Figure 15 a & b).

Figure 15 a & b: New double skin facade

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[6] Technische Regeln für die Bemessung und die Ausführung punktförmig gelagerter Verglasungen (TRPV), final version August 2006

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# Multifunctional Facade System for Efficient Modernisation of Existing Buildings

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## Summary

The Schüco ERC50 modernization façade offers maximum efficiency in saving and generating energy and also efficient process flows for design, fabrication and installation, for clients, developers, users and metal fabrication companies. Highly energy-efficient components, which in terms of installation procedures have been specially developed for use in building renovation, prevent high overhead costs due to loss of rental, accelerate the construction process and raise the value of the property in the long-term.

Figure 1: Schüco Modernisation Facade ERC 50

# 1 Philosophy

The new Schüco façade system for efficient modernization of existing buildings arose from the every-day challenges of modernization projects: as a rule, tenants / users of rooms adjacent to the façade have to vacate their workspace during building work, so that old window and façade units can be taken out and new units installed and attached. This results in stress and discomfort for the users and ultimately high consequential costs (rental etc.) for the landlord / building owner, not to mention enormous logistics problems.

The new aluminium system construction method puts the client in a position to keep the building in operation all throughout the building work. An external load-bearing structure is fitted with fixing brackets from ceiling to ceiling over a specified distance onto the grid of the building structure. In this way non-loadbearing spandrel areas can be bridged. This load-bearing structure is used as the basic framework for the integration as a whole of the following system modules:

Façade-integrated …

- Solar shading systems
- Decentralized ventilation, cooling and heating
- PV façade modules, incl. infrastructure
- Aluminium window systems up to passive-house-quality

## 1.1 Features and Benefits

- Comparable with the conventional modernization solutions in terms of costs (rear ventilated curtain walling, ribbon windows)
- Less loss of utility / virtually no loss of rental (as a result of new installation principle)
- Reduction in drilling work and necessary fixing material (less noise / lower costs)
- No load-bearing spandrels required, as the system can span from floor to floor
- Simple attachments to building structure using innovative system components
- Compatible with standard Schüco curtain wall systems
- Planning reliability and cost certainty with a system solution

# 2 Modernizing Existing Buildings – Why?

Because in terms of their energy levels, around 70% of existing German buildings are below the first, 1977, thermal insulation regulations. On average they consume 5 to 6 times more heating energy than modern buildings. The situation is similar in many European countries.

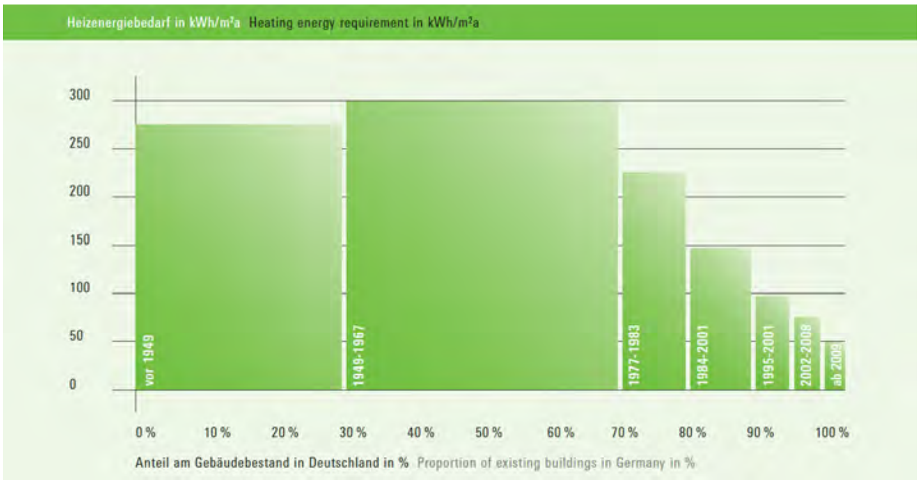

Figure 2: Heating energy requirement in kWh/m$^2$a

Modernizing existing buildings with a new building envelope improves the comfort, functionality and value of a property. The operating costs are reduced at the same time. Rental income and returns therefore offer significant potential for growth.

**“Maximum Use – minimum operating costs”**

### 2.1 Creating Added Value

Modernized facades give existing buildings a contemporary and future-proof design with added value.

### 2.2 High Energy Efficiency

New facades save energy for heating, cooling and air conditioning. They can generate energy at the same time using photovoltaic modules.

### 2.3 Intelligent Functionality

Efficient façade systems integrate functions, such as decentralized ventilation, heat recovery, solar shading, solar electricity generation and the building management system.

### 2.4 Optimum Comfort

Comfort and efficiency increase due to effective insulation, solar shading and decentralized ventilation.

### 2.5 Attractive Appearance

When it comes to design, there are no Limits to the way architectural demands can be met.

### 2.6 Sustainable Climate Protection

New building envelopes make a significant contribution to climate protection due to the combination of saving and generating energy.

## 3 Schüco Modernization of Existing Buildings – Potential for Success

As a result of the use of a new type of installation technology and the relocation of all functions to the externally-mounted building envelope, a new Schüco-façade can be installed while the building is still in use with hardly any disruption and within a short period of time. This reduces the consequential costs and the building can continue to be used during modernization.

**“Successful modernization in the shortest possible time”**

Modernizing without disruption! Reliable cost planning! The requirements of building renovation are clear. The project should be completed in the shortest time possible to reduce loss of utility and rental. Noise a disruption to operational processes must be avoided. The key requirements are reliable planning and costing. Three arguments speak in favour of modernization with Schüco.

### 3.1 No Disruptions to Operations

Efficient modernization should minimize the disruption to the users during the work. To achieve this, it is ideal if almost all building work is carried out outside the building and new building envelope is complete before building work begins on the inside. Or if relocation is not necessary and ongoing business operations are hardly disturbed.

### 3.2 Planning Reliability and Costing Certainty

Perfect modernization also means achieving maximum planning reliability, due to the high level of prefabrication of all the building components to be fabricated. Specific processes guarantee optimum time and cost management with maximum adherence to deadline and budget.

### 3.3 Low Noise Emission

The modernization of a façade is undoubtedly associated with noise. However, modern processes reduce such noise emissions to a minimum and guarantee that day-to-day business is largely undisturbed.

## 4 From Old Facades to Attractive Projects – The Schüco System ERC50

Figure 3: Schüco ERC50 – Energy Efficiency Renovation Construction

The new Schüco ERC50 (Energy Efficiency Renovation Construction) system façade offers a superior range for well-directed modernization. Modular system components guarantee a high level of energy saving, excellent functionality and new comfort in an old building. Efficient installation reduces to a minimum any disruption to operations in the building. There is no loss of rental. Schüco offers unique benefits for increasing the long-term value of existing buildings.

### 4.1 Schüco Aluminium Window Systems

Modern aluminium windows from Schüco guarantee maximum energy efficiency up to passive house standard. Mechatronic fittings, such as Tip Tronic, which are also suitable for hybrid ventilation and automatic night-time cooling, provide maximum comfort. Schüco window systems can be easily integrated into building management system.

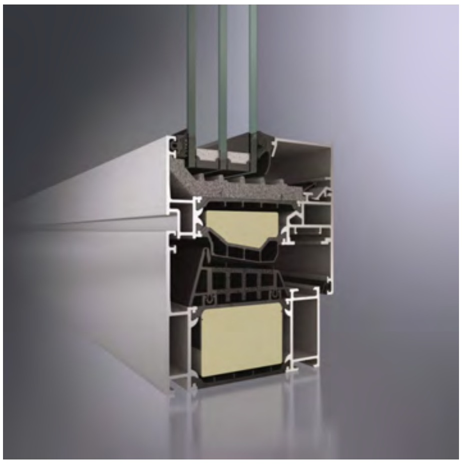

Figure 4: Schüco Aluminium Window Systems

### 4.2 Schüco CTB – High Performance Solar Shading

The high performance solar shading from Schüco combines optimum shading properties with a high degree of transparency. The Schüco CTB is flush-fitted and concealed in the modernization façade. Maximum wind stability ensures that it can be used at all times.

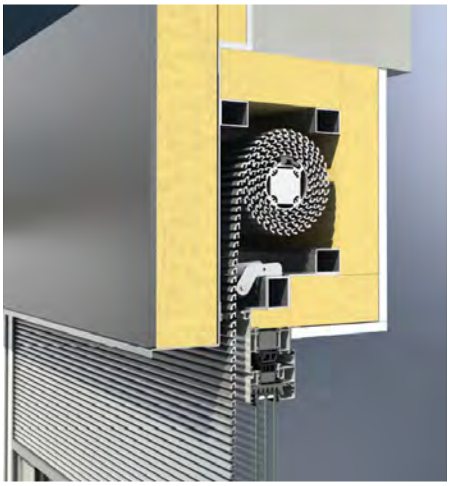

Figure 5: Schüco CTB – High Performance Solar Shading

### 4.3 Decentralized Ventilation

Efficient solutions from Schüco for decentralized ventilation in the ERC50. This ensures that the comfort levels for the building users are maximized, as ventilation devices fitted with CO2 sensors guarantee a constant exchange of fresh air, and significantly reduce heat loss through ventilation by means of simultaneous heat recovery.

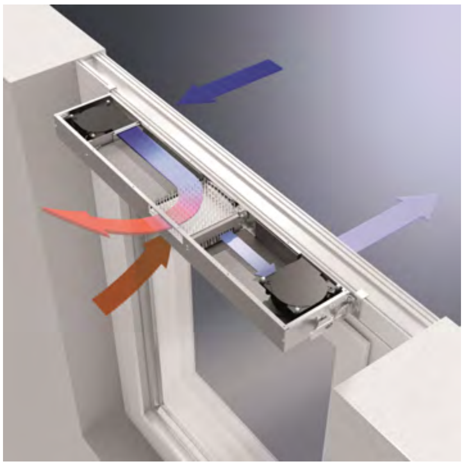

Figure 6: Decentralized Ventilation

## 4.4 Façade-integrated PV – Schüco ProSol TF

Façade-integrated PV uses the large available surfaces of the building envelope to generate solar energy. The outstanding performance characteristics make it particularly suitable for use in façade, for example as a cladding panel in the spandrel area of the modernized façade.

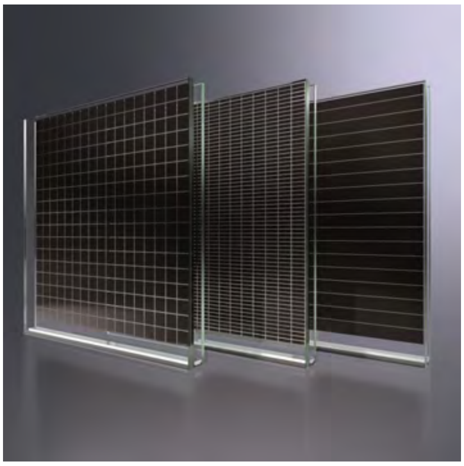

Figure 7: Façade-integrated PV – Schüco ProSol TF

## 4.5 Building Automation

Schüco systems with mechatronic features can be easily integrated in the existing building management system and enable the users to control functions such as ventilation, solar shading, etc. The comfort of the building occupants is significantly improved after modernization.

Figure 8: Building Automation

## 5 Installation while the Building is still in Use

The Schüco ERC 50 modernization façade is installed and wired entirely from the outside, whilst the building is still in use. This means the window units on the inside can be removed efficiently and to precise deadline.

This is how it works:

1. The old structure with an existing façade with an in-filled, reinforced concrete skeleton structure.
2. The load-bearing pilaster of the modernization façade is fixed to the building structure above a fixing bracket as a vertical load-bearing system.
3. The new window units are installed on the inside of the load-bearing pilaster, whilst the old windows initially remain in the façade.
4. After sealing the new window units to the building structure, the remaining building areas are insulated.
5. Installation and wiring of the concealed, flush-fitted solar shading system.
6. The different infill units, such as glass, sheet metal or Schüco ProSol TF photovoltaic units, can now be efficiently and quickly mounted on the installed load-bearing structure.
7. Once the outside is complete, the old window units on the inside are removed. The reveals are clad with panel units made from wood, sheet metal or plasterboard.
8. The modernization is complete. View of the redesigned and perfectly insulated façade, which now accommodates numerous functions.

Step 1 Step 2 Step 3

Step 4 Step 5 Step 6

Step 7 Step 8

Figure 9: Installation while the building is still in use

# Energy-oriented Facade-Renovation of Architectural Monuments

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### Summary

Architectural monuments are a vivid picture of history and play an important role for the identity of the society. Energetic enhancement and the climate change adaption presents a major challenge to architectural monuments. As a part of building stock they cannot escape from this problem. This paper describes the energetic renovation of two significant monuments. It includes a description of the buildings as well as a variety of solutions and their practical implementation. The conflict between both, an energetic renovation and a sensitive handling with historical landmarks leads to new developments and concepts. These results can be transferred to comparable buildings.

**Keywords:** Bauhaus Dessau, Schillerpark Berlin, Energy-Efficiency, Facade-Upgrade

## 1 Bauhaus Dessau

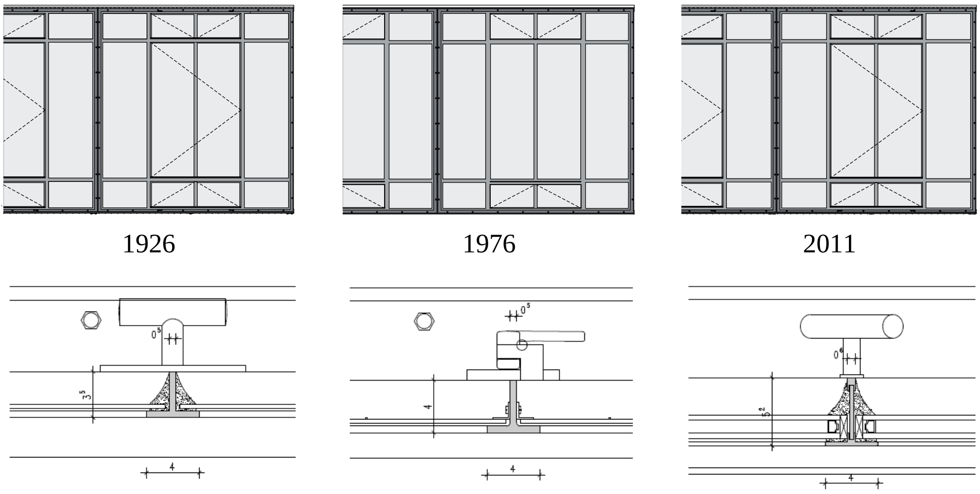
### 1.1 Introduction

With regard to the high level of occupancy, heating loads and rising energy prices, constantly rising operation costs occur for the Bauhaus-building in Dessau. Consequently, first ideas for an energetic enhancement of the building started in 2009. The main focus has been put on the preservation of the original appearance and the quality of the monument. Apart from the financial aspect of the high facility costs, the thermal comfort shall be improved. Because of the radiative cooling of single glazing, some users complained about strong drafts in the rooms. Very soon it became obvious that only the development of an overall concept can protect the value of the monument.

The complex of buildings of the Bauhaus in Dessau consists of five main parts – workshop wing, north wing, bridge, atelier building and intermediate building – which were built within one year (1925/1926) and inaugurated in December 1926. Figure 1 gives an overview of the Bauhaus-building.
The workshop wing is fully glazed on the upper floors. The glazing itself is impressing due to its filigree work and transparency. Destroyed areas had been closed with a perforated facade after World War II and restored during the first general renovation in 1976. The design of the curtain wall of the workshop wing was oriented on the original construction, but instead of the original steel profiles aluminum profiles with larger dimensions were used. Because of the status as an architectural monument renovation works cannot be done on this facade.

Figure 1: Bauhaus-building Dessau.

The north wing shows continuous strip windows that were put in front of the facade. It was used as a commercial vocational school. The atelier building includes a perforated facade to the east and the west of the building. All window constructions of the Bauhaus-building originally consisted of hot rolled steel profiles with a single glazing. Currently only in some areas the old windows are still present. The window elements of the strip windows and the window constructions of the live-in studios have the same appearance as the original windows, but the shape of the profiles has been simplified. Furthermore, the number of opening casements was reduced and the opening function modified. Figure 2 shows the views and sectional drawings of windows of the north wing from the beginning (1926), after the first renovation (1976) and after the current renovation (2011). The most important change between 1926 and 2011 is the change of the single glazing into an insulation glass under restoring the opening functions which were changed in 1976.



1926 1976 2011

1926 1976 2011

Figure 2: Historical and modern glazing of the north wing.

## 1.2 Variety of Solutions

To determine the areas with the highest losses of energy more than one energetic concept has been developed. After the implementation of a selection process the company TRANSSOLAR GmbH from Stuttgart worked out an energetic overall concept in 2011. The aim was the analysis of heating and cooling systems, utilization of the buildings, behaviour of the users, power consumption and options for power generation instead of great intervention in the construction. In this way it was possible to show various potentials in saving and optimizing the consumption of energy. Because of the high amount of glazing the designers expected the most saving potential in these fields. Therefore, the glazing was divided into three categories – preserve, examine, change.

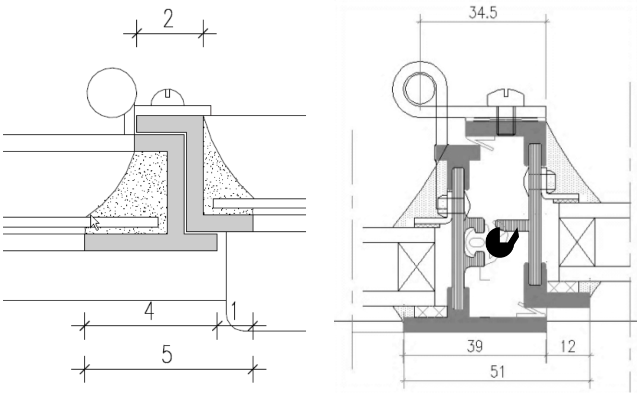
In a first step the designers wanted to change the windows, which were declared as changeable, to insulating glass. After a few steps of simulation they noticed, that this method would be very inefficient. Due to the high amount of leakages and no thermal separation of the steel profiles the designers expected only a small benefit. Therefore, an energetic improvement and a technical approval of the steel profiles were necessary. In further investigations it became clear that the original windows consisted of crystal plate glass. This glazing has a high transparency and creates - depending on lighting conditions and viewing direction – laminar reflections. Since this glass is not any longer produced today, it is important to find a suitable replacement.

Because of the status as an architectural monument the solid areas of the facade and the original substructure of the strip windows in the north wing of the north facade cannot be renovated with regards to energetic properties. This would require building physics studies for critical areas.

## 1.3 Practical Implementation

Because of the status as an architectural monument the Bauhaus-building in Dessau allows minimal structural modifications. Therefore, the first steps of renovation were organizational measures for a better adaption of the utilization. Consequently, the offices of the workshop wing and the other buildings moved into the north wing. Because of the temporary occupancy of the workshop wing a reduced heating with a lower limit of 16 °C could be realized. Furthermore, the heating and cooling control systems was optimized, which means 50 % less heating load. To compensate the loss of energy in this wing, a photovoltaic system will be installed on the north wing of the Bauhaus-building and on an adjacent building.

To use the energetic advantages of new insulation a thermal separation of the steel profiles was required. Very soon it became clear that profiles with a sufficiently fine sash and frame were not available on the market. In cooperation with the company MHB bv from the Netherlands, a suitable thermal separated profile had been developed. Based on the existing product SL30-ISO®, designers found a solution which enabled an energetic optimization as well as the reflection of the original shape. In order to receive a technical approval, the Technische Universität Dresden carried out a lot of tests in its testing facilities. As a result the product CLASSIC-ISO® was developed. It consists of hot-rolled flat steel with laser-welded U-profiles and a thermal separating bar of fiber reinforced plastic. The width of the bars and their location for the thermal separation is variable. The variability allows the development of different profiles with different specifications, based on one system. The CLASSIC-ISO®-System allows sightlines of 30 mm for frames and 51 mm for the sash. Depending on the glazing the whole window-element can reach a U-value of $U_W = 1.2$ W/m²K. Figure 3 shows drawings of the original profiles and of a prototype of a profile which has been tested in the testing facilities of the Technische Universität Dresden.



Original profile CLASSIC-ISO®

Figure 3: Original and new steel profiles.

The sealing of the stationary glass elements is achieved by putty. In the area of the sash, three integrated strip seals guarantee the sealing. Visible drainage does not exist.

Another problem was the choice of the new glass for the windows. It should reach the same high level of quality in flatness and the surface as the original crystal plate glass. Modern insulating glass often includes coating systems based on metal oxides to improve the energetic properties. After several tests with different glasses from different manufacturers in test facades the designers realized that the reflection behavior of the glasses is influenced by the different coating systems. As a result they used a krypton-filled insulating glass with uncoated iron oxide reduced white glass. In contrast to insulating glass with coating, which have a U-value of $U_g$ = 1.0 W/m²K to 1.6 W/m²K, this glass has an U-value of only $U_g$ = 2.6 W/m²K.

Areas which are not renovated because of their status as an architectural monument have to be investigated with a focus on building physics. As a result designers used a mineral insulating plaster in the reveals of the atelier building. The original steel sub construction of the strip windows in the north wing was not thermally separated. Therefore, an electrical trace heating in form of heating tapes has been added. These two measures could not prevent the condensation of water at reveals and walls during extreme temperature and humidity conditions. So, the users had been introduced in the proper ventilation behavior. In some areas electronic humidity controls had been installed. These systems emit a signal, which triggers the ventilation. Figure 4 shows the renovation of the steel sub construction of the strip windows at the north wing.

Figure 4: Bauhaus-building during renovation.

## 1.4 Results

All measures on the Bauhaus-building in Dessau led to a simulation result of 39 % in energy saving at the north wing and 66 % at the eastern facade. It is a fact that there is a low value of saved energy in the north wing in contrast to the eastern facade due to uninsulated areas and the electrical trace heating. All participants agreed that an architectural monument with the status as a world cultural heritage cannot be compared to a new building in term of energy saving. So, the energetic renovation will take second seat behind heritage protection. The designers accepted a glazing with a U-value of $U_g$ = 2.6 W/m²K. By comparison to the original windows with a U-value of $U_w$ = 5.88 W/m²K, this still means a huge improvement of the indoor climate and the quality of occupancy. During this renovation obtained results and technical solutions represent a progress in the renovation of steel windows for buildings of the International Style.

# 2 Schillerpark Berlin

## 2.1 Introduction

The residential estate Schillerpark, which was built in the 1920s and 1950s by the architects Bruno Taut and Hans Hoffmann belongs together with five other estates of the “Berliner Moderne” to the UNESCO World Cultural Heritage. For this renovation, the focus was put on the development and implementation of a sustainable energetic concept.

The estate is composed of six construction stages. The first three sections were built between 1924 and 1930, sections four to six in the years between 1954 and 1959. The blocks of flats of the construction stages five and six possess plastered facades and were designed as 2½ - room flats. After World War II the buildings were built with a high level of transparency. Figure 5 shows the facade to the backyard which is almost completely glazed. The window areas of the balconies consist of two layers of single glazing, which are divided by a 50 cm wide space. This type of glazing is also called “Blumenfenster” (flower window) and has a high priority for the energetic renovation as well as for the status as a monument.

Figure 5: Balconies with the Blumenfenster.

On the one hand it is a major part of the monument and on the other hand it is critical for the energetic performance of the building. Figure 6 shows a thermal image, which has been made during the investigation of the Technische Universität Dresden.

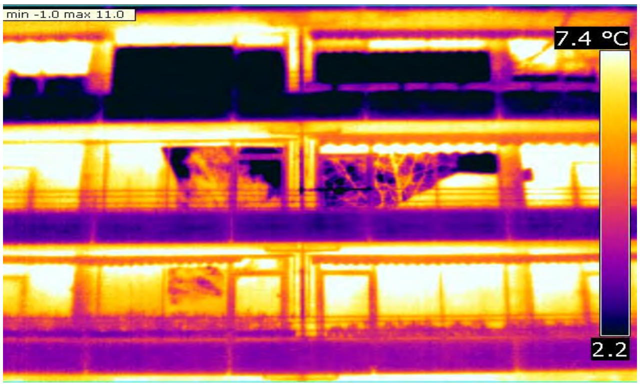


Figure 6: Thermal image of the balconies with the Blumenfenster.

The remaining windows are composite windows consisting of two panes. The external walls, which represent the most area of the outer shell, consist of 24 cm hollow blocks and are plastered on both sides. A brick-chippings-concrete-ceiling is the bottom of the heated volume. The floor consists of 2 cm slag wool, 3 cm screed and the floor covering. The bottom side is covered by “Heraklit”-panels. The massive roof construction consists of two shells of brick-chippings-concrete with an insulation layer between them. The lower shell was built as a ribbed slab and the upper shell with an overhang.

## 2.2 Variety of Solutions

For the development of an energetic concept for the residential estate “Schillerpark” the designers in cooperation with the Technische Universität Dresden both used experiences of renovations of similar buildings and modern simulation software. Two concepts were investigated.

For concept A an insulated composite system with a thickness of 8 cm, consisting of high quality insulation material with a conductivity of $\lambda = 0.022$ W/mK is used. The external pane of the Blumenfenster is replaced by an insulating glass. The single glazing of the inner pane will not be changed. To prevent thermal bridges, an additional insulation in the space between the two layers of the Blumenfenster is necessary. The other windows of the flat also will be replaced by insulation glass. The roof construction gets a subsequent insulation on the outside by 20 cm expanded polystyrene hard foam (EPS) with a conductivity of $\lambda = 0.035$ W/mK. The cellar ceiling also gets a subsequent insulation by 4 cm mineral wool. The thickness of the insulation is very small because of the low floor heights. Thus, an expensive lowering of the floor can be avoided. A major component of the concept is the ventilation concept. Because of a negative pressure in the flats the air will flow through the Blumenfenster. According to the simulation, the insulation of the external walls will just save 33 % of heating energy. The overall concept would reduce the heating load to 41 % in dependence of the start consumption.

Concept B is a standard-concept according to the guidelines of the current building regulations (EnEV). It contains an insulated composite system of Polystyrene with a thickness of 14 cm and a conductivity of $\lambda = 0.035$ W/mK. All windows get replaced by a triple glazing. The inner pane of the Blumenfenster is completely removed. This would cause the positive effect of a bigger floor area. To prevent a discomfort caused by cold air downdraughts, the position of the radiators in living and sleeping rooms has to be changed. This causes a large intervention in the substance of the monument. Like mentioned in concept A the roof construction gets a subsequent insulation on the outside by 20 cm EPS-insulation. The cellar ceiling also gets a subsequent insulation by 10 cm mineral wool. This causes an expensive lowering of the floor. The ventilation concept is realized in form of classic window ventilation, which creates a few disadvantages: first uncontrolled air and humidity conditions would be created, and second no positive effects of heat recovery would be gained.

Overall the amount of saved energy from concept B is nearly the same as in concept A. Figure 7 shows the consumption of the building at the actual state as well as the simulated heating loads for the actual state and for the concepts A and B.

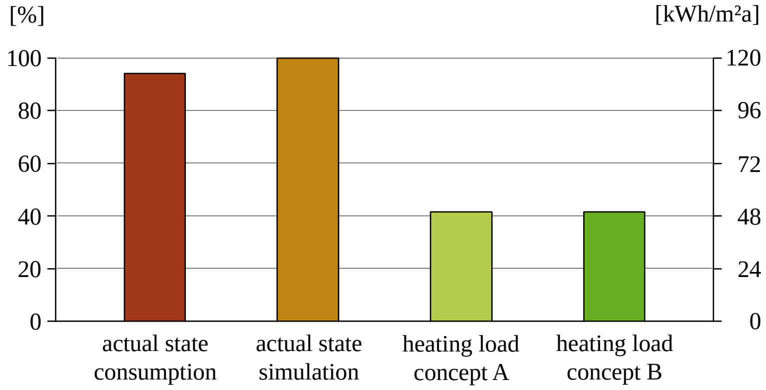


Figure 7: Consumption and heating loads.

Furthermore the simulation shows that the thermal bridge grows in the result of the reduction of the inner pane of the Blumenfenster.

## 2.3 Practical Implementation

Simulations showed that concept A is advantageous for the thermal comfort in the rooms. The risk of radiation asymmetry due to differences of temperature of the surfaces decreases. The PMV-value as an index of comfort is in the uncritical range of -0.3 to + 0.3. Based on the results of the simulation and under the aspect of the status as an architectural monument, the designers developed a renovation concept. This concept is based on an altered concept A which contains ideas of concept B for special areas.

All opaque areas with insulation get a mineral plaster, which imitates the originally plaster in its optic. To save the appearance, a variable thickness of insulation around the building was used. The areas of entrance and the gable wall get an insulation of EPS with a thickness of 14 cm. Thus, the windows can be placed into the layer of insulation and the originally depth of the reveals can be preserved. The facade with the balconies is isolated with a high quality and expensive “Resol”-hard foam with a thickness of 8 cm. This minimizes the change of the geometry of the building. The entrance element remains in the original style. The filigree steel profile construction of the staircase has to be preserved. Therefore, corroded parts must be derusted and repaired. To carry the new insulation glazing, the steel profiles had to be reinforced with additional steel profiles on the inside. The whole facade must be placed flush with the new insulated external wall.

In the area of the balconies the ends of the balustrades and the partition walls have to be shortened in the thickness of the insulated composite system. All windows must be replaced but the color, profiles and geometry should be the same as in the original windows. The single glazing of the entrance is replaced by a triple glazing and profiles with greater dimensions. The Blumenfenster remain in their original type. Only the outer pane is replaced by an insulated glazing. Figure 8 shows the view of the balconies before and after the renovation. The major difference is the color of the parapets, which was changed to the original color.

Before renovation

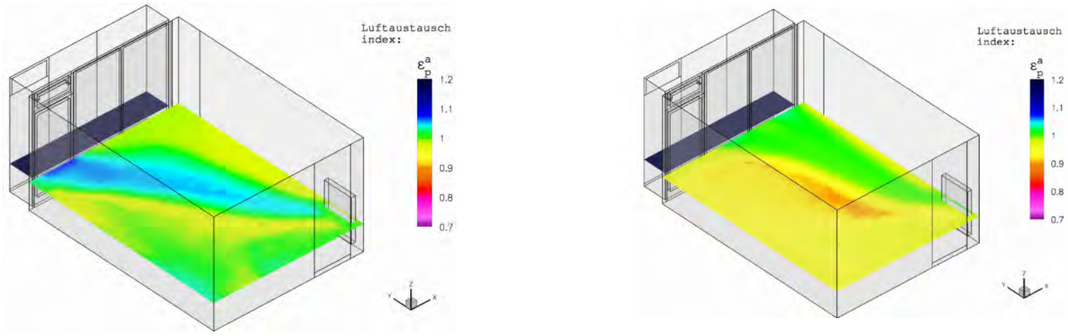
After renovation

Figure 8: Comparison – Blumenfenster before and after energy-oriented renovation.

To realize the ventilation concept apertures were installed in the frame of the outer pane of the Blumenfenster. So, the outside air is heated in the space between the two layers of the Blumenfenster, flows into the room and is removed through the chimney.

## 2.4 Results

During the renovation of the residential estate “Schillerpark”, one flat was modified to the renovation concept under supervision of the Technische Universität Dresden. Especially the ventilation concept was under investigation, because it has a great influence on the thermal behavior of the building. With the help of a Blower-Door-Test, the air flow inside the flat was investigated. The emphasis was primarily on the inflow in the area of the Blumenfenster. The test also was used to validate the simulations of thermal comfort which are shown in figure 9.



Air exchange-index before renovation

Air exchange-index after renovation

Figure 9: Comparison – air exchange-index before and after energy-oriented renovation.

A measurement of the flow velocity confirmed a slow and evenly inflow of the air. The maximum speed was unpleasant, which saves the user from unpleasant drafts. The measurements confirmed the efficiency of the ventilation system and the results from the simulation by the Technische Universität Dresden. When the renovation works will be finished a controlled commissioning with an optimization of the systems will start. A comparison to the consumption before and after the renovation cannot be done because of a missing billing of the operation costs.

## 3 Acknowledgements

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Figures 1, 2, 3, 4, 5, 8: Winfried Brenne Architekten. Figures 6, 7, 9: Technische Universität Dresden.

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# Novel Protection Against Radon

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## Summary

A new principle for pressure reduction of the zone underneath the ground floor construction of prefabricated lightweight elements were introduced and demonstrated. The principle was demonstrated on a ground slab floor, constructed of a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. The thermal insulation and the capillary-breaking layer consisted of a rigid insulation material. The novel solution introduced integrates the capillary-breaking layer and a radon–suctioning layer in one element. The novel solution introduces the radon-suction layer as a horizontal grid of air ducts with low pressure to catch air and radon from the ground. The new principle was shown to be effective in preventing radon from polluting the indoor air by introducing low pressure in the horizontal grid of air ducts. A pressure lower than the pressure inside the building must be introduced. The element was integrated into the insulation material of the ground slab floor. The element and the insulation material were made of expanded polystyrene.

**Keywords:** Element, EPS, Radon, Protection

## 1 Introduction

Radon is a radioactive noble gas that develops as a result of the decay chains of uranium and thorium (Clavensjö 2004). When radon decays into different radon daughters, it generates alpha, beta and gamma radiation. Radiation is harmful to human beings. Radon originates in the ground and is the primary source of natural radiation in most countries [1]. Therefore the geological character of the ground, on which a building is situated, sets the level for how high the radon concentration of the indoor air can become. Radon mainly penetrates into a building by air infiltration from the ground through cracks or other unintended openings in the ground construction [2].

In 2009, the World Health Organization, WHO, recommended that requirements to the accepted maximum radon concentration in the indoor air should be tightened from 200 Bq/m$^3$ to 100 Bq/m$^3$. The new recommendations are a result of WHOs evaluation that radon is responsible for 3-14% of lung cancer incidents, depending on the average radon exposure in different countries [3]. These results show radon as the second-largest cause of lung cancer; smoking is still the principal cause. Radon exposure must be taken seriously in the fight against radon-induced lung cancer due to the large number of people that are exposed daily in buildings and especially in residential buildings [3], as a large number of residential buildings are built with a slab on ground. An investigation shows that if people spend their whole life in a building with an average radon concentration in the indoor air exceeding 200 Bq/m$^3$, their risk of getting lung cancer is higher than 1%. This is far too high and higher than what in other contexts is an acceptable single-factor risk [4]. Ensuring a good quality of the indoor air includes a focus on radon and methods to control the radon concentration in the indoor air.

In 2010, the requirements recommended by WHO were implemented in the Danish Building Regulations. The Danish Building Regulations now stipulate a maximum radon concentration of 100

Bq/m$^3$ in the indoor air in all new buildings. For existing buildings, simple and cheap actions are recommended if the concentration ranges between 100 Bq/m$^3$ and 200 Bq/m$^3$ in the indoor air; however, if the radon concentration exceeds 200 Bq/m$^3$, immediate intervention is necessary and more efficient efforts and improvements are recommended in order to lower the concentration of radon in the indoor air [5]. The first radon provisions were introduced in the Danish Building Regulations in 1995 [6].

Solutions to prevent radon from polluting the indoor air are traditionally based on a combination of three different principles: i) establishing a skin against radon by using airtight materials and membranes, ii) introducing pressure reduction of the zone underneath the ground floor construction, and iii) providing effective dilution of the indoor air with outdoor air. Of these the principle ii), pressure reduction, is considered by far the most efficient. The paper presents a new prefabricated lightweight element designed to reduce and control the pressure reduction of the zone underneath the ground floor construction. The effect of the element was demonstrated on a ground slab floor, which was constructed of a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. The thermal insulation and the capillary-breaking layer consisted of a traditional rigid insulation material of expanded polystyrene, EPS. The new element integrates the capillary-breaking layer and the pressure reduction zone, denoted the radon–suctioning layer, in one element. The novel solution introduces a horizontal grid of air ducts, the radon-suction layer, with low pressure to catch air and radon from the ground. Results showed the pressure needed in the air ducts underneath the ground floor construction as a function of the pressure inside. The low pressure prevents radon from polluting the indoor air. Simulations were made by using a finite difference program. The element that was made of EPS was designed to be handled on site by one man. The element was integrated into the insulation material of the ground slab floor.

## 2 Measures to Control Radon Concentration Indoors

Solutions to prevent radon from polluting the indoor air and to control radon concentration in the indoor air are based on a combination of three different principles: 1) A layer protecting against radon infiltration established by using airtight materials and membranes, 2) Pressure reduction of the zone underneath the ground floor construction, and 3) Effective dilution of the indoor air with outdoor air. The three principles are shown in Figure 1.

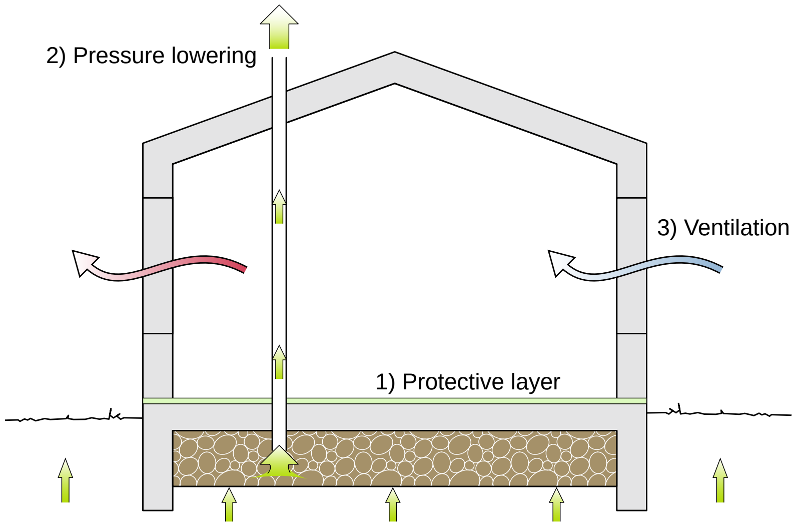

Figure 1: By combining three principles, the radon penetration and concentration indoors can be controlled. 1) Establishing a protective layer that prevents air infiltration from the ground. 2) Lowering the pressure difference over the floor construction of the building facing the ground. 3) Diluting the indoor air in the building with outdoor air.

## 3 Pressure Lowering

The most effective way of preventing air that can contain radon to infiltrate from the ground into a building is considered to be a radon-suction system [7]. The principle is that the pressure of the zone underneath the ground slab floor of the building is lowered. The pressure difference can be up to 10 MPa between the interior of the building and underneath the ground slab floor. This pressure difference can be equalised by establishing a connection between the atmosphere and a highly permeable layer underneath the building. In such a construction, the pressure difference, over the floor construction of the building facing the ground, will decrease and result in a decrease of the amount of ground air that can infiltrate. The radon-suction system can either be passive or active, i.e. creating suction through the stack effect only or creating suction by means of mechanical ventilation. A pipe can be led directly from the radon-suction layer and above the roof. Suction is introduced through the pipe to the radon-suction layer.

## 4 Theory

The Heat2 [8] finite difference program was used for the pressure equalisation calculations. It was assumed that the pressure difference was so low that the air would not be compressed. Additionally, it was assumed that the speed of the air through the materials of the ground slab floor was in the range of a laminar airflow. Furthermore, the individual materials were porous and homogeneous. Under these conditions, air flowing through a porous material can mathematically be described in the same way as a stationary thermal conductance problem. A stationary thermal conductance problem is described by:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)=0 \tag{1}$$

Where,
$T$ is the temperature
$k_x$, $k_y$, $k_z$ are the thermal conductance in the x, y, z direction, respectively.

The differential equation, Equation (1) expresses that the total effect that is supplied to and removed from a control volume is equal to zero.

The result of a thermal conductance problem is a temperature distribution within the analysed element. From the temperature distribution the effect that needs to be removed or absorbed through the borders, to maintain the stationary temperature distribution can be determined. In the same way, the air pressure distribution can be calculated and the amount of air that needs to be removed or absorbed through the borders, to maintain the stationary pressure distribution, can be determined for porous materials.

Using the finite difference program Heat2 [8] for air-pressure calculation, the temperature was substituted by the air pressure, the thermal conductance was substituted by the air permeability and the effect was substituted by the amount of air per time. A stationary air pressure problem described by Equation (1), then expresses that the amount of air that is brought in and the amount of air brought out of the control volume is equal to zero.

Using the Heat2 program and a PC for the pressure analyses, the input data for the thermal conductance values were substituted by the air-permeability values and the prescribed temperatures were substituted by the prescribed air-pressure values. Stationary-state calculations were carried out reaching air-pressure equilibrium between the air pressure indoors and the air pressure in the ground. For the state of pressure equilibrium, the amount of air per time that needs to be removed or absorbed through the upper surface of the concrete slab facing the indoor environment was determined.

Usually the air permeability of a material is given as the resistance known as the Z-factor with the unit (h m$^2$ Pa)/g describing a specific building component of a specific thickness. For these calculations, the air permeability must be determined as the reciprocal value of the Z-value multiplied by the thickness of the building component.

# 5 Novel Radon Suction Layer

The highly permeable and capillary braking layer underneath the building often consists of i.e. shingles, pebbles or coated ceramic pellets but can also be a layer of EPS with a horizontal grid of air ducts.

## 5.1 Material

The prefabricated element was made of EPS to form an element that could be used as the capillary-breaking layer and the radon–suctioning layer integrated in one element. The element was produced as one element through a production including an injection moulding process. The EPS is produced from a mixture of about 5-10% gaseous blowing agent (most commonly pentane or carbon dioxide) and 90-95% polystyrene by weight. The solid plastic is expanded into a foam by means of heat, usually steam. The polystyrene is filled with trapped air, which gives it low thermal conductivity, [9]. The air permeability was 0.0144 g/(m h KPa).

## 5.2 Design

The prefabricated element was produced as units of 600 mm in length and 400 mm in width and 50 mm in thickness. A horizontal grid was cut out and removed from the upper surface of the element, thus creating air ducts 30 mm in width and 30 mm deep with a centre distance of 100 mm. At the border towards the upper surface of the element, an air duct 15 mm in width and 30 mm deep was cut out and removed. The element is shown in Figure 2 and Figure 3.

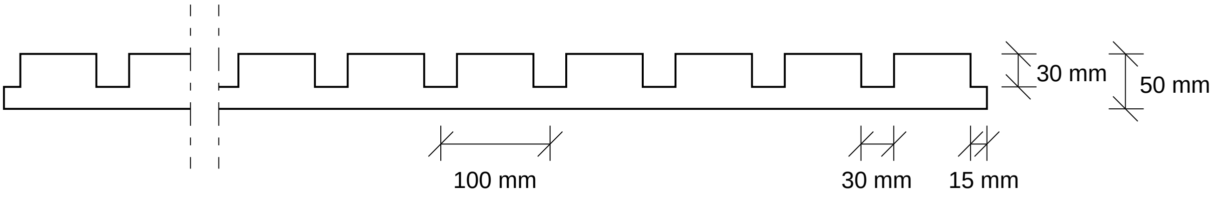

Figure 2: The new prefabricated element made of EPS.

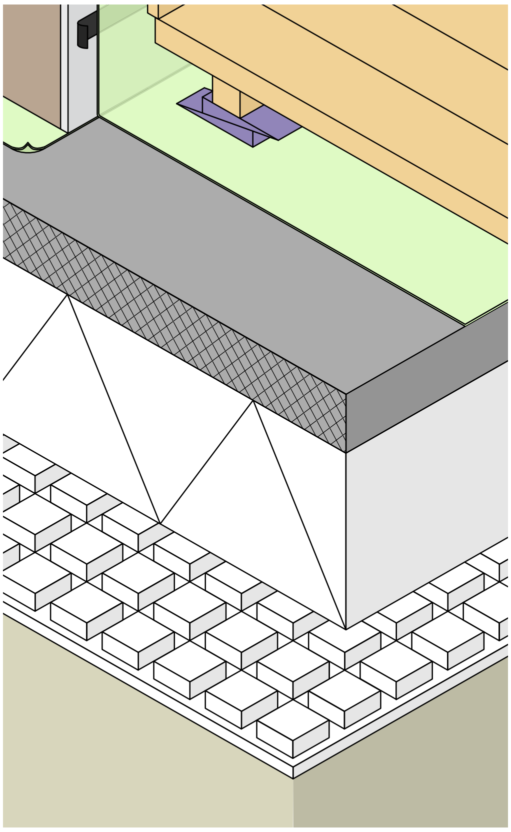

Figure 3: The EPS element used as the integrated capillary-breaking layer and radon–suctioning layer of a traditional ground slab floor. The ground slab floor was constructed of a concrete slab on top of a thermal insulation layer above the element, that works as the integrated capillary-breaking layer and the radon-suction layer, mounted on stable ground.

## 6 Modelling

Calculations of the airflow through the ground slab floor were carried out by using a PC and the finite difference program Heat2 [8] version 7.0. Calculations were stationary-state calculations with a constant air pressure indoors and a constant air pressure in the ground. Heat2 [8] was used for calculating the amount of air passing through the upper surface of the concrete slab, using a constant air pressure above the concrete slab representing the air pressure inside and a constant air pressure in the air ducts of the element combined with a constant air pressure in the soil underneath the ground slab floor. The air pressure in the soil underneath the ground slab floor was 101 328.6 Pa. The Ground slab floor is shown in Figure 4 and the model used for the calculations is shown in Figure 5.

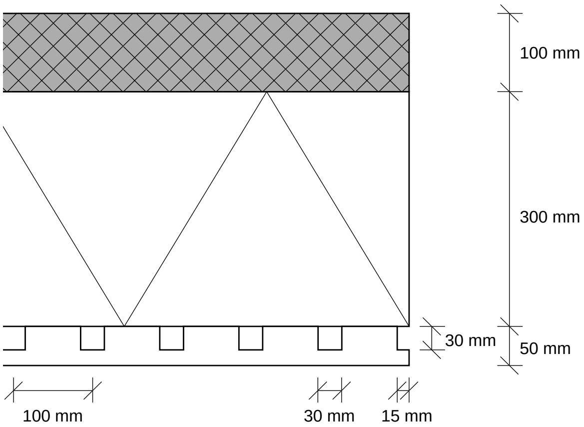

Figure 4: The ground slab floor constructed of a concrete slab on top of a thermal insulation layer above the new element. The combined capillary-breaking layer and the radon-suction layer are shown as the new integrated element.

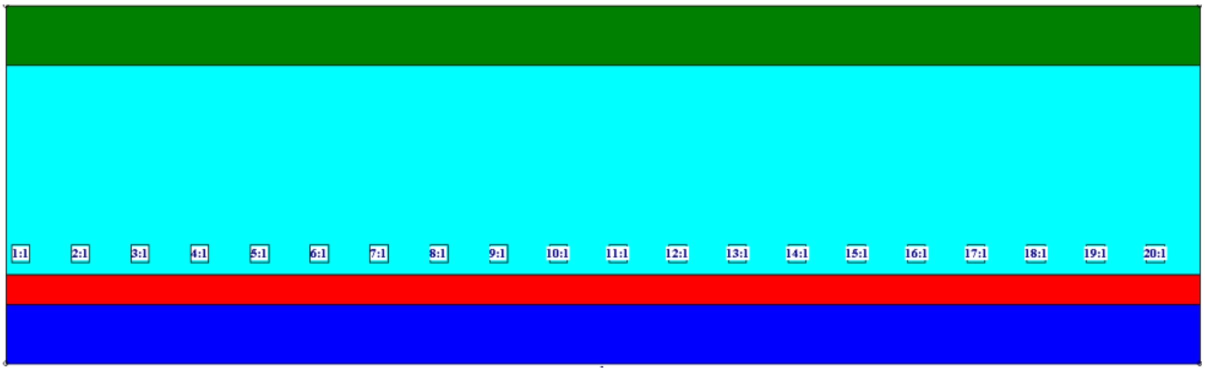

Figure 5: The model used for calculations. The model includes a concrete slab on top of a thermal insulation layer above the new element mounted on stable ground. The horizontal grid of air ducts are shown as square units that are numbered 1:1 to 20:1. Usually the top-soil layer is removed from an area covering the area of the building. The excavated area is then covered with gravel to level the excavated area. Included in the model were 50 mm of gravel and 100 mm of soil. The model was 2.0 m in length.

## 7 Results

For the calculations the air permeability of a the concrete, the soil and the gravel were 0.018 g/(m h KPa), 0.36 g/(m h KPa) and 0.576 g/(m h KPa), respectively. The atmospheric pressure was 1 atm equal to 101 325 Pa. For the calculations the pressure inside were 101 321.25 Pa, 101 323.24 Pa and 101 324.85 Pa, respectively in combination with a number of different pressure levels in the air ducts of the new element, between 101 325.00 Pa and 101 320.00 Pa. The thickness of the concrete and the layer of thermal insulation were 100 mm and 300 mm, respectively. The thermal insulation was EPS. Results are shown in Figure 6.

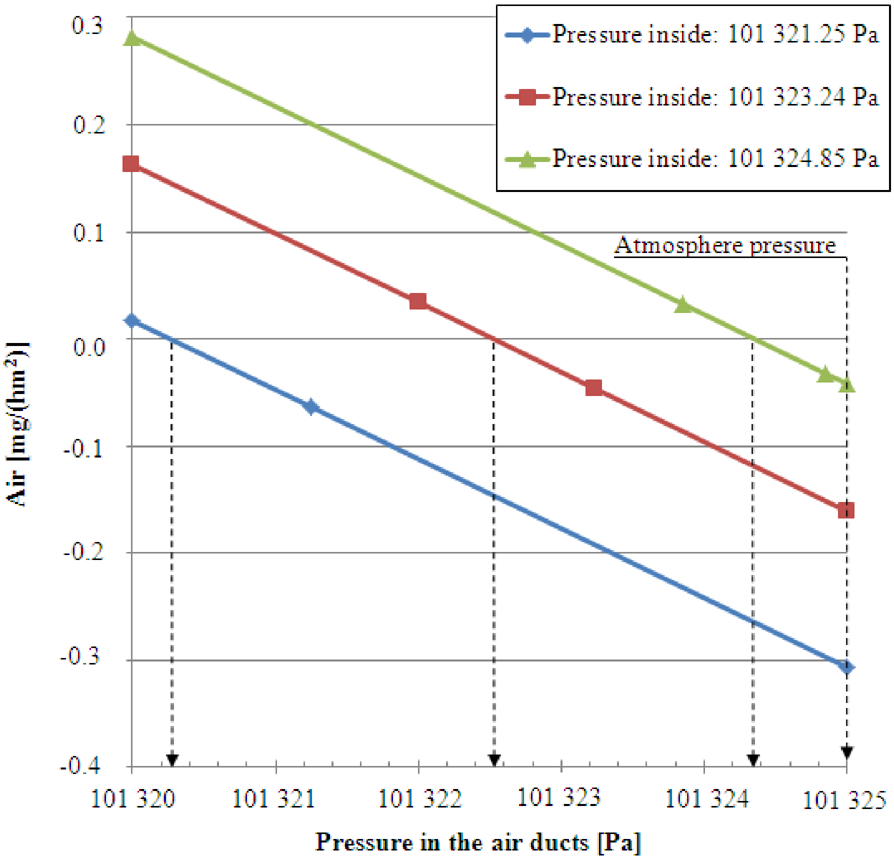

Figure 6: Amount of air passing through the upper surface of the concrete slab in milligram per hour each square metre. A positive number for the amount of air represents air moving through the ground slab floor towards the air ducts.

## 8 Summary and Conclusion

A new prefabricated lightweight element that can be used to reduce the air pressure in the zone underneath the ground floor construction has been introduced. The new element is made of expanded polystyrene, EPS. The element is produced as one integrated element consisting of units of 600 mm in length and 400 mm in width and 50 mm in thickness. A horizontal grid of air ducts is cut out from the upper surface of the element, thus creating air ducts 30 mm in width and 30 mm deep with a centre distance of 100 mm. At the border of the upper surface of the element, air ducts 15 mm wide and 30 mm deep are cut out and removed. The element is designed to be handled on site by one man.

Traditionally, a ground slab floor is used that is constructed of a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. The thermal insulation layer consists of a rigid insulation material. The capillary-breaking layer consists of either a layer of a rigid insulation material on a thin layer of gravel used to level the excavated area or a layer of i.e. shingles, pebbles or coated ceramic pellets. The new element makes it possible to combine the capillary-breaking layer and the radon–suctioning layer in one integrated element of EPS. The most effective way of preventing radon from infiltrating from the ground into the indoor air of a building is to lower the air pressure of the zone underneath the ground floor construction. By lowering the air pressure of the zone underneath the ground floor construction, the pressure difference over the floor construction can be lowered. A pipe can be led directly from the radon-suction layer and above the roof. Suction is introduced to the radon-suction layer through the pipe. The suction can either be passive or active i.e. creating suction through the stack effect only or creating suction by means of mechanical ventilation. A horizontal grid of air ducts in a layer of EPS is shown to be able to be used as, a permeable layer that can be used as a radon-suction layer underneath a floor construction of a building. The novel element can be used to lower the pressure difference over the floor construction of the building facing the ground, and in this way prevent ground air from infiltrating from the ground, and additionally prevent the risk of radon polluting the indoor air.

Calculations of the airflow through a ground slab floor were carried out by using a PC and a finite difference program. Mounted on stable ground, the ground slab floor was constructed of a concrete slab on top of a thermal insulation layer above the new element that works as the combined capillary-breaking layer and the radon-suction layer. Stationary-state calculations with a constant indoor pressure and a constant pressure in the ground were made. Calculating the amount of air passing through the upper surface of the concrete slab shows that the air pressure in the air ducts of the radon-suction layer needs to be lower than the pressure inside to prevent radon and ground air to infiltrate from the ground through the floor construction. Figure 6 shows that the amount of air passing through the upper surface of the concrete slab is approximately zero for an indoor air pressure equal to 101 321.25 Pa, 101 323.24 Pa and 101 324.85 Pa and an air pressure in the air ducts equal to 101 320.28 Pa, 101 322.53 Pa and 101 324.35 Pa, respectively for an outdoor air pressure of 101 325 Pa. The needed pressure difference over the ground floor construction decreases as the air pressure inside gets nearer the outdoor air pressure.

If the pressure underneath the building is lower than the pressure inside, air could be drawn from the inside. This might be a concern if there is a risk of warm, moist air being drawn down through the floor construction, where it is cooled down in organic material resulting in risk of mould growth.

## 9 Acknowledgement

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# Prototype of the New Lightweight Modular Facade FB720: Report on the Life Cycle Analysis of the Materials Used and their Effects. A Case Study

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## Summary

The Façade FB720 project is the result of research funded by the Spanish Government's Centre for Industrial Technological Development (Centro para el Desarrollo Tecnológico Industrial, CDTI) (IDI-20090761). The aim of the project was to design and develop a lightweight, modular, unitized façade with low environmental impact and high energy efficiency, mainly for use in the Iberian Peninsula (temperate climates). The basic technical strategies to achieve this aim were as follows:

- Reduce the consumption of building materials
- Use renewable or recycled materials
- Optimize the façade structure and the transparent surfaces as elements to control solar radiation.

**Keywords:** prototype, lightweight modular façade, life cycle analysis, case study

## 1 Introduction

The architectural design of the façade is based on a proposal by the company b720 arquitectos, with the participation of various companies and technology centres acting as consultants. The Universitat Politècnica de Catalunya (UPC) provided advice on the life cycle analysis, in collaboration with the environmental consultancy Societat Orgànica. The consultancy JG Ingenieros was involved in the thermal and light evaluation. The characteristics of the new FB720 façade were verified by assessing their environmental impact in all the life cycle phases. This was achieved by means of energy simulations of the use phase and real trials carried out using several prototypes. While these processes were carried out, a series of rectifications and adaptations were made to optimize the design.

The results of the verification were validated by comparing the FB720 façade with a standard, lightweight, modular, quality façade. It was found that the energy consumption and the CO2 emissions due to the production of materials, transport, construction, maintenance and dismantling were substantially lower for the FB720 façade, with improvements of over 50% attained. With respect to the light and thermal evaluation, the energy saving in the areas of the building that are immediately next to the façade was approximately 34% in the most favourable cases. The project has not been published yet and was completed in December 2011.

Figure 1: Photographs of different prototypes that are versions of the FB720 façade system

## 2 Technical Characteristics

### 2.1 General Approach

FB720 is an innovative lightweight façade system of the modular “unitized” type. The aim was to benefit from the main advantages of this kind of systems – lightness, easy assembly and technical reliability – and improve the environmental and energy features. The system was developed using standard approaches to this kind of façade. Additionally, the following technological innovations were incorporated:

- The thickness of the façade itself was used as solar protection, by placing the strong substructure (uprights) towards the exterior.
- Alternative materials with less environmental impact were incorporated.
- A system of variable solar protection glass that has been developed specially for this project was incorporated.

The combination of these strategies provides an opportunity to increase the visibility of actions to improve sustainability that are promoted by architectural approaches. The final result is a building solution that is competitive due to its initial costs, which are appropriate for mid- to high-range projects; the impact of the built area, which is lower than that of other double skin façades; and the use of passive means of climate control.

### 2.2 Depth and Protection

One of the main characteristics of the FB720 system is that the uprights and crossbeams have been moved to the exterior. Although this approach was used in the first curtain walls, in contemporary systems the substructure has tended to be situated preferentially towards the inner face, to obtain better continuity of thermal protection and impermeability. Due to current technical requirements, the following design adaptations had to be made to recover the exterior position of the uprights:

- The assembly and replacement of glazing is expected to be carried out from the inside.
- Thermal break elements are positioned in alignment with the interior face of the frames.
- The joints between wider panels are on the inner face to enable anchor to be fastened on the central part of the frame.

The aim of moving the substructure frames to the exterior is to provide better solar protection for the façade, by taking advantage of the shadow that it casts on the plane of the wall. This is really a reinterpretation of a design that always been used in architecture: thick walls and deep openings. The result is a lightweight façade in which the main feature is depth and shadow, rather than glass and its reflections. Improved solar values can be obtained through an appropriate substructure design. For example, a façade located at latitude 41º (Barcelona), with uprights placed every 60 cm, the total incident radiation is reduced during the summer by approximately 53% if the façade is south facing, 38% if it is south-west or south-east facing and 27% if it is west facing.

As an additional advantage, the external position of the substructure provides an exterior pre-environment that forms part of the thickness of the façade and could be used for various purposes. Thus, additional sheets could be installed over the frame to create ventilated air chambers in opaque modules or complementary solar control systems could be hung in front of the glazed areas. All of these would form part of the original thickness of the façade. Other technical devices could be incorporated, such as solar collections, photovoltaic panels, large format screens for transmitting information and even plant modules.

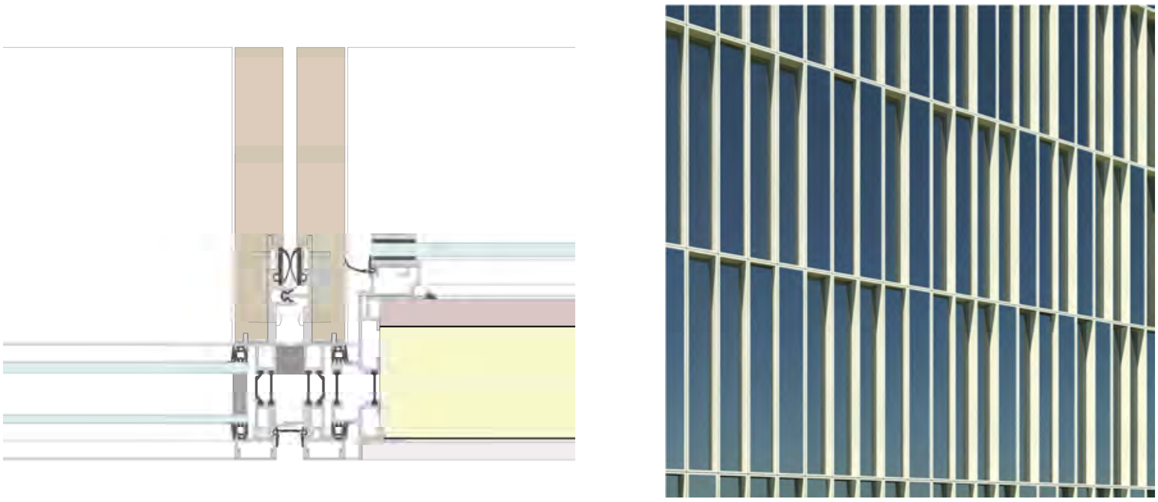


Figure 2: Detailed view of a horizontal cross-section and view in perspective of a possible architectural configuration of the entire FB720 façade system

## 2.3 Materials and Components

Three basic strategies were proposed to effectively reduce the environmental impact associated with the materials used in the façade system:

- Reduce the dimensions, by optimizing the aluminium frames.
- Use a high percentage of recycled materials in the aluminium frames.
- Design mixed components that enable the incorporation of alternative materials with less environmental impact.

The aim was to develop an alternative lightweight façade system that reduces the excessive reliance on the use of materials with a high environmental impact (aluminium, steel, polymers, etc.) and promotes the use of local materials that are renewable or recycled and industrial. The proposed substructure is made up of a framework with a small cross-section of aluminium bars that have a high proportion of accredited recycled material. These provide the basic specifications for assembly, mechanical work, water- and air-tightness. The load-bearing capacity is complemented by additional reinforcements that have no other purpose than to provide strength. Consequently, a wide-range of alternative materials can be used that are more environmentally friendly. Among those that have been tested are laminated wood, “technological wood” (composed of wood and plastic residues), recycled PVC and UHPC (ultra-high performance concrete that is reinforced with fibers).

Likewise, alternative materials can be incorporated into the infill panels in opaque modules to reduce the environmental impact. Examples of materials include: composites of natural fibres (sheep's wool, cotton), sheets of recycled textile waste, boards comprised of reused waste from carpets and laminated plasterboards containing recycled paper fibres. This range of alternative materials means that the FB720 construction system can be adapted to the financial, cultural and industrial context of each building design. Therefore, it is not a "closed" solution, but an approach that is open to the opportunities that arise in each case.

Figure 3: Photographs showing views of the various alternative materials tested

## 2.4 Variable Solar Protection Glass

To complement the basic solar protection system that takes advantage of the façade's own shadow, a new kind of glazing has been developed. This was designed to improve passive solar protection and has specifications that vary depending on the angle of incidence of the sun's rays. A design that is specifically adapted to the orientation of each façade and the latitude of each building can be obtained by combining several sheets of laminated glass with various superimposed layers of reflective, semi-transparent metal coatings. The special geometry of this glazing means that solar protection values are different in summer and winter, thus reducing the contribution from the sun's rays in the hot months and increasing it during the cold period.

Unlike other products with similar specifications, the treatment applied to the glass can be customized and adapted precisely to each case and specific orientation of the façade. Thus, areas with greater visibility and different degrees of transparency can be incorporated into the same unit of glass. The formal result is a window of glass with a variable degree of reflection and transparency according to the interior and exterior environmental conditions in each case. As protection from the sun is incorporated in the glass itself, we eliminate the problems of durability and maintenance that are associated with standard elements of solar protection (blinds, awnings, slats, etc.). In addition, less material resources are needed to construct the façade. As this material is manufactured in the form of flat glass, it can be combined with other sheets of glass to provide, for example, units of insulating glazing with air chambers, low emissivity treatments or acoustic insulation. It can be used in any kind of wall or façade system

The solar protection values that are obtained depend on the final composition of the glass, the orientation of the façade, and the type of layer used in the treatment. For example, in the case of glass made up of an exterior sheet 4+4+3 mm with the variable protection treatment described above, an air chamber of 24 mm and a laminated interior sheet of 10 mm with a low emissivity treatment, the solar factor varies between 0.33 and 0.14 for incident angles of 25º and 72º respectively, which correspond to the incidence at midday (12 am) on the summer and winter solstices, with a south-facing façade at a latitude of 41º. This variable solar factor provides passive solar protection with seasonal differentiation, without requiring sophisticated operations to regulate it or depending on the uncertain management of the user. This leads to greater reliability in the final performance of the glazed wall, which is of particular interest in buildings with a high proportion of occasional users: for example, public buildings with administrative and residential uses.

# 3 Environmental Impact and References

## 3.1 Objective

Numerous variants of the FB720 façade can be constructed as a result of the combination of different materials, the types of glass, the proportion of transparent area and the distance between uprights. On the basis of a preliminary design created by the team of architects, the following questions were drawn up:

- Is it possible to carry out a summary LCA of different versions of the same development of a new curtain wall called FB720? The versions are based on different combinations of materials (exterior uprights, thermal insulation, interior walls, etc.), types of glass (clear, seasonal, low emissivity, etc.), proportions of the transparent part of the wall (75% and 37%) and separation between the axes of the uprights (60 cm and 120 cm), all for a 50-year life cycle.
- Which of the possible configurations of the FB720 façade leads to the greatest reduction in environmental impact?
- How does the LCA of the new FB720 façade compare with that of a standard modular curtain wall (MCW) and that of a standard traditional facade (TF)?

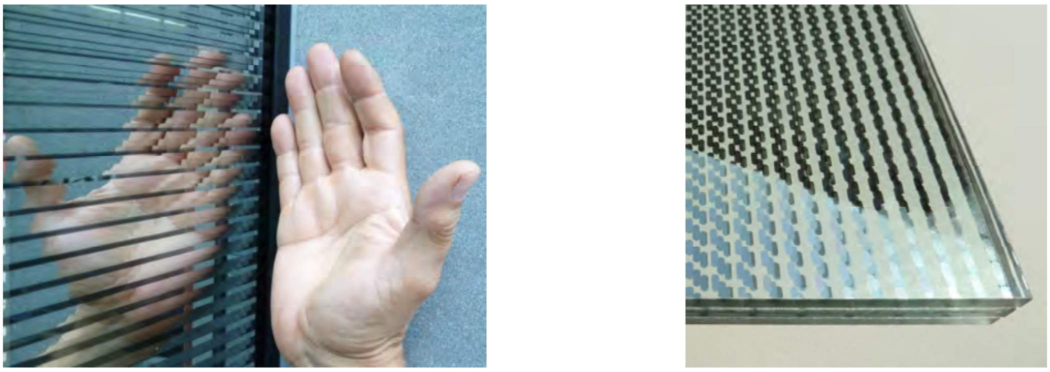
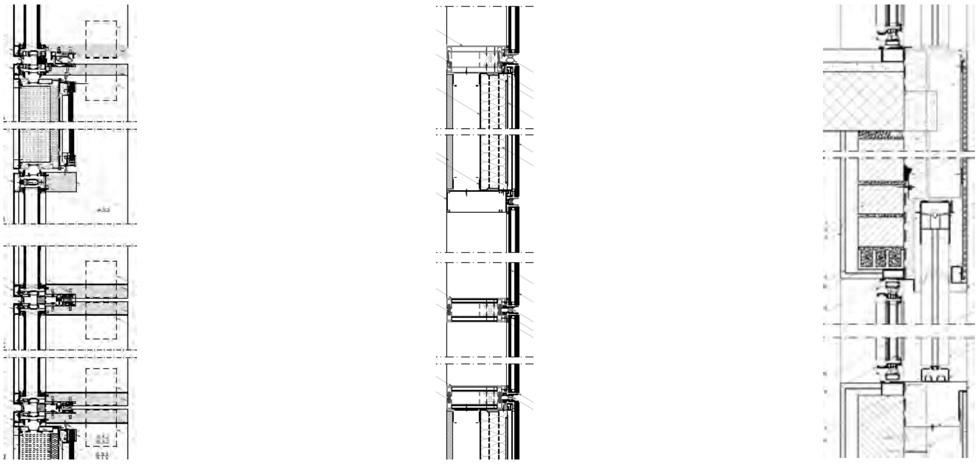


Figure 4: Photographs of the new glazing with variable solar protection

To answer these questions appropriately, an LCA advisory team was formed by the UPC's Architecture Technology and Innovation Laboratory (Laboratori d'innovació i Tecnología a l'Arquitectura, LiTA) and the Societat Orgànica consultancy company, which is made up of PhD graduates trained at the UPC. The environmental assessment that is presented here refers only to the environmental impacts of the cycle of materials during the useful life of the façade. The environmental analysis of the façade's thermal and light behaviour as the skin of the building was carried out by another technical team and is not described in this paper.



FB720 façade (ground plan) MCW (ground plan) TF (cross section)

Figure 5: Technical details of the different variants considered

## 3.2 Method

The method used in this case was a LCA with a shortened procedure, considering that the aim was to support the team in their decision making. The following considerations were taken into account:

- Functional unit: 1 m2 of façade, with a useful life of 50 years.
- Phases considered: production of materials [1], transport [2], construction [3], maintenance [4], demolition and final waste management [5].
- Impacts assessed: weight of materials [Kg/m2], energy consumption [MJ/m2], and CO2 emissions [KgCO2/m2]. In some phases, the following parameters were also included: solid waste [kg/m2], recycled or renewable material at the beginning of the life cycle [Kg/kg], recyclable or compostable material at the end of the life cycle [kg/kg] and environmental toxicity [ECA Kg/Kg].
- Assumptions and limits of the shortened procedure: phase [1] of the LCA summary includes all the operations of extraction and transport of raw materials to the factory where the building materials are manufactured. Transport from these factories to the curtain wall workshops, the manufacture of the walls and assembly of components are also assessed. The material intensity per service unit (MIPS) is excluded. In [2], the use of fuel in the modes of transport is included. The life cycle of vehicles and infrastructures is excluded. In [3], the energy consumption (electricity, diesel, etc.) of machinery is assessed. The energy costs of human activities and the depreciation of production tools are not taken into account. In [4], maintenance operations, partial and total replacement within 50 years are included. Phase [5] includes dismantling of the wall until its component materials have been separated and management of non-recyclable waste
- Tools and bases: almost all of the calculations were carried out with the help of standard spread sheets, but without the use of expert programs. The materials databases that we consulted were BEDEC PR/PCT of the ITeC, ICE of the University of Bath, EMPA of the Swiss Consortium of Public Universities, ELCD of the European Union and, in some cases, ECOINVENT and IVAM. Calculations were carried out with the SIMAPRO program (obtained from the Sustainable Building Initiatives Centre [Centro de Iniciativas de la Edificación Sostenible] research project) or we used our own calculations to determine the specific weight, volume and density of the materials used in the various building solutions. With respect to the operations of transport and loading, as well as waste generation, we consulted the PR/PCT bank, as well as information provided by manufacturers, other studies, calculations and our own estimations.

To express energy consumption (in electric KWh or litres of diesel) as CO2 emissions, we used the conversion factors established in the Spanish energy certification processes. In the case of recycled or renewable and recyclable or compostable materials, we used our own calculations as well as information provided by manufacturers or others.

## 3.3 Results of the LCA Summary Procedure

The application of the environmental strategies for construction materials, defined in project FB720’s method for the design of façade variants, led to considerably lower environmental impacts over a 50-year life cycle than the lightweight façade itself and the reference façades MCW (standard modular façade) and TF (standard traditional façade). Although improvements were also observed in the solid residues indicator, the evaluation of energy and CO2 emissions indicators is more suitable for analysing the complete life cycle, as it takes into account all of the phases. The following environmental strategies were applied in relation to the construction materials:

- Reduce the amount of material per unit of service.
- Replace the materials and systems that have the greatest associated impact.
- Use recycled industrial materials or renewable natural materials.
- Increase the reuse (of materials and components).
- Minimize waste generation and manage waste so that it is recycled.
- Increase durability and decrease maintenance.
- Use local materials and techniques.

The following environmental improvements were obtained using these strategies:

- Extraction and manufacture of materials. The study confirmed that the use of natural materials with few additional industrial processes is the option that leads to the lowest environmental impact. However, some factors, such as the distance between uprights (the further apart the better) and the full/empty ratio (the higher the better) are also essential to achieving the best environmental results. The materials used in all of the FB720 versions that have the greatest environmental impact, even in the best design options and taking into account that the amounts employed are significantly lower than in conventional façades, continue to be aluminium (even when 100% recycled aluminium is used), glass and synthetic materials (joints, spacers between glass sheets, etc.).
- Transport. The raw materials or materials that are already incorporated into the façade modules are transported over considerable distances and may even travel part of a route more than once. Therefore, it is essential to consider the flows of materials resulting from the location of prefabricated façade workshops, materials suppliers and the building sites. Another extremely important aspect is to optimize the load capacity of the mode of transport. For example, lorries are not always at full capacity on journeys between the warehouse and the building site. Finally, we should consider using modes of transport that are more efficient than road transport, taking into account the ratio between kg transported/energy consumed. One option is rail transport.
- Construction. The differences in the impacts of prefabricated and in situ systems are most evident in this phase. This is due to the fact that many operations are brought together and made efficient in prefabricated systems. As a result, there is less use of machinery in the workshop and on the building site, less direct consumption of materials (which does not mean that the total materials requirement, counted from the extraction of raw materials, is also lower) and less waste generation. In addition, waste that is generated in the workshop is easier to classify and consequently a higher proportion can be recycled. However, packaging materials (which become waste as soon as they reach a building site) also represent a considerable fraction of the energy and emissions cost of construction systems: up to 30% and 20% of the total in prefabricated systems (FB720 and MCW) and in situ (TF) respectively.
- Maintenance. In this 50-year phase (35 initial years of maintenance and a second period of 15 years, once the first period has been completed and the walls replaced), the differences between the façade systems are again notable. In other phases, the ranges of impact values enable us to group the performance of the prefabricated façades FB720 and MCW together, and place the in situ TF in another group. However, in the maintenance phase, the order of environmental performance, from best to worst, is FB720, followed by TF and finally by MCW. There were considerable gaps between the values for the first and second positions (1.8 and 2.6 times greater impacts) and between the first and third positions (between 1.9 and 3.5 times greater impacts). This is mainly due to the completely different strategies for the materials in each of the prefabricated options: natural renewable materials and recycled industrial materials that are separable and recoverable in the case of FB720, and industrial materials, few of which are recycled, that often cannot be separated or recovered in the case of MCW. As a result, the replacement of the wall at 35 years in the second case has an impact equivalent to the construction of a curtain wall for the first time.
- Demolition/dismantling. There are variations in the mechanical work required in the operations of demolition and dismantling. It is much more intensive in the first case, due to the force of striking and breaking the façade as well as the additional equipment required to move machines, workers and waste. In addition, each one of the façade systems differs in the amount of waste that is generated at the end of its life cycle. The dismantling of façade FB720 enables the separation of reusable or recyclable materials, as this was one of its design premises. In contrast, the dismantling of façade MCW and the demolition of the TF façade do not enable resources to be recovered in the same way, as they were not designed for this. Therefore, the loading, transport and final waste management operations that are needed for these two façades make their environmental impact higher than that of FB720.

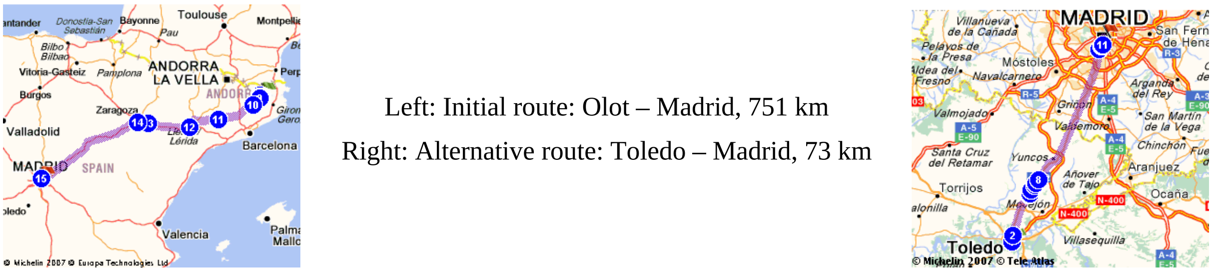
### 3.4 Sensitivity Analysis: Improvement Hypothesis

As part of the process of developing the FB720 façade project, various ways of reducing the environmental impact were studied for implementation in each phase of the life cycle. Some of these alternatives were not included in the final design for several reasons: the technical difficulties involved (for example, the introduction of new materials that would have required the development of different manufacturing molds to those already in use); financial concerns (for example, the redesign of a product and the process of manufacturing a standard building component would have been a major expense); or practical considerations (for example, the location of factories for manufacturing the materials or products and the location of the curtain wall workshop). Below, in the same order as the phases of the life cycle analysis, we present five alternatives to reduce environmental impact parameters (energy, CO2 emissions, materials, waste, etc.). The alternatives are assessed in a simplified way using an energy consumption indicator. Finally, we assess the impact of incorporating all of these alternatives into the FB720 system.

Figure 6: Technical details of the different improved versions considered

Extraction and manufacture of materials phase: the proposal was changing some of the 100% recycled aluminium frames for laminated wooden strips. The technical details were redefined (Fig. 6). We used as a hypothesis the A/II/37/120 configuration of the wall and proposed the replacement of up to 2.2 kg/m2 of aluminium with 3.07 kg/m2 of laminated wood. This resulted in a reduction in the energy used to produce the materials of 65 MJ/m2, compared to the original configuration. This represents 4.5% of the 1447.5 MJ/m2 of energy consumption of all the materials in the original configuration of this façade. This may appear to be a negligible energy saving, but it represents over 6 times the energy used in the construction and dismantling of the façade (between 11 and 12 MJ/m2).

Transport phase: the proposal was to situate the façade manufacture workshop as close as possible to the areas of large cities in which there is a potential demand for installing curtain walls in new buildings or in renovations. The aim of this measure is to reduce the fuel consumed by the lorries that travel between the factory and building sites. This would reduce the energy consumed and the associated CO2 emissions. We considered reducing the distances in the study (by moving the façade manufacture workshop from Olot, which is 750 km from the building site, to Madrid, where one of the hypothetical building sites is located). This is a reduction in the order of 10 to 1. In other words, the journey would be only 75 km if the manufacturing workshop was situated in Toledo and the building site in Madrid. The initial situation results in diesel consumption of 2.44 litres/m2 or 102.71 MJ/m2. If the journey from the workshop to the building site was 75 km instead of 751 km, the diesel consumption would be 0.74 litres/m2 or 31.31 MJ/m2. The energy reduction attained is 71.40 MJ m2, which is 69.5% of the total energy in the transport phase.



Left: Initial route: Olot – Madrid, 751 km

Right: Alternative route: Toledo – Madrid, 73 km

Figure 7: Planned route and proposed alternative route

Construction phase: the proposal was that the packaging materials should be reusable and 100% recyclable. The installation of the FB720 system hardly generates construction waste, as the building work only involves anchoring the wall to the structure of the building. Therefore, the main waste is the materials used to package the façade panels. These materials have two main impacts: during their production (extraction-manufacture) and their final management as waste (separation, loading, transport and final treatment). In terms of energy consumption, the production of the packaging materials that are used (mainly polythene, expanded polystyrene, wood and steel) represent 3.78 MJ/m2. The management of the waste generated by this disposable packaging has an energy impact of 0.51 MJ/m2. The energy saving brought about by employing a reusable, recyclable packaging system is estimated at 80% of this consumption, taking into account a minimum of five uses and complete recycling (which would avoid final waste management, but not the energy consumed loading and transport processes). Under the previous hypothesis, the energy consumption in this phase could be reduced to 0.78 MJ/m2.

Figure 8: Standard packaging procedures and the waste that is generated

Maintenance phase: the proposal was to increase the useful life of the entire façade from 35 to 50 years. In the initial hypothesis of this study and on the basis of existing market knowledge on the durability of curtain walls, we considered that almost the entire façade would need to be replaced at 35 years. This is the case of curtain walls constructed in the 1970s, whose main faults are a loss of water and air tightness due to the deterioration of joints, and little thermal insulation or solar protection. However, we still do not know the durability of recently manufactured curtain walls. They could be more durable if the flexible materials used in the joints are found to have a longer useful life. The total replacement of the FB720 façade (activities of removal, loading and transport, as well as identical operations for the new façade) represents an energy consumption of 442.91 MJ/m2 (if we assume that a certain proportion of materials are recovered and that only the part proportion to 15 years of useful life is affected, i.e. from year 35 to year 50 in this study). In contrast, if we manage to increase the useful life of the façade to 50 years (this durability is potentially attainable in all the materials except for the joints and the sealing chords) and resealing is planned at 15 years, which is taken into account in the calculation, and again at 30 years, the energy impact is just 0.027 MJ/m2 (taking into account the contribution of the sealing material and the additional construction equipment needed to apply this material up on the façade). Therefore, the energy saving could reach almost 100% of the impact of this phase.

Figure 9: Views of on-site usually procedures to replace sealing elements

Dismantling: the proposal was to redesign the glazed panels with air chambers in order to be completely disassembled and recycled. Currently, waste management is complex for various types of glass including glazing with air chambers, laminated glass, and printed, inked, coated and silk-screened glass. The composition and type of joints between the different types of glass that make up the panels are not reversible, which means that the original materials cannot be recovered in a state that enables them to be recycled in a technically and financially simple manner. Consequently, much of the glass that is used in construction is not recycled but downcycled (it is ground up and used as a component of lower quality compounds). The aim of the proposed measure is to avoid two environmental impacts: that due to downcycling (which could be avoided by dismantling and selective separation of the glass components) and that due to the production of new materials (which would be avoided if the existing glazing could be reused or recycled). Even when we take into account that most of the materials would be recovered to be reused or recycled, the environmental impact of disassembly in terms of energy is 10.99 MJ/m2. If we exclude the operations of disassembly, loading and transport to a recycling centre where the panels would be taken apart, the environmental impact that could be avoided with this measure is 0.15 MJ/m2 corresponding to waste management at a dump (the joints and the glass panels with an air chamber) and 0.25 MJ/m2 corresponding to transport from the site where the façade module is disassembled to the dump. In addition, up to 204.5 MJ/m2 would be saved due to the reuse of the glass (assuming 50% of the total is reused), as this would reduce the need to produce new material.

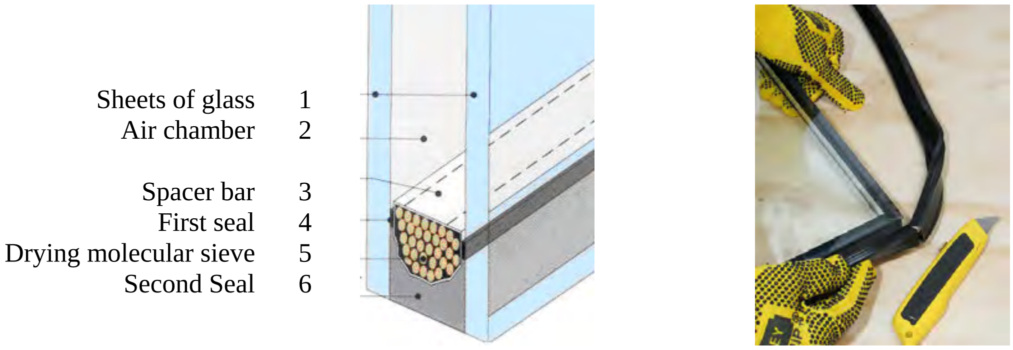


Figure 10: Detailed view of glazing with an air chamber and the process of removing a seal

Impact of the proposals to improve the life cycle: figure 11 shows the combined positive impacts of the different proposals to improve environmental performance, in absolute and relative terms (taking into account total energy consumption for the FB720 façade of 2,278.08 MJ/m2 throughout the entire life cycle).

| Improvement measure | Savings (MJ/m$^2$) | Percentage of total savings |
|---|---|---|
| 1. Replacement of aluminium frames with wood | 65.00 | 2.85 |
| 2. Façade workshop close to the building site (75 km) | 71.40 | 3.13 |
| 3. Reusable packaging and recyclable materials | 3.43 | 0.15 |
| 4. Useful life of the joints extended to 50 years | 442.91 | 19.44 |
| 5. Glass panels that can be totally disassembled | 204.90 | 8.99 |
| **Totals** | **787.64** | **34.57** |

Figure 11: Table of the combined positive impacts of the various improvements proposed, in absolute and relative terms

Although the degree of difficulty in implementing the various proposed improvement measures varies (relocating a façade manufacturing workshop is not as complicated as developing new packaging), there are sufficient opportunities to make improvements that have a positive impact. When these measures are combined, they could lead to savings of up to a third of the total initial energy.

Barcelona, December 2011

# Life Cycle Performance of Building Skins. LCA of Insulation Materials Comparing Passive Houses and Low Energy Houses

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## Summary

Several post-occupancy-evaluations of Passive Houses (PH) have been performed by BOKU Vienna in order to assess user satisfaction and real energy performance. This paper is based on these studies and investigates the environmental life cycle performance of PH compared with Low Energy Houses (LEH). Scenarios for the insulation thickness and for insulation materials have been calculated for the Viennese housing estate Mühlweg-C. The crucial research questions were: How much environmental benefit can actually be achieved by the PH standard? How much impact has the electrical energy consumption for mechanical ventilation? How much additional ecological effort is needed for the building skin in PH standard and when does it pay back? What are the effects of different insulation materials on the life cycle performance and payback time?

The results show about 10 % to 20 % environmental improvement by the PH standard compared to LEH standard. This concerns nonrenewable primary energy and greenhouse gas emissions for the whole life cycle of residential buildings. Mechanical ventilation systems improve the environmental performance (about 5 %) and also have further benefits e.g. higher indoor air quality. The additional ecological effort to produce, maintain and dispose PH-insulation is about 1 % for EPS-skins. But the environmental improvement for the whole life cycle is about 2 %. The environmental payback time for PH-skins with EPS is about 6 to 10 years compared with LEH-skins. Shorter payback times can be achieved by alternative insulation materials e.g. mineral wool, wood fiber or flax boards. Wood fiber insulation improves the environmental life cycle performance by about 5 %.

**Keywords:** Life Cycle Assessment, LCA, Passive House, Low Energy House, ETICS, insulation, Mühlweg

## 1 Introduction

Austria has the most useable living area in Passive House (PH) standard per resident worldwide and Vienna has the most PH-area in housing estates of all towns worldwide. The biggest PH (Roschégasse 20) was realized in Vienna and currently the biggest PH construction site – Eurogate – is located in Vienna. [1]

Until 2015 the PH-Standard as target value for all subsidized residential buildings in Austria is sought for. In 2008, 7 % of all new buildings in Austria were constructed in PH standard. The actual performance of PH was investigated by post-occupancy-evaluation and energy monitoring. Housing estates in Vienna (VIE) [1] and in the urban development project solarCity Linz-Pichling (SCP) [2] were analyzed. The energy monitoring covered 2665 apartments in total with 521 apartments (10 buildings) in PH-standard. The actual energy consumption of PH was compared to a selected group of housing estates of the same construction period (2003-2008). Many of the reference buildings already comply with the LEH-standard. The results indicated that the planned target values for space heating had been achieved. The target-actual-comparison based on measured energy consumption showed good matches in general for all housing estates. The consumption of useful energy was about on the same level as the calculated demand values for space heating considering an actual indoor air temperature of 23 °C and actual climate data. [1], [2], [4]

The PH standard saved about 30 kWh/(m².a) delivered energy on average compared with conventional housing estates of the same construction period [1]. Many of the conventional reference buildings already comply with LEH standard because of legal regulations for subsidized residential buildings.

Nevertheless, critical voices claim that PH might have a worse life cycle performance than LEH e.g. due to higher electrical energy consumption for the ventilation system or due to higher ecological effort for the production of the building skin. Therefore the main questions of this paper were:

- How much environmental benefit is actually achieved by PH compared to conventional residential complexes?
- Impact of different insulation materials and different insulation thickness of external thermal insulation composite systems (ETICS) on the life cycle performance?

# 1 Methodology

## 1.1 Life Cycle Assessment of Buildings and Building Materials

Building materials were investigated from cradle (raw materials extraction) to grave (dismantling and end-of-life assessment). The methodology of the BNB system “Assessment System for Sustainable Building” (BMVBS [6]) of the German federal ministry of transport, building and urban development has been applied. This methodology is mandatory for federal buildings in Germany and the life cycle assessment is consistent with the certification system of ÖGNI (Austrian sustainable building council) and DGNB (German sustainable building council) as well as with EN 15978 and EN 15804. According to this methodology a service life of 50 years is assumed for the assessment of residential buildings and maintenance is taken into account by default values for the service life of building materials.

The environmental impact was calculated with the database “Ökobau.dat 2009” [5] that is used for the BNB, ÖGNI and DGNB certification and is based on the database of PE International and on EPD datasets (environmental product declarations according to ISO 14025) verified by IBU (Institute Construction and Environment e. V., Königswinter). As functional unit or service unit 1 m² gross floor area with climatic conditioning according to OIB [3] was used. The conversion factors of the Austrian building directive [3] have been used and are listed in table 1.

Table 1: Conversion factors for primary energy and greenhouse gas emissions [3]

| Delivered energy | Nonrenewable primary energy kWh/kWh | $CO_2$ emissions* g/kWh |
|---|---|---|
| Electrical energy | 2.15 | 617 |
| Fossil gas | 1.17 | 236 |

* The OIB directive [3] for the calculation of the energy certificate of buildings uses $CO_2$-emissions instead of $CO_2$-equivalents as indicator for climate protection.

## 1.2 Description of Passive Housing Estate Mühlweg-C

The housing estate Mühlweg-C was completed in 2006 in Passive House standard with support of the impulse program “Building of Tomorrow” of bmvit (Federal Ministry for Transport, Innovation and Technology). The complex consists of four buildings with a mixed structure of massive timber and concrete. 70 residential units have been realized with an eligible useable living area of 6748 m².

Planning team:

- Developer: BAI Bauträger Austria Immobilien GmbH.
- Architect: Dietrich I Untertrifaller
- Building physics and PH consulting: IBO Austrian Institute for Healthy and Ecological Building (T. Zelger); Schöberl & Pöll

Area data:

- Address: 1210 Vienna, Fritz-Kandl-Gasse 1
- Gross floor area (GFA) with climatic conditioning: 8205 m²
- Opaque building skin: 7528 m²
- Surface-volume-ratio (A-V): 0.37 $m^{-1}$

Energy data:

- Energy supply with fossil gas and solar heat; space heat emission with mini-radiators
- Central ventilation unit with high efficient heat recovery for each building
- Useful energy demand for space heating: 10 kWh/(m².a) per gross floor area
- Thermal insulation: Mix of EPS, XPS, wood fiber, glass wool and rock wool. Insulation thickness is 25 cm – 32 cm for walls, 45 cm for roof and 35 cm for basement ceiling.
- Mean heat transfer coefficient of the building skin (Um): 0.24 W/(m².K)
- Windows: 31 % of outer walls area ; U-value 0.74 W/(m²K) with timber-aluminum frame
- Shading factors: North: 0.90; East/West: 0.53 – 0.77; South: 0.55

Figure 1: Passive Housing estate Mühlweg-C in Vienna. Photo: Bruno Klomfar, © BAI.

## 1.3 Description of Scenarios

The analysis of different building skins was done by scenarios of the Passive housing estate Mühlweg-C in Vienna (table 2 and table 3). The PH skin was compared with scenarios for LEH skins taking into account different insulation materials. LEH standard is defined in ÖNORM B 8110-1 with a limiting value for the useful energy demand for space heating. This value depends on the surface-volume-ratio of building skins and amounts 32.9 kWh/(m².a) for Mühlweg-C. The effects of scenarios on energy efficiency were calculated with the original energy calculation tool (PHPP Passive House Planning Package, Vers.2004) for Mühlweg-C. The savings of useful energy during building operation were converted to savings of fossil gas demand by means of a COP of 0.85.

For the comparison of different insulation materials the physical properties of table 4 have been taken into account to calculate the equivalent insulation thickness. For the comparison of different LCA-databases the datasets of table 4 and table 5 have been taken into account.

Table 2: Comparison of LEH skin with PH skin

| Major energetic differences | Optimization strategy | Analysis within this paper | Data sources for the analysis |
|---|---|---|---|
| 1. Thermal ventilation losses | Mechanical ventilation with heat recovery | Analysis of several PH-housing estates: Comparison with a scenario for window ventilation | Measuring of electrical energy consumption for ventilation. Calculation of thermal ventilation losses. |
| 2. Thermal transmission losses of windows | Triple glazed windows with heat protective coating and insulated frames | Production and disposal of different windows. Scenario for Mühlweg-C. | LCA-datasets of ECOINVENT 2.2 [7]<br>PHPP-Calculation. |
| 3. Thermal transmission losses of opaque building skin | Thermal insulation | Scenarios for Mühlweg-C. Comparison of different insulation materials | PHPP-Calculation<br>LCA-datasets of Ökobau.dat 2009 [5] |

Table 3: Investigated scenarios for less energy efficient building skin of housing estate Mühlweg-C.

| Scenario # | Scenario Title | Scenario Description | Useful heating demand * [kWh/(m²·a)] |
|---|---|---|---|
| 0 | Actual state | PH standard,<br>Uw = 0.75 W/(m².K); g = 0.51 | 10.0 |
| 1 | No ventilation | Without mechanical ventilation | 24.8 ** |
| 2 | LEH-windows | Uw = 1.1 W/(m².K); g = 0.62 | 13.3 |
| 3 | Standard windows | Uw = 1.3 W/(m².K); g = 0.62;<br>Close to legal limit | 16.0 |
| 4 | Less insulation | 15 cm less insulation | 15.4 |
| 5-a | LEH-1 | Without mechanical ventilation, LEH-windows, 13.2 cm less insulation | 32.9 ** |
| 5-b | LEH-2 | Without mechanical ventilation, standard windows, 6.2 cm less insulation | 32.9 ** |

* Useful energy demand for space heating per gross floor area was calculated with PHPP2004
** Additional reduction of electricity demand due to window ventilation: about 2.7 kWh/(m².a) [4]

Table 4: Physical properties of insulation materials and data sets for LCA

| Insulation material | Thermal conductivity [W/(m.K)] | Equivalent thickness [cm] | Density* [kg/m³] | LCA dataset for production [5] | LCA dataset for end-of-life [5]*** |
|---|---|---|---|---|---|
| Mühlweg | 0.0423 | 13.2 | - | - | - |
| EPS | 0.035 | 10.9 | 30 | “2.02 EPS PS 30”<br>Expanded polystyrene | „6.8 Verbrennung PS in MVA incl. Gutschrift“<br>TT with ecological credit |

Table 4 - continued: Physical properties of insulation materials and data sets for LCA

| Insulation material | Thermal conductivity [W/(m.K)] | Equivalent thickness [cm] | Density* [kg/m³] | LCA dataset for production [5] | LCA dataset for end-of-life [5]*** |
|---|---|---|---|---|---|
| Glass wool board | 0.035 | 10.9 | 50 | “2.01 Glaswolleplatte – ISOVER” | “9.5 Bauschutt-Deponierung”<br>Construction waste landfill |
| Rock wool board** | | | | „2.01 Steinwolleplatte – ISOVER“ | “9.5 Bauschutt-Deponierung”<br>Construction waste landfill |
| Wood fibre board | 0.045 | 14.0 | 150 | “2.10 Holzfaserdämmplatte (Nassverfahren)”<br>Wet processed | “2.22 EOL Holzfaserdämmplatte”<br>TT with ecological credit |
| Flax board | 0.040 | 12.5 | 25 | “2.12 Flachsvlies”<br>incl. 15 % polyester fibers | “3.4 EOL Holzwerkstoffe in MVA”<br>TT with ecological credit |
| Hemp board** | | | | “2.13 Hanfvlies”<br>incl. 15 % polyester fibers | “3.4 EOL Holzwerkstoffe in MVA”<br>TT with ecological credit |

* ON-V 31: Bauwesen 1 - Katalog für wärmeschutztechnische Rechenwerte von Baustoffen und Bauteilen.
** Insulation material used for comparison of LCA datasets
*** TT = Thermal treatment in waste incineration plant with cogenerated heat and power.

Table 5: LCA data sets of Ecoinvent and Baubook

| Insulation material | Ecoinvent [7] | Baubook [8] |
|---|---|---|
| EPS | Polystyrolplatte expandiert, ab Werk (ID DB 998);<br>EPS-Isolation flammgeschützt in Beseitigung (ID DB 2039) | Reference value, EPS, 30 kg/m³ |
| Glass wool | Glaswollematte, ab Werk (ID DB 995),<br>Mineralwolle in Beseitigung (ID DB 2023) | Reference value, glass wool, 68 kg/m³ |
| Rock wool | Steinwolle, verpackt (Flumroc 2009), ID DB n114a8 (combination of several Ecoinvent data sets)<br>Mineralwolle in Beseitigung (ID DB 2023) | Reference value, rock wool, 130 kg/m³ |
| Wood fibre board | ID DB n134a3: ID DB 2446, Industrierestholz (ID DB 2467)<br>Entsorgungsmix Faserplatte weich (n119a1) | Reference value, Holzfaserdämmplatte, 160 kg/m³ |
| Flax board | Not available in list of EMPA | Reference value, Flachs mit Polyestergitter, 30 kg/m³ |
| Hemp board | Not available in list of EMPA | Reference value, Hanfdämmplatte mit Stützfasern, 30 kg/m³ |

# 2 Results

## 2.1 Life Cycle Performance of Passive Housing Estate Mühlweg-C. Comparison of Actual State with Low Energy House Scenario

The following figure shows the impact of the scenarios on the useful energy demand for space heating. Scenario "No ventilation" seems to have the most impact with additional 15 kWh/(m².a) energy demand but the reduction of electrical energy for ventilation also has to be taken into account. The scenarios "Standard windows" and "15 cm less insulation" cause about the same effect: about 5 kWh/(m².a) additional energy demand. The combined scenario for LEH causes about 23 kWh/(m².a) additional useful energy demand for space heating corresponding with approximately 27 kWh/(m².a) additional delivered fossil gas.

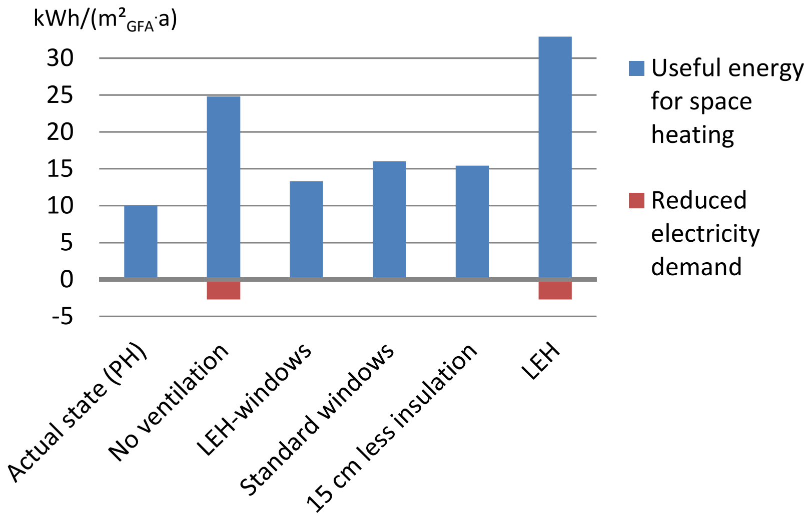

Figure 2: Passive House Mühlweg-C. Comparison of actual state with scenarios for less energy efficient building skin. Increase of useful energy for space heating and reduction of electricity demand due to window ventilation.

## 2.2 Impact of Opaque Building Skin on the Life Cycle Performance

The environmental impact of the opaque building skin of Mühlweg-C was compared with a scenario for a building skin meeting LEH standard (scenario 5a). The comparison was done for a time frame of 30 years, corresponding with useful life period for thermal insulation (figure 3).

The ecological profile shows the additional environmental burden for the production of the opaque PH skin (left side of the figure) and the environmental savings during building operation. The operation period was estimated with 30 years and landfill or thermal treatment was considered at end-of-life (buckling at right side of the figure).

The energy payback time for nonrenewable primary energy is about 5 to 11 years. The higher value applies for EPS and wood fiber, the lower value applies for flax boards and glass wool. Regarding the total balance for the whole life cycle, wood fiber insulation saves about 50 % more nonrenewable primary energy than the other three insulation materials, which are about on the same level.

The payback time for greenhouse gas emissions is about 0 to 7 years. The higher value applies for EPS and glass wool. Flax boards have a payback time of about 2 years and wood fiber already starts with a greenhouse gas credit caused by $CO_2$ storage during the growth of trees. Regarding the total balance for the whole life cycle, wood fiber insulation saves about the double amount of greenhouse gases during the whole life cycle than the other three insulation materials, which are about on the same level.

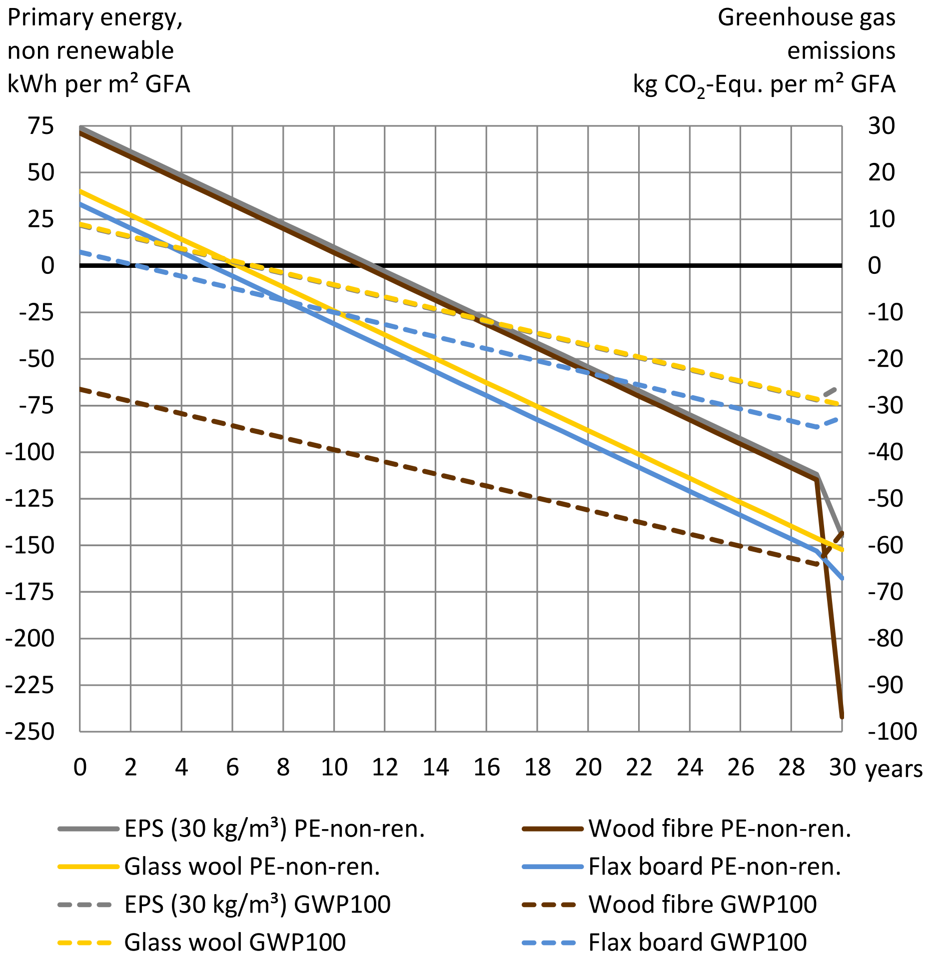

Figure 3: Ecological profile of insulation materials per square meter gross floor area. Comparison of opaque PH skin Mühlweg-C with LEH-skin scenario 5-a. Differences of nonrenewable primary energy demand and greenhouse gas emissions per gross floor area (GFA) for production, disposal and 30 years building operation.

## 2.3 Differences of LC-Databases

A sensitivity analysis was done for the assessment of insulation materials by comparing different databases with life cycle impact data for insulation materials. The data for production (cradle to gate analysis) and production combined with end of life processes were analyzed. Databases Ökobau.dat 2009 (ÖBD) [5], Ecoinvent 2.2 (ECOINV) [7] and Baubook [8] have been compared. Major differences of the methodology behind the databases are:

- Energy mix (electrical energy mix) for production and for environmental credits of thermal treatment with combined heat and power generation.
- Share of secondary raw materials: E.g. the share of waste glass for glass wool production is 65 % in Ecoinvent and 0 % in Ökobau.dat.
- $CO_2$ intake of biogenic material by photosynthesis: Considered in Ökobau.dat and Baubook
- Environmental credits at end of life:
  - Ökobau.dat includes environmental credits e.g. the end-of-life process for wood fiber boards is thermal waste treatment with combined heat and power generation that substitute electrical energy (German mix) and fossil gas.
  - Ecoinvent does not consider environmental credits. The recovery of energy by thermal waste treatment is considered within the process(es) for waste treatment and improves the energy mix.
  - Baubook does not include end of life processes

Generally there are considerable differences for all insulation materials and the range and ratio of impact data are varying for each material (figure 4):

- Glass wool: Nonrenewable primary energy demand is significantly lower in Ökobau.dat. Greenhouse gas emissions are lower in Ecoinvent. The impact of end-of-life processes is not noticeable.
- Rock wool: Nonrenewable primary energy demand and greenhouse gas emissions are lower in Ecoinvent. The impact of end-of-life processes is not noticeable.
- EPS: The values for production regarding nonrenewable primary energy demand are about on the same level and regarding greenhouse gas emissions the values of Ökobau.dat are lower. There are significant differences if end-of-life processes are integrated. The values of Ökobau.dat are nearly 50 % lower than those of Ecoinvent, which is caused by environmental credits for energetic recovery during thermal waste treatment.
- Wood fiber: The values for production can vary because of different additives and different production types (wet processing and dry processing). Nonrenewable primary energy demand for production is significantly higher in Baubook. $CO_2$ intake by photosynthesis cause negative values for greenhouse gas emissions in Ökobau.dat and Baubook. The environmental benefit is about 50 % lower in Baubook than in Ökobau.dat. Taking end-of-life processes into account, Ökobau.dat shows environmental benefits for nonrenewable primary energy and greenhouse gases, whereas Ecoinvent shows environmental burdens for both.
- Hemp and flax insulation boards: The values for production can vary because of different additives and different shares of synthetic fibers. No data exists in the Empa list [7]. The nonrenewable primary energy demand for production is about on the same level in Ökobau.dat and Baubook. Regarding greenhouse gas emissions the values of Baubook are significantly lower. Taking end-of-life processes into account, Ökobau.dat shows a drastic rise of greenhouse gas emissions and a slight reduction of nonrenewable energy demand.

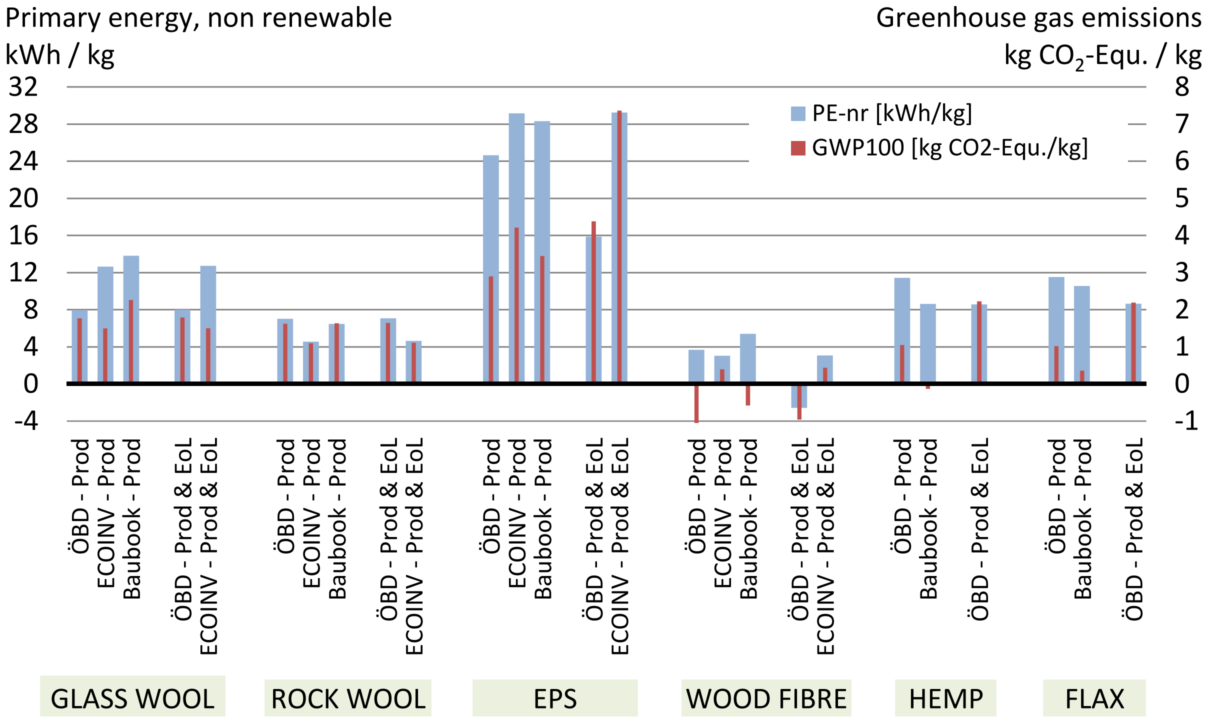

Figure 4: Comparison of databases: Ökobau.dat 2009 (ÖBD) [5], Ecoinvent 2.2 (ECOINV) [7] and Baubook [8]. Life cycle impact data for production (Prod) and end-of-life processes (EoL) of insulation materials.

### 2.4 Impact of Windows on the Life Cycle Performance

PH windows save about 3 kWh/(m².a) to 6 kWh/(m².a) useful energy for space heating compared with LEH-windows and compared with standard windows (see figure 2). Triple glazing with heat protective coating and insulated frames make the difference. The LCA for the production and disposal of windows shows no big difference between double glazed and triple glazed windows but big differences for different frame materials. Windows with aluminum frames need two times more nonrenewable primary energy and cause two times more greenhouse gas emissions than windows with timber frames. This is true for double glazed and triple glazed windows. The database Ecoinvent 2.2 [7] has been used for this comparison because there is more window specific data included than in ökobau.dat 2009. Yet it has to be taken into account, that the Ecoinvent data for window frames is related to a heat transfer coefficient of 1.5 to 1.6 W/(m².K). This value is insufficient for PH windows but has been used for the comparison. Because of the lack of data for PH window frames and the big variety of materials for qualified PH window frames the comparison is not further investigated here. Nevertheless it can be assumed, that the frame material has the most importance for the ecological impact (of window production and disposal). Since there are full solid timber frames with certification of PH-Institute Darmstadt available, this seems to be one of the best solutions regarding the environmental life cycle.

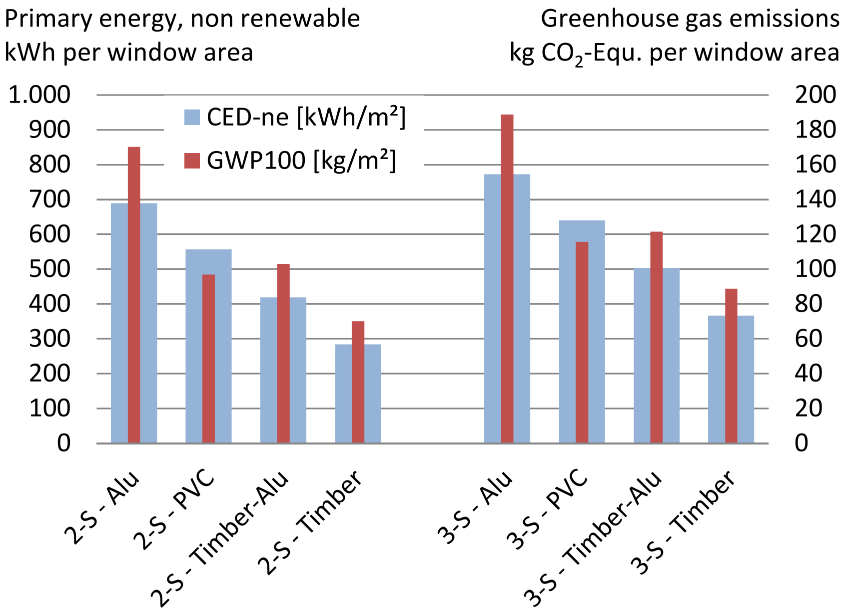

Figure 5: Life cycle assessment of production and disposal of windows based on ECOINVENT 2.2 [7]. Nonrenewable primary energy demand and greenhouse gas emissions per window area for double glazed (2-S) and triple glazed (3-S) windows with different frames.

## 3 Conclusions

The results show a significant environmental improvement by the PH standard compared to LEH standard. For the Passive housing estate Mühlweg-C about 26 kWh/($m^2_{GFA}$.a) nonrenewable primary energy and 5 kg/($m^2_{GFA}$.a) greenhouse gas emissions per gross floor area could be saved by a more energy efficient operation phase.

Mechanical ventilation cause significant environmental improvements for gas supplied buildings. The effect of space heating savings is much more important than the additional electrical energy demand for the ventilators. Additionally, there are other benefits e.g. a higher indoor air quality.

The building skin of Mühlweg-C was investigated separately for the opaque and transparent parts of the skin. The results for both parts indicated that the production, maintenance and disposal of the PH skin compared with the LEH skin can have a higher or a lower environmental impact depending on the material used for insulation and window frames.

Production, maintenance and disposal of the opaque building skin in PH standard caused additional 1 – 2 kWh/($m^2_{GFA}$.a) nonrenewable primary energy and additional 0.25 - 0.5 kg/($m^2_{GFA}$.a) greenhouse gas emissions per gross floor area, depending on the insulation material (EPS, glass wool or flax board). In case of insulation with wood fiber the PH skin would slightly improve the overall life cycle impact by 2 kWh/($m^2_{GFA}$.a) nonrenewable primary energy and 0.75 kg/($m^2_{GFA}$.a) greenhouse gas emissions.

The overall environmental life cycle performance for all insulation materials shows a positive environmental impact. The environmental payback time for PH-skins with EPS is about 6 to 10 years compared with LEH-skins. Shorter payback times can be achieved by alternative insulation materials e.g. mineral wool, wood fiber or flax boards.

Environmental impact data of different LCA-databases show significant differences for all investigated insulation materials. A major reason for these differences are different methodological approaches for environmental credits considering energy recovery at end-of-life and considering $CO_2$ intake by photosynthesis for biogenic materials. These environmental credits are not included in Ecoinvent data. Further reasons for varying impact values are different production processes, different additives and different electrical energy mixes.

Therefore the comparison of insulation materials can produce different results depending on the data source for environmental impacts. Taking the energy savings of the operation phase into account, the differences of LCA-databases shift the payback time for greenhouse gas emissions and nonrenewable primary energy by about 1 to 4 years for the investigated housing estate Mühlweg-C.

The transparent building skin in PH standard has a significant positive contribution for the operation phase of the building. There is a lack of LCA data for PH windows and big variety of suitable windows. Nevertheless, the results of the comparison of different windows show that the frame material has the most importance for the ecological impact (of window production and disposal) and full solid timber frames seem to be one of the best solutions regarding the environmental life cycle.

Regarding the impact on the overall environmental life cycle performance, data for a virtual reference housing estate of the same construction period was used [4]. The improvement by the operation phase amounts about 14 %. The additional ecological effort to produce, maintain and dispose PH-insulation is about 1 % for EPS-skins. But the environmental improvement for the whole life cycle is about 2 %. Wood fiber insulation improves the whole life cycle performance by about 5 %.

Regarding the total LCA of housing estates the differences of LCA-data for insulation materials cause a small but noticeable variation of the results. With data of Ecoinvent, the nonrenewable energy demand and greenhouse gas emissions are about 1 % higher in case of EPS insulation and about 3 % higher in case of wood fiber insulation. Nevertheless, the overall environmental life cycle performance for all insulation materials shows a positive impact and improves the total balance by about 1-2 %.

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# Predictable Sustainability? The Role of Building Certification in the Design of Innovative Facades

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## Summary

The papers provides an overview of current standardization work of CEN regarding sustainability of construction works as well as the role of building certification systems in the design of innovative façades. In the first part, the upcoming CEN standards are explained as well as the new Construction Products Regulation with its new Basic Requirement No. 7 – Sustainable use of natural resources. In the second part of the paper current international and national building certification systems are described. In the third part with a comparison of building certification systems regarding their relevance and completeness of assessment criteria for façades is undertaken. In the case of the Multifunctional Plug and Play Façade (MPPF) the design consequences for the development of innovative façades are explained and it is investigated the extent to which the assessment criteria used in building certification systems can be influence by façade design according to the MPPF design principles. In the last part of the paper it is explained how this might be integrated in the planning process to guarantee a better predictability of sustainability in the development of façades. Using a systematic approach could be one way in coping with the complexity of different requirements.

**Keywords:** Building Certification, Sustainability, Multifunctional Plug and Play Façade, Design consequences of innovative façades, LCA, LCCA, CPR

# 1 Introduction

## 1.1 Green and Sustainable Building

The construction sector has a great influence on sustainable development since it plays a key role in the consumption of energy and resources as well as in solid waste accumulation [1, 2]. It is therefore of high importance to quantify the environmental performance of buildings in order to communicate their potential environmental impacts. [3, 4, 5]

Assessment methods for sustainability have been developed since the early 1990s. The International Standardization Organization (ISO), for example, prepared the first standards to address specific issues and aspects of sustainability relevant to buildings and civil engineering works (e.g. ISO 21930[6]). Already these standards were based on the Life Cycle Assessment methodology (LCA) in ISO 14040 [7].

On the basis of the ISO work, the European Committee for Standardization is working on a set of standards to harmonize the methodology for a sustainability assessment of buildings using the life cycle approach. According to the upcoming European Standards [8, 9 ,10 ,11 ,12] the assessment of the environmental performance of buildings is based on LCA expressed with quantitative categories and Life Cycle Cost Assessment (LCCA).

In the past few years a growing number of building certification systems for green and/or sustainable buildings has been emerging in the market [13, 14, 15] parallel to standardization work to endorse green and sustainable buildings. As several building certification systems involve the assessment of the environmental and/or economic performance, these methodologies are definitely worthwhile looking at more closely [16, 17, 18].

A first evaluation of national and international building certification systems used in Austria shows that most of them do not include the assessment of the environmental performance with the use of LCA and the economic performance with the use of Life Cycle Cost Assessment (LCCA) explicitly and are currently not fully in line with the upcoming European framework of CEN/TC 350.

## 1.2 Goal and Scope

The aim of the present work is to compare current building certification systems used in Austria and to show how they implement the assessment of façade systems. Furthermore, the Multifunctional Plug and Play Façade (MPPF) is investigated to determine how many of the assessment criteria used in building certification systems can be influence by façade design.

In the conclusion and outlook we show how this might be integrated in the planning process to guarantee a better predictability of sustainability in the development of façades.

## 1.3 Integrated Performance of Buildings According to CEN/TC 350

The European Committee for Standardization (CEN/TC 350 - sustainability of construction works) has been assigned by the European Commission to provide a framework for the harmonization of the sustainable assessments of buildings.

In the framework document of CEN/TC350 EN 15643-1:2011[8], the goal is defined by supplying a common framework methodology which includes the principles, requirements and guidelines for a holistic assessment of the sustainability of buildings concerning their environmental, economic and social performance over the whole life cycle. The item to be assessed is the building including the site on the basis of user-requirements in terms of a so-called "functional equivalent". The standardization documents will not include regulations regarding evaluation, quality-levels, or classes (benchmarks).

It is generally assumed that most of the CEN/TC 350-sustainability-standards should be available by 2013. Figure 1 shows the concept of the integrated building performance that incorporates environmental, social and economic performance as well the technical and functional performance which are intrinsically related to each other.

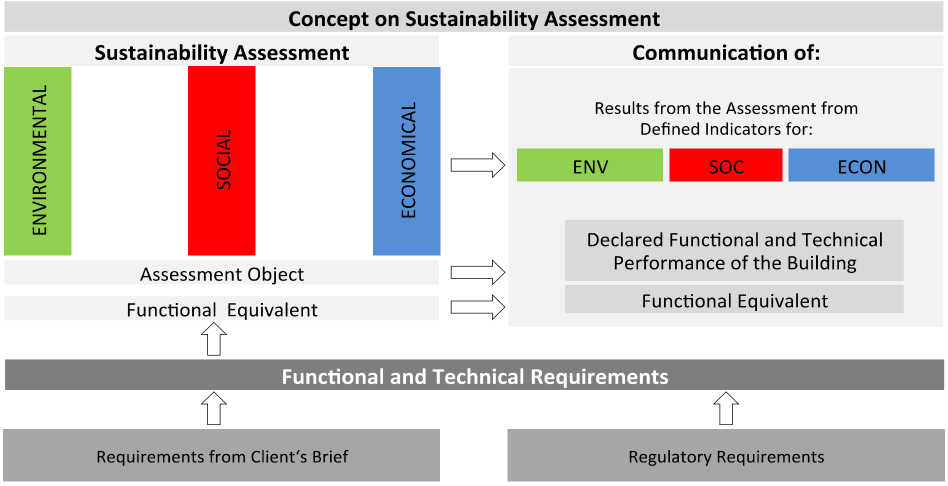

Figure 1: Concept of sustainability assessment of buildings [8]

### *1.3.1* Economic Performance of Buildings

The current point of view is that the assessment of the economic performance of buildings should be mainly based on performance expressed in terms of cost over the life cycle or in terms of financial value over the life-cycle. The economic performance primarily includes reduction in life cycle costs and the sustainable conservation of value/ increase in value of a building. In this way, ISO 15686-5 [20] differentiates between "whole life cost" and "life cycle cost". It is due to this that future assessments of buildings and, consequently, real estate valuations will have to enlarge their system boundaries compared to today's practice. Currently, only the initial costs (e.g. manufacturing costs) and sometimes the cost of operation without consideration of technical and functional aspects form the basis for these assessments. However, in future assessments the latter will probably be weighted more highly (e.g. energy efficiency). The inclusion of holistic assessments in real estate evaluations is hardly predictable.

### *1.3.2* Environmental Performance of Buildings

The scope of this working group is based on the description of applicable quantitative indicators. For this reason, LCA-methodology is used with data, preferably based on environmental product declarations (EPD´s) [10]. Additionally to CEN/TC 350 activities, the present Construction Products Directive (CPD) is currently being revised and enlarged with the basic requirement No. 7. (sustainable use of natural resources)[21,22]. Currently 22 indicators are being discussed regarding inclusion in LCA investigations [12].

### *1.3.3* Social Performance of Buildings

Looking at the latest discussion in working group 5 [19], the social performance measures will be represented through performance categories such as accessibility, health and comfort, loadings on the neighborhood, maintenance, safety / security, sourcing of materials and services and stakeholder involvement.

### *1.3.4* Functional and Technical Performance of Buildings

In Austria, the technical and functional performance in the context of sustainability assessments of buildings has not been specified yet. In contrast, the technical and functional requirements are defined in the Austrian OIB-guidelines 1-6 [23], which are largely in line with the essential requirements of the construction product directive [21,22]. A first definition of technical and functional performance is given below. Thus functional requirements are qualitative requirements used to describe a defined goal (e .g. demand on energy efficiency construction methods). The fulfillment of functional requirements is determined by the following different performance requirements (or technical requirements):

- Quantitative performance requirements (product-specific, construction-specific and building-specific) and descriptive/defining performance requirements
- The aggregation of the fulfillment of all described functional requirements as well as quantitative performance requirements and/or descriptive performance requirements leads to functional qualities and technical performance characteristics of a building, in accordance with the technical regulations e.g. [24].
- In other words, "functional quality" depicts the aggregation of the degree of fulfillment of the functional requirements. "Technical quality" reflects the degree of fulfillment of the aggregation of the individual technical requirements.

### 1.4 The Construction Products Regulation

The Construction Products Regulation (305/2011/EU - CPR[1]) – replacing the Construction Products Directive (89/106/EEC - CPD[2]) is laying down harmonised conditions for the marketing of construction products. The European Parliament and the Council of the European Union adopted the CPR on March 9th 2011. However, the main parts of its substantial articles will apply first from 1 July 2013. Until then, the CPD therefore remains in application. The already applicable parts of the CPR focus on the notification and designation processes of the Notified Bodies (NB) and the Technical Assessment Bodies (TAB). The CPR is to ensure reliable information on construction products in relation to their performances, which is achieved by providing a *common technical language*, offering uniform assessment methods of the performance of construction products. These methods have been compiled in harmonized European standards (hEN) and European Assessment Documents (EAD). This common technical language is to be applied by:

- the manufacturers when declaring the performance of their products, but also by
- the authorities of Member States when specifying requirements for them, and by
- their users (architects, engineers, constructors…) when choosing the products most suitable for their intended use in construction works.

One the major revisions concerns the basic requirement *hygiene, health and environment* and the addition of a new basic requirement (No. 7) *sustainable use of natural resources*.
This means that construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:

a) reuse or recyclability of the construction works, their materials and parts after demolition;
b) durability of the construction works;
c) use of environmentally compatible raw and secondary materials in the construction works.

How this will be implemented e.g. in an OIB-guideline is still under discussion [21].

## 2 Building Certification Systems

In the past few years, an increasing number of building certification systems have been placed on the market. Due to multi-characteristic influences in the context of sustainability assessments of buildings a complete evaluation criteria-structure is essential. A very large number of international building certification systems have existed since the 1990s. In the following, the two most common, LEED and BREAM, will be briefly described. In Austria, three national certification systems currently exist, DGNB/ÖGNI, klima:aktiv and ÖGNB (TQ-B). As regards assessment of buildings, these certification systems implement different approaches to environmental performance, e.g. completely or partly using LCA methodology. The differences between the three certification systems used in Austria are described below taking into account certifications on "new construction dwellings". Apart from already existing building certification system, reference is also made to the ongoing R&D European projects developed under the FP7 framework European as OPEN HOUSE[3] or SuPerBuilding[4].

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[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:088:0005:0043:EN:PDF

[2] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1989:040:0012:0026:EN:PDF

[3] OPEN HOUSE - Benchmarking and mainstreaming building sustainability in the EU based on transparency and openness (open source and availability) from model to implementation. http://www.openhouse-fp7.eu/

## 2.1 International Building Certification Systems

### *2.1.1* LEED

The Leadership in Energy and Environmental Design (LEED™) Green Building Rating System is a third-party certification program developed by the U.S. Green Building Council (USGBC) in 2000. Its latest version is LEED v2009. LEED is a point-based system for buildings of all types and sizes where building projects earn LEED points for satisfying specific green building criteria. The five categories include sustainable sites (SS), water efficiency (WE), energy and atmosphere (EA), materials and resources (MR) and indoor environmental quality (IEQ) and an additional category, innovation in design (ID) which addresses sustainable building expertise as well as design measures not covered under the five environmental categories.

According to [25], the USGBC is moving in a careful way to integrate life cycle information into the LEED framework. This means that LEED's implementation of LCA is partial in many ways (implicit). Each credit was evaluated against a list of 13 environmental impact categories, including climate change, indoor environmental quality, resource depletion and water intake, among many others [26].

Comparing it to other building certification systems, LCA aspects are not assessed in an explicit (transparent) way, i.e. an explicit LEED credit, to compare buildings using LCA benchmarks. As stated in [16] the LEED credits actually implemented are not always the most beneficial for the environment.

### *2.1.2* BREEAM

BRE Environmental Assessment Method (BREEAM) [27] is a voluntary design and assessment method for sustainable buildings that was established in the UK by the Building Research Establishment (BRE). It can be used to assess the environmental performance of any type of building. BREEAM uses an explicit weighting system derived from a combination of consensus-based weightings and ranking by a panel of experts within the categories: management, health & wellbeing, energy, transport, water, materials, waste, land use & ecology, pollution and innovation (additional).

In the materials group, the number of credits achieved for this BREEAM issue are based on a spreadsheet-based calculator for each applicable element’s Green Guide rating using the Ecopoint method. The Ecopoint used is a single score that measures the total environmental impact of a product or process as a proportion of overall impact occurring in Europe. Green Guide ratings are derived by sub-dividing the range of Ecopoints/m² achieved by all specifications considered within a building element and are based on LCA data generated using the BRE Environmental Profiles Methodology. These can, therefore, not be compared with the indicator values according to CEN or other building certification systems.

### *2.1.3* DGNB

The German Sustainable Building Council (DGNB) [28] together with the Federal Ministry of Transport, Building and Urban Affairs (BMVBS) developed a voluntary certification system for sustainable buildings in 2007. The building certification system of DGNB is based on the CEN/TC350 approach. The DGNB certification system criteria-set includes five weighted topics (main criteria groups): ecological quality (22.5%), economic quality (22.5%), social quality (22.5%), technical quality (22.5%), quality of process (10%) and one additionally not weighted, separately evaluated topic (main criteria group) quality of the location.

The assessment is based on a holistic life cycle approach considering the before-use phase, use phase and end-of-life phase with a reference study period of 50 years.

DGNB implemented an explicit LCA method [29]. The goal of the assessment is to quantify and document the environmental performance of the building under consideration (office building, retail, hospital, school, etc.) by means of applying LCA methodology and to compare the results with a defined benchmark.

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[4] SuPerBuilding - Sustainability and Performance assessment and Benchmarking of Buildings . http://cic.vtt.fi/superbuildings/node/2

### *2.1.4* SBTool

The SBTool[5] is based on the philosophy that a rating system must be adapted to local conditions before its results can become meaningful. The system is therefore designed as a generic framework, with local non-commercial organizations being expected to define local context conditions and to develop appropriate weights and benchmarks. The system has been designed to facilitate such a regional calibration; in fact, the system requires the insertion of regionally meaningful benchmarks.

SBTool covers a wide range of sustainable building issues, not just green building concerns, but the scope of the system can be modified to be as narrow or as broad as desired, ranging from 120 criteria to half a dozen;

The system allows third parties to establish parameter weights that reflect the varying importance of issues in the region, and to establish relevant benchmarks by occupancy type, in local languages. Thus, many versions can be developed in different regions that look quite different, while sharing a common methodology and set of terms. The main advantage, however, is that an SBTool version developed with local knowledge is likely to be much more relevant to local needs and values than other systems;

The system provides separate modules for Site and Building assessments, with Site assessments carried out in the Pre-design phase and Building assessments carried out in Design, Construction or Operations phases;

SBTool takes into account region-specific and site-specific context factors, and these are used to switch off or reduce certain weights, as well as providing background information for all parties. Weights for criteria that remain active are re-distributed, so that the total always remains 100%.

There is a capacity to carry out assessments at four distinct stages of the life-cycle and the system provides default benchmarks suited to each phase.

## 2.2 National Building Vertification Systems in Austria

### *2.2.1* Klima:aktiv (Building and Refurbishment)

The klima:aktiv building and refurbishment certification system for New Construction Office [30] is divided into four assessment categories according to a system of 1000 points. The categories are design and construction (Category A maximum 120 points), energy (Category B, maximum 600 points), building materials and construction (Category C, maximum 160 points) and comfort and indoor air quality (Category D, maximum 120 points).

Klima:aktiv assessment allows LCA to be carried out in two different ways. On the one hand, category C 2.1a (ecological benchmark of the whole building) and alternative category C 2.1b (ecological benchmark of building envelope). The assessment considers three environmental impact categories GWP, AP and PEI.n.e. (or CEDnr). For the final assessment these three environmental impact categories are aggregated into one ecological benchmark (OI 3).

In the first case, the assessment goes only partly in line with the CEN/TC 350 approach. The Use phase only focuses on environmental impacts. Due to the fact that the construction and maintenance processes are considered by the assessment, environmental impacts caused by energy demand during use phase are not included in the aggregated results. Environmental impacts are partly embedded in category B 2.2 (CO2 emissions) and B 2.3 (cumulative energy demand).

In the second case, due to time-related focus of the before use phase and the spatial-related focus of the building envelope as well as the declaration of environmental impacts in CO2-emissions, the environmental assessment concept does not correspond to the CEN/TC 350 concept, which is based on a holistic approach. The influence of neglecting spatial and/or time related aspects is shown in detail in [5].

At most, 100 points (or 10%) can be achieved by using case one, and 75 points can be reached by accomplishing LCA in case two. Taking into account the previously mentioned categories B 2.2 (125 points) and B 2.3 (125 points), a total of 350 points using case one, and 325 points using case two, can be achieved.

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[5] Overview of the SBTool assessment framework, Nils Larsson, iiSBE and Manuel Macias, UPM Spain, April 2012

### *2.2.2* ÖGNB (TQB)

The ÖGNB (Austrian Association of Sustainable Building) [31] certification system (also named TQB) is separated into five main categories behind a 1000 point system as in the klima:aktiv certification system. The main categories are quality of the location and infrastructure (Category A, maximum 200 points), economic and technical object quality (Category B, maximum 200 points), energy (Category C, maximum 200 points), health and comfort (Category D, maximum 200 points), materials and construction (Category E, maximum 200 points).

LCA is embedded in category E.3.1 ecology of materials and construction. In contrast to klima:aktiv, the environmental assessment is based on the new assessment concept which was developed during a national research project named "Nachhaltigkeit Massiv" [33] which allows focusing on the spatially related system boundaries of flexible assessment. The time-related system boundary chosen for ÖGNB-assessments for dwelling-types considers before-use, use and end-of-life-phase. Compared to case two assessments in klima:aktiv, the spatially related system boundaries have been enlarged. Next to the building envelope, finishes are also included, but the technical equipment is not included due to missing data-sets. Environmental impacts are assessed in a similar way to the klima:aktiv assessment system, thus it is also not in line with CEN/TC350. The reference study period is stated to be 100 years. At most, 60 points (or 6%) can be achieved with LCA within the sustainability assessment by ÖGNB certification system.

### *2.2.3* ÖGNI

The Austrian Green Building Council (ÖGNI) [34] was founded in 2009. Due to a cooperation agreement with the DGNB, signed in June 2009, a substantial basis for the operation of the council was established, and thus the German certification system for sustainable buildings (DGNB) has been successfully adapted to Austria. The DGNB/ÖGNI certification scheme criteria-set includes the same criteria as DGNB. Each of the main topics is divided into several assessment criteria. For instance, the Global Warming Potential, Total Primary Energy Demands and Proportion of Renewable Primary Energy, Thermal Comfort in Winter and Summer or Energetic and Moisture Proofing Quality of the Building’s Shell are considered for the evaluation of a building. For each criterion, measurable target values are defined, and a maximum of 10 points can be assigned. The measuring methods for each criterion are clearly defined. The certificate follows the concept of integral planning that defines the aims of sustainable construction with the related building performances at an early design stage. This means sustainable buildings can be designed which are based on the latest state of technology, and their performance can be communicated with the relevant criteria in the pre-certificate at the planning stage and in the certificate after completion. The consulting auditor accompanies the owners during the certification process and prepares an accompanying planning and construction documentation in accordance with the specifications of the documentation guidelines. Having completed the building, the auditor compares and checks the building specifications with the realized project.

Finally, DGNB/ÖGNI reviews the entire certification process and performs a conformity inspection based on the documentation guidelines, makes plausibility checks and takes control samples, and checks whether everything was executed properly according to the documentation. If all requirements are fulfilled, the owner receives a certificate. [35]

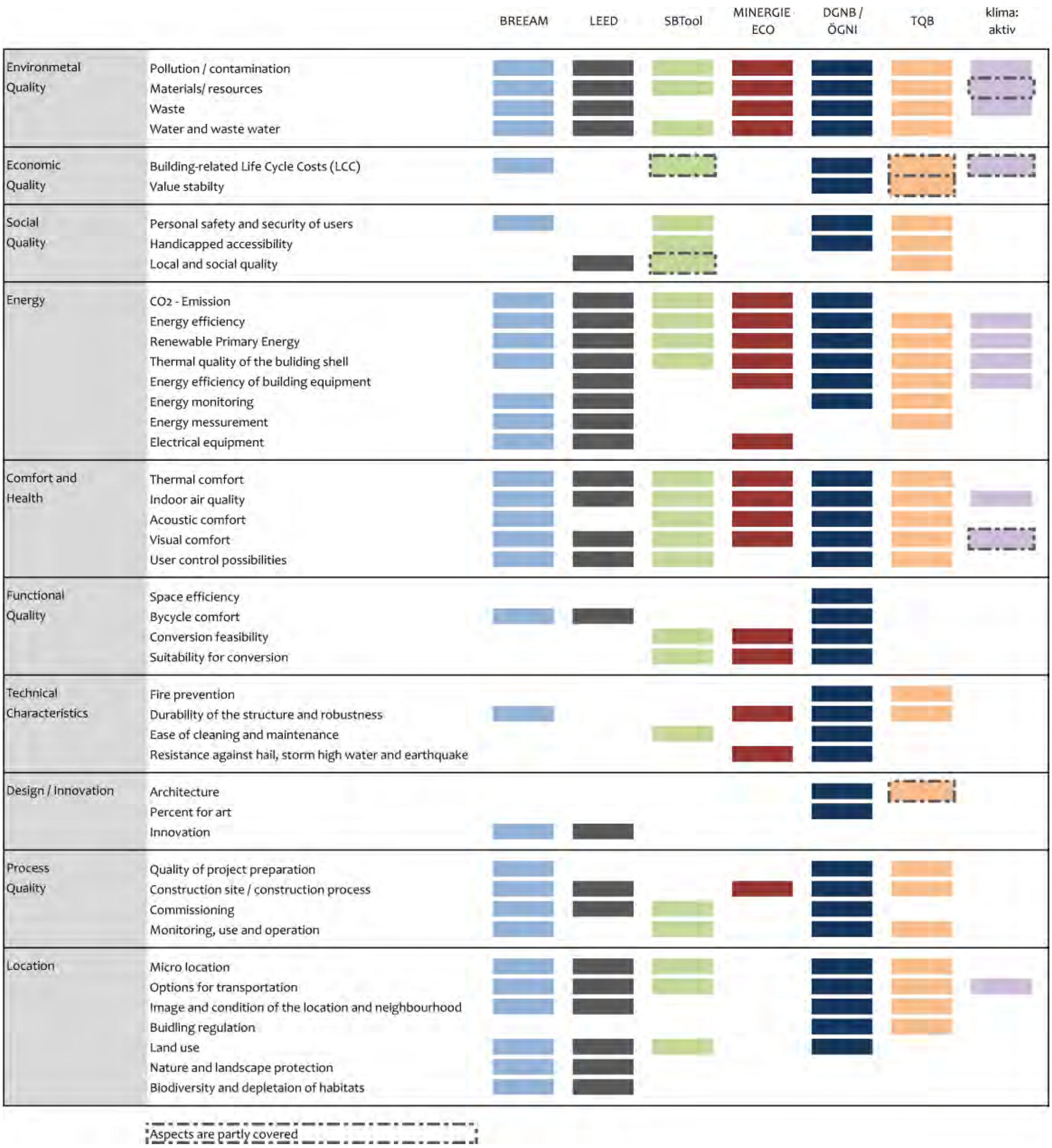
## 3 Design Consequences for the Development of Innovative Façades

There is no doubt about that the sustainability performance of buildings will play a major role in the future. But the question is, what are the difference between the various approaches and how they affect the design of façades.

Future design and construction of buildings concluding functional and technical requirements can be accomplished on the basis of the CEN/TC 350 framework going in line with the current essential requirement and future basis requirements of the construction product regulation [21]. This means the installation of suitable building products that include the interaction between products, construction and building that fulfills the product-, construction-, and building requirements supplemented with descriptive/defining performance requirements. Anyway, the fulfillment of requirements 1 to 6 is the primary assumption for sustainability assessments according to future basic requirement No. 7. However most of the Architects and Engineers feel overstrained with the multiplicity of requirements.

## 3.1 Comparison of Building Certification Systems and Assessment Criteria

Therefore at first in the following Figure 2 a comprehensive comparison of the different assessment criteria in the mentioned building certification system is pictured. It can be seen that the various building certification system have both similarities and differences. Due to the fact that in the DGNB/ÖGNI building certification system most of the technical and functional performance criteria are considered, this system is taken for the further investigations.



| | | BREEAM | LEED | SBTool | MINERGIE ECO | DGNB / ÖGNI | TQB | klima: aktiv |
|---|---|---|---|---|---|---|---|---|
| Environmental Quality | Pollution / contamination | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| | Materials/ resources | ■ | ■ | ■ | ■ | ■ | ■ | ⬚ |
| | Waste | ■ | ■ | | ■ | ■ | ■ | ■ |
| | Water and waste water | ■ | ■ | ■ | ■ | ■ | ■ | |
| Economic Quality | Building-related Life Cycle Costs (LCC) | ■ | | ⬚ | | ■ | ⬚ | ⬚ |
| | Value stabilty | | | | | ■ | ⬚ | |
| Social Quality | Personal safety and security of users | ■ | | ■ | | ■ | ■ | |
| | Handicapped accessibility | | | ■ | | ■ | ■ | |
| | Local and social quality | | ■ | ⬚ | | | ■ | |
| Energy | CO2 - Emission | ■ | ■ | ■ | ■ | ■ | | |
| | Energy efficiency | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| | Renewable Primary Energy | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| | Thermal quality of the bulding shell | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| | Energy efficiency of building equipment | | ■ | | ■ | ■ | ■ | ■ |
| | Energy monitoring | ■ | ■ | | | ■ | ■ | |
| | Energy messurement | ■ | ■ | | | | ■ | |
| | Electrical equipment | ■ | ■ | | ■ | | | |
| Comfort and Health | Thermal comfort | ■ | ■ | ■ | ■ | ■ | ■ | |
| | Indoor air quality | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| | Acoustic comfort | ■ | | ■ | ■ | ■ | ■ | |
| | Visual comfort | ■ | ■ | ■ | ■ | ■ | ■ | ⬚ |
| | User control possibilities | ■ | ■ | ■ | | ■ | ■ | |
| Functional Quality | Space efficiency | | | | | ■ | | |
| | Bycycle comfort | ■ | ■ | | | ■ | | |
| | Conversion feasibility | | | ■ | ■ | ■ | | |
| | Suitability for conversion | | | ■ | ■ | ■ | | |
| Technical Characteristics | Fire prevention | | | | | ■ | ■ | |
| | Durability of the structure and robustness | ■ | | | ■ | ■ | ■ | |
| | Ease of cleaning and maintenance | | | ■ | | ■ | | |
| | Resistance against hail, storm high water and earthquake | | | | ■ | ■ | | |
| Design / Innovation | Architecture | | | | | ■ | ⬚ | |
| | Percent for art | | | | | ■ | | |
| | Innovation | ■ | ■ | | | | | |
| Process Quality | Quality of project preparation | ■ | | | | ■ | ■ | |
| | Construction site / construction process | ■ | ■ | | ■ | ■ | ■ | |
| | Commissioning | ■ | ■ | ■ | | ■ | | |
| | Monitoring, use and operation | ■ | | ■ | | ■ | ■ | |
| Location | Micro location | ■ | ■ | ■ | | ■ | ■ | |
| | Options for transportation | ■ | ■ | ■ | | ■ | ■ | ■ |
| | Image and condition of the location and neighbourhood | ■ | ■ | | | ■ | ■ | |
| | Buidling regulation | | | | | ■ | ■ | |
| | Land use | ■ | ■ | ■ | | ■ | | |
| | Nature and landscape protection | ■ | ■ | | | | | |
| | Biodiversity and depletaion of habitats | ■ | ■ | | | | | |

⬚ Aspects are partly covered

Figure 2: Comparison of assessment criteria. Source: extended table [36], based on Fig. 04 [37] and Fig 4.12 [38]

## 3.2 Multifunctional Plug & Play Façade (MPPF)

In the last decades industrial prefabrication has been used mainly for building products and to some extend for building elements. The lack of technical knowledge and the lack of possibilities for individualization of components often lead therefore to a monotone design of elements and buildings.

Again the poor standard raised a poor sectorial image of prefabrication technology. Recently some things have changed to a better starting position. The rapid growth and availability of computer capacity to perform calculations and newest prefabrication technologies allow for the first time a combination of highly efficient prefabrication technologies with design tools simultaneously allowing a high individualization of products i.e. façades. In practice, this leads to enormous time- and cost savings as well as following possibilities:

- Comprehensive high quality transdisciplinary integral planning
- Efficient high quality prefabrication
- Minimization of installation times with lower error rate
- Mass production of basic elements due to prefabrication
- Expanding design options due to a modular approach
- High potential for enhancement of sustainability performance

Due to this initial position the K-Project, “Multifunctional Plug & Play Façade” (acronym: MPPF), launched in 2008. The research project MPPF aims the development of a multifunctional façade system to be used in modular construction methods with the highest possible level of prefabrication. The approach lies in “the expansion of the functionality of these prefabricated façade elements with building engineering functions (like e.g. heat, cold input, air input, lighting, water, power and IT supply) as well as by solar energy technologies (solar thermal, PV)”[39]. Figure 3 shows the function modules (1-18) integrated in the first version of the MPPF test facade of the consortium’s leader FIBAG in Stallhofen, Styria.

Function modules in MPPF Protoype 1

01) opaque polycrystalline PV ceiling - south
02) opaque polycrystalline PV centre - south
03) opaque polycrystalline PV baseline - south
04) opaque polycrystalline PV ceiling - west
05) opaque polycrystalline PV centre - west
06) opaque polycrystalline PV baseline - west
07) amorphous semi-transparent (10%) PV - south
08) amorphous semi-transparent (20%) PV - south
09) daylight photovoltaics module (PTM) - south
10) Solar thermal ceiling module - south
11) Solar thermal centre module - south
12) Solar thermal baseline module - south
13) Solar thermal ceiling module - south
14) Solar thermal centre module - south
15) Solar thermal baseline module - south
16) HVAC module - west
17) HVAC electrochromic glazing - south
18) HVAC electrochromic glazing - west

Figure 3: Different function modules integrated in the test facade. Source [39]

## 3.3 MPPF Design Principles

Within the MPPF project a criteria list for requirements for a Multifunctional Plug & Play Façade was developed [40]. These requirements are based on following design principles [acc. to 41]:

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1. Adjustment of lifetime of structural components to estimated service life of the façade
2. Promoting of recyclability due to
   a. Simple disassembly
   b. Ease of dismantling and
   c. Recyclability of materials.
3. Components shall be
   a. Accessible,
   b. Verifiable,
   c. Repairable and
   d. Replaceable.
4. Reduced cleaning effort due to
   a. Accessibility of the surfaces and
   b. Material surfaces itself.
5. Reduction of transport related environmental impacts due to
   a. Optimization of transport routes (components to prefabrication site and building site),
   b. Optimization of truck capacity utilization (volume and mass goods) and
   c. Fuel-efficient and low-emission vehicles.
6. Requirement of documentation of the façade construction
   a. Materials and components,
   b. Maintenance and inspection schedule.
7. Development of a maintenance strategy
   a. Service schedule,
   b. Inspection plan,
   c. Replacement and improvement strategies
8. Use of components which guarantee following:
   a. Reduced primary energy and low impacts and
   b. Recycling materials or materials with high recycling content.
9. Reduction of the energy demand in the use phase due to
   a. Excellent thermal insulation properties of the façade and
   b. Special attention to technical connection details,
   c. Heat protection during the summer.

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In addition to these *MPPF design principles* it could also be shown [43] that the MPPFaçade guarantees best possibilities in terms of dismantling und recyclability. More than 84% of the used materials can be directly used for recycling, if a carefully planned recycling concept is implemented.

## 3.4 Design Influence

In addition to the above listed differences in the building certification systems a screening of the assessment criteria of the DGNB/ÖGNI certification system regarding the possible influence of the design of façade and the related assessment criteria was undertaken. Table 1 shows the criteria list with the maximum target achievement of each assessment criteria. The assessment criteria which can be influenced by the design of a MPPF façade are marked with an “x”.

Table 1: Assessment criteria related to façade design in the case of ÖGNI/DGNB [42]

| **Criteria** | **Description** | **Weighting** | **MPPF** |
|---|---|---|---|
| LCA[6] | Life Cycle Assessment | 13,5% | X |
| C6 | Risks to the local environment | 3,4% | X |
| C8 | Sustainable use of resources / wood | 1,1% | X |
| C14 | Drinking water demand and volume of waste water | 2,3% | |
| C15 | Space demand | 2,3% | |
| LCCA | Building related life-cycle costs | 13,5% | X |
| C17 | Suitability for third-party use | 9,0% | X |
| C18 | Thermal comfort in the winter | 1,6% | X |
| C19 | Thermal comfort in the summer | 2,4% | X |
| C20 | Interior air hygiene | 2,4% | X |
| C21 | Acoustic comfort | 0,8% | X |
| C22 | Visual comfort | 2,4% | X |
| C23 | User control possibilities | 1,6% | X |
| C24 | Quality of outdoor spaces | 0,8% | |
| C25 | Safety and risk of hazardous incidents | 0,8% | X |
| C26 | Handicapped accessibility | 1,6% | |
| C27 | Space efficiency | 0,8% | X |
| C28 | Suitability for conversion | 1,6% | X |
| C29 | Public access | 1,6% | |
| C30 | Bicycling convenience | 0,8% | |
| C31 | Assurance of design and urban development quality in a competition | 2,4% | |
| C32 | Percent for art | 0,8% | |
| C33 | Fire prevention | 4,5% | X |
| C34 | Sound insulation | 4,5% | X |
| C35 | Quality of building envelope with regard to heat and humidity | 4,5% | X |
| C40 | Ease of cleaning and maintenance | 4,5% | X |
| C42 | Ease of dismantling and recycling | 4,5% | X |
| C43 | Quality of project preparation | 1,3% | |
| C44 | Integral planning | 1,3% | X |
| C45 | Optimization and complexity of planning method | 1,3% | X |
| C46 | Evidence of sustainable aspects in call for and awarding of tenders | 0,9% | X |
| C47 | Creation of conditions for optimal use and management | 0,9% | X |
| C48 | Construction site / construction process | 0,9% | |
| C49 | Quality of contractors / prequalification | 0,9% | X |
| C50 | Quality assurance for construction | 1,3% | |
| C51 | Commissioning | 1,3% | X |
| | ***Sum*** | ***100%*** | ***84,0%*** |

In total 31 out of 43 assessment criteria can be possible influenced by different design options of the façade, which means that up to 84 percent of the assessment performance respectively. The big influence is due to the reason that the MPPF project aims the expansion of the functionality of these prefabricated façade elements with building engineering functions as well as by solar energy technologies. This means that the design process of the MPPFaçade has a very big influence on the overall sustainability performance of a building.

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[6] The assessment criteria for LCA (01, 02, 03, 04, 05,10 and 11) are listed as one "LCA".

### 3.5 Conclusions & Outlook

The demand on buildings, which allow the enhancement of the principles of a sustainable development, will gain more and more importance in the private as well as the public sector. This trend is based not only on marketing demands but also due to the need of better life cycle performance. One of the instruments in proofing the performance is building certification, which includes aspects as e.g. LCA and LCCA as well as user comfort (as part of the functional performance) or technical aspects.

For the design of façades this results in increased requirements. This means not only the development of "innovative" building products or elements but also in the "active" provision of adequate product information i.e. EPDs (Environmental Products Declarations) as well as the optimization of processes through out the value chain. Major trend is the assessment of the whole building where every part / component must ensure its contribution to the overall building performance.

For the MPPF project it could be shown that the design of the Façade has a big influence on building certification results. Additionally the upcoming requirements i.e. sustainable use of natural ressources by the CPR or the assessment critrion "ease of dismantling and recycling" can only be fulfilled by a design process, which considers all these aspects and by façade systems, which integrate building engineering functions as well as solar energy technologies. Prefabrication technology makes it feasible to predict the performance of the façade.

Due to the fact that the façade influences many of the assessment criteria, at least in the case of ÖGNI/DGNB, it is crucial to take a closer look on the assessment criteria and the required performance to gain a better (predictable) result for the whole building, when it is completed (and certified). This means the optimization of the energy performance as well as the optimization of the material choice in the construction (e.g. in terms of LCA or risks to the local environment), functional or technical assessment criteria.

One should bear in mind that the improvement of building performance is a non-linear approach as different assessment criteria influence each other (i.e. an interdependency of criteria) [36, 44]. Only by ensuring that already the design options are based on a holistic life cycle performance assessment, the demanding challenge of a holistic improvement of building performance can be reached in future[36]. Using a systematic approach could be one way in coping with the complexity of different requirements.

## 4 Acknowledgements

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The analysis described in chapter 3.1 is part of the PhD research of H. Kreiner [44] at Graz University of Technology with the working title Interdependency between LCCA and LCA in the assessment of buildings, supervised by P. Maydl and A. Passer, which is not yet appropriated.

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# Well Formed, Wrinkled, Rippled – Interesting Skins with New Materials

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## Summary

The skin of a building is the main architectural intend of a building. A skin becomes interesting if it has an unusual topography. This paper wants to show different types of modern building skins. To beam with joy can form a human face and can be an aim in a façade application.

Some samples of realized projects with a new material are presented in this paper. The basis is the knowledge about the material. Only with this knowledge it is possible to design appropriate for the material involved.

**Keywords:** New Material, Acrylic, Examples, Plexiglas

## 1 Introduction

A skin of human beings is very interesting. On one hand you have the total appearance. It is the first impression of your vis-à-vis. If you have the second look you can see more details of the person. For example some wrinkles, indicating a lot of fun and laughter of a person. In detail the skin is the biggest organ of the body. This organ is responsible for the climate, protection etc. in total it is very important for the well-being of the whole person.

The building skins are the counterpart in a whole building. The skin is the main architectural afford of a building. It becomes interesting if it has an unusual topography. The following examples want to give an impression of the possibilities in facades.

At the façade of the fashion label Reiss in London the Architects wanted to have translucence at daylight and an interesting lighting at night. The idea was realized with a milled plastic material. The milled surfaces give different impressions. They are milled structured, satiniced and transparent to have a lined façade like a barcode.

The second example I will discuss is the liquid wall in Berlin. Due to polished surfaces in a convex and concave way, the look through the sheets of the flagship store of Raab Karcher is similar to the look into water.

The third example is the shin of the friendly alien of Graz, the Kunsthaus Graz. In the middle of the old town of Graz the city decided to build one of the most modern facades. The art gallery itself is surely a piece of art. At night a special translucence let it be a multi media façade.

Those examples want to explain an idea of a skin and its transformation into reality.

## 2 Material PMMA

Polymethyl methacrylate, PMMA for short, is the chemical name of a highly transparent plastic. Brand names for it are Plexiglas® or Acrylite® for example. PMMA belongs to the group of transparent thermoplastics and stands out due to good weathering resistance and a relative hard surface as well as its transparency. For sheet material there are mainly two manufacturing processes, extrusion and cast.

The material characteristics are dependent on the type of manufacturing and the environmental influences such as temperature and exposure time. The most important material characteristics under standard climate conditions according to DIN 7823 are summarized in Table 1.

Table 1: Material characteristics according to DIN 7823

| | Extruded PMMA | Cast PMMA | Unit |
|---|---|---|---|
| Young´s Modulus | ≥ 2900 | ≥ 3000 | MPa |
| Tensile Strength | ≥ 60 | ≥ 70 | MPa |
| Tensile Strain | ≥ 2 | ≥ 4 | % |
| Flexural Strength | 100-115 | 100-115 | MPa |
| Density | 1,19 | 1,19 | g/cm$^3$ |
| Thermal Expansion Coefficient | 7 x $10^{-5}$ | 7 x $10^{-5}$ | 1/K |

In Figure 1 the dependence that Young’s Modulus has with the temperature is shown. At 23°C you can see a young´s modulus of 3300 MPa. At 60°C it drops down to 2500 MPa.

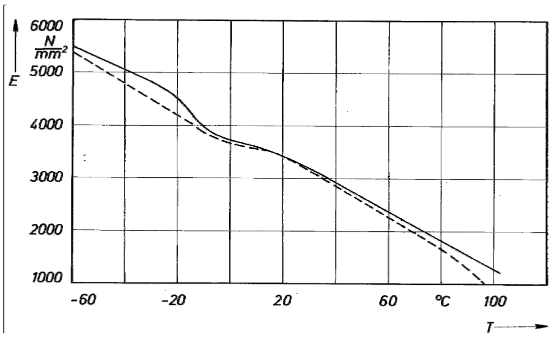

Figure 1: Temperature dependency of young´s modulus [Evonik Industries]

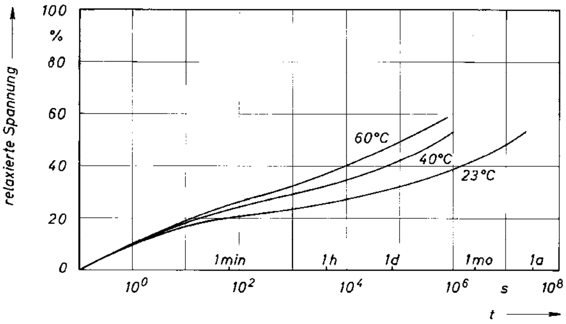

Figure 2: Relaxation [Evonik Industries]

The strain can be divided into three different parts. An energy elastic strain occurs immediately when a load is applied. The second part is an entropic elastic strain, with which the position of the molecule chains relative to one another is changed. This part of the strain is slowly reduced after the load is relieved. The third part is a viscous flow that represents an irreversible deformation. In Figure 2, the stress relaxation over the duration of the load is plotted. With a steady deformation, the stress is relaxed significantly over time. The relaxation is dependent on the level of stress that is applied. PMMA has a very high transmission, which results in the material heating up only a very small amount in the sun.

# 3 Examples

## 3.1 Reiss Façade, London

The fashion label Reiss built his new flagship store in the middle of London, GB. The facade of the store had to illustrate the brand philosophy into architecture.

The idea for the light transmitting facade with the machined Plexiglas® was born by the London architects Squire & Partner. The whole façade is routed with different structures in the surfaces. Those different structures give a linear impression. PLEXIGLAS® blocks in 50 mm thickness, vertically routed to different depths, were used to give the façade a three-dimensional effect.

Figure 3: Reiss Façade, London

The refraction of light caused by different routing patterns creates a constantly shifting play of light for the viewer, both outside and inside, depending on the lighting situation. At the same time, the heterogeneously machined surface provides pleasant light, without glare, which is especially important for the offices and workshops behind the façade. At night, individually controlled LED strips beneath the individual panels transform the façade into a translucent curtain of glistening light, and demonstrate the high light conductivity of the PLEXIGLAS® material.
The demand on the material was transparency combined with translucency, achieved with the possibility for machining PMMA. The applied material is a Plexiglas® with 50mm thickness, machined on a mill.

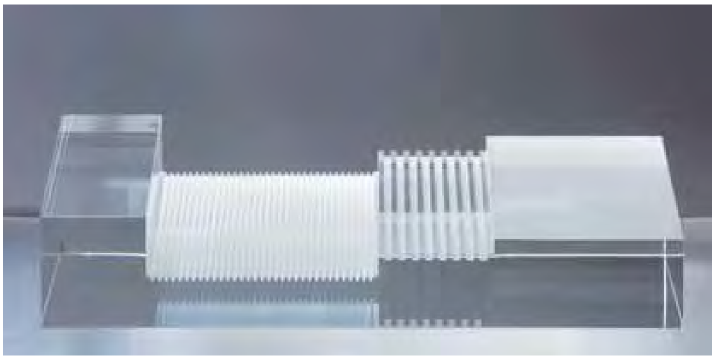

Figure 4: Routed sample

## 3.2 Raab Karcher Store, Berlin

The company Raab Karcher opened their first Flagshipstore “home couture” in the middle of Berlin 2004. In this showroom the newest flagging is displayed. The architect for the store was Bernhard Franken.

The basic design element for the store is the shop window with a deforming effect. A 50 mm Plexiglas block was milled, formed and polished to get convex and concave surfaces like a lense. This form has the effect of a moving room while passing the window and adjusts the view into a swimming pool.
To realize the effect it had to be possible to machine the material with a polishing option for the finish. At the end 50mm Plexiglas® were milled 3-dimensional and hand polished. The thickness of the material was important to have enough for the convex and concave form. Another important demand was the absolute weather resistance. Acrylic material is often used in glasses. Therefore it was nearby to use the same material in this object.

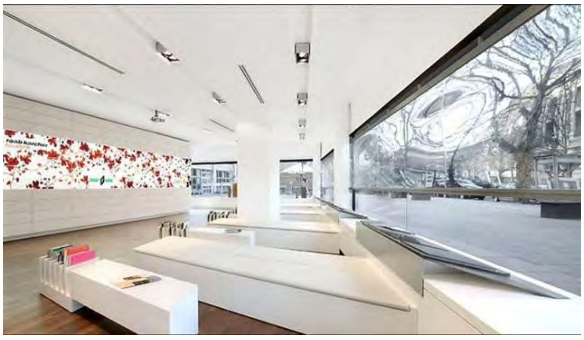

Figure 5: Raab Karcher Store, Berlin

### 3.3 Palacio de Congresos, Badajoz

The Conference Center of Badajoz, opened in 2006, is already considered one of Spain‘s most emblematic modern structures. Its designers and builders have thus put the city of 130,000 inhabitants firmly on the map of contemporary architectural sights worth seeing.

The conference center is hidden among the remains of an old fortress, the Baluarte de San Roque. From a distance, all that can be seen is a white cylinder poking out of the green fortress walls. This is a 16-meter-high tower whose entire outer surface is composed of a staggered arrangement of white tubes, forming ring upon ring. The tube structure provides glimpses of the orange and white corridors of the foyer. By contrast, PLEXIGLAS and other plastics used here are unlike to the subterranean conference rooms, according to architect José Selgas, for „lightness and emptiness, for the wind“.

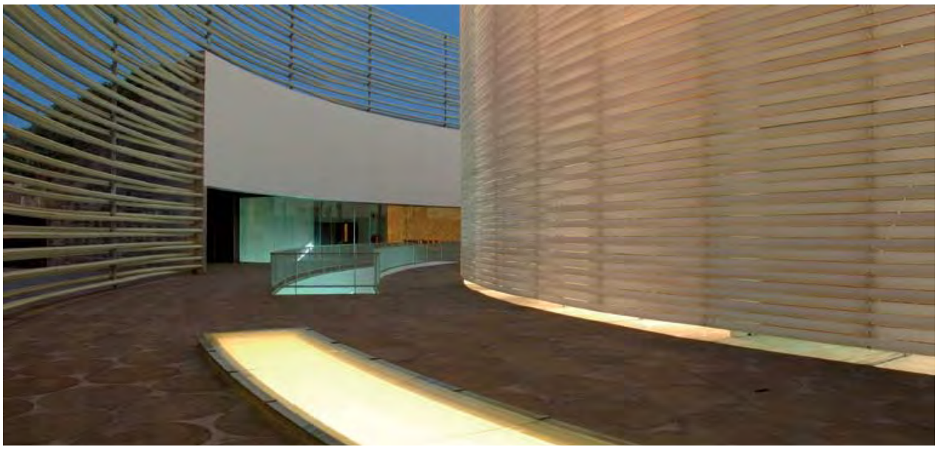

Figure 6: Palacio de Congresos, Badajoz

A special installation process was used to prevent the glowing outer shell from casting undesired shadows. The 4.39 m long white tubes were linked with each other by clear, 16 cm long ones. Specially developed silicone gaskets provide the requisite stability. The 4,248 white tubes and 4,104 connecting tubes were made from special colored, weather resistant material and thermoformed to the desired shape. The use of products with standard geometries, manufactured with specially adjusted properties in individual lengths for this project, makes a clear architectural statement. So does their simple modification by means of forming and their consciously spare, clean assembly.

### 3.4 Kunsthaus Graz

The terrifying scenario of an alien invasion is normally the stuff of science fiction novels. Not so in Graz, Austria, chosen as European Cultural Capital 2003. In that city, a friendly alien has landed, with a 3D formed outer skin.

Figure 7: Kunsthaus Graz

The Kunsthaus that opened in late September 2003 really does stand out from its environment like something from another planet. It took many years and many discussions to persuade the authorities to let the alien dock into the neighboring “Eisernes Haus” (cast-iron house), parts of which are listed as historical monuments. The structure concocted by Cook and Fournier was unanimously chosen as the winner from 102 entries in an architects’ competition announced throughout Europe. “Many people have thought about curved, organic buildings. But very few have actually built them,” says Colin Fournier.

Figure 8: Media facade

The 4800m² Plexiglas façade is also a Media façade. It can be illuminated at night by round light points. The material thickness is 20mm, every sheet is formed individually. The illumination of the façade and the formability were the main aspects to use Plexiglas®. Every sheet was formed in a different way. The ease of the forming process was essential to the material decision.

## 4 Summary and Outlook

With new materials like Plexiglas new forms of facades are possible. Especially with various demands the choice of the material becomes difficult and the performance of common material might be limited. Acylic material has advantages in the possibilities of machining and illuminating. The examples tried to show the possibilities in forming like the façade of the Kunsthaus Graz or in structuring like the Liquid wall or the Reiss façade. The possibilities are not totally used by now. Even in extreme applications like mega glazing of deep see aquariums or for the windows of deep going submarines the material is in use.

This paper tried to give an impression of the use of the material and want to inspire for new applications.

# Geometric Figures and Potential Component Families of Metal Sheets for the Use in Architecture

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## Summary

The usage of metal sheets in visible components of building exteriors has become an important tool in the repertoire of modern architecture. A drawback of such building envelopes is a requirement of a dedicated supporting structure underneath their surface. Load carrying sheet metal parts are well known in mechanical engineering. However, if confronted with aesthetic requirements their manufacturing process still poses a challenge to the principles of their manufacturing procedures. Within the Collaborative Research Centre 666 (CRC 666) a process chain is being developed, which allows the manufacturing of complexly curved sheet metal structures stiffened by rips. The rips are on one side of a sheet whereas a smooth surface with no visible joints is retained on the other side. The new possibilities in architectural design resulting from this technology are methodically investigated within the CRC 666. With provision to the limitations of a cost-efficient manufacturing possible shapes and their assembly to free formed surfaces are derived and analyzed.

**Keywords:** Metal sheet facades, metal forming, linear flow splitting, constructional and light facades, innovative technologies, plane load-bearing structures, building skins

## 1 Introduction

New possibilities in CAD (computer aided design) and CAM (computer aided manufacturing) allow a new exploitation of geometry in contemporary architecture. More complex shapes and volumes can be accomplished with these mathematical tools. Only a few years ago architects working with a CAD application were limited to the pre-set abilities of the available software. In more recent versions of CAD and CAM software tools such restrictions are eased. New CAD applications, such as ‘Rhinoceros’ with its plugin ‘Grasshopper’ allow creating more complex freeform shapes in digital designing. If the pre-programmed tools are not sufficient, the architect has the possibility to script the tools he may need. The feasibility of new designs is facilitated by new manufacturing methods based on CAM process chains. However currently we are restricted by certain limits. One problem of the new architect´s original language consists in the fact, that the shape-giving skin of buildings can be realized only by very costly and expensive substructures. The skin of the building itself is limited exclusively to the aesthetic qualities and fulfills no structural or structural-physical properties. Furthermore, the realization of these structures is still very expensive, which is due to two factors: first, production costs of the building´s skin, as this is usually made of a large amount of unique items. Second, recent dimension tolerances in the construction branch require a high degree of adaption on building sites. In the mechanical engineering industry these tolerances are only at a fraction of the construction tolerances existing in the building industry. The Collaborative Research Centre 666 'Integral Sheet Metal Design with Higher Order Bifurcations' at the Technische Universität Darmstadt can integrally produce innovative products from sheet metal. Using this method load-bearing and thin facade components become possible [1]. This new manufacturing process enables the serial production of components for the building industry with small tolerances. When using this new manufacturing process, it is very important to create modular component systems to realize the new freeform architecture with as few components as possible. One way to understand how freeform geometries can be modularized, is to decode how it works for rule geometries. On the basis of these findings, strategies can be developed how any freeform geometry can be modularized.

## 2 New Methods for Manufacturing Sheet Metal Building Skins

In mechanical engineering a common approach to lightweight design is to combine several functions into a single part. Modern car bodies for instance consist of complex sheet structures providing functions like load carriage, protection from environmental influences and visual appearance. A similar approach can be taken for applications in architecture by recombining the same three functions into elements of a building envelope.

Stiffness and stability of sheet surface structures are determined by their curvature, cross-section and material properties. Since material strength is limited and curvatures are given by the parts function or design requirements, an important way of improving stiffness and stability is to adapt the cross-section of sheets for instance by adding ribs or stringers.

In doing so an architect has to face two problems: If a differential design is used (sheets and stringers are created separately and then joined together afterwards) extensive joint operations are necessary leading to tight positioning tolerances during manufacturing [2] and ultimately to two unsmooth surfaces. On the one side there are the stringers and on the other there are visible joints (welding seams, rivets etc.). The use of state of the art integral design (sheet and stringers are created out of one piece of metal) results in costly and energy consuming manufacturing processes [3, 4].

Within the Collaborative Research Centre 666 – 'Integral Sheet Metal Design of higher Order Bifurcation' a new process chain is being developed, which allows a cost and energy efficient manufacturing of spatially curved metal sheets with integrally formed stiffeners on one side and a smooth surface on the other. This processes chain consists of bend splitting (linear flow splitting respectively) and hydroforming. As a side effect the splitting process induces a particular grain structure in the material, which significantly increases material strength.

### 2.1 Linear Flow Splitting and Bend Splitting

Linear flow splitting is a forming process for the mass production of bifurcated profiles [5, 6]. The produced parts are characterized by a web and two flanges in integral style (figure 1, right). The semi-finished product, a plane sheet metal strip, is provided in form of a coil. After uncoiling and trueing it is moved through a series of rolling stands as in a regular roll forming process. Within the existing production line roll forming processes, which bend the sheet metal strip with rotating rolls, and splitting processes are combined. The new process of linear flow splitting enables splitting the edges of the sheet metal strip. The splitting stands consist of two supporting rolls and two splitting rolls (figure 1, left). The supporting rolls fix the sheet vertically in the web area. The splitting rolls are positioned at the sheet edges. In each stand the web width is reduced by the splitting rolls, thus material of the web is displaced into the flanges. The whole process takes place at room temperature.

A number of linear flow splitting stands is arranged consecutively in order to form the flanges to the desired length. Ten stations have been used to form a plane sheet metal to the double Y-profile shown in figure 1. Linear flow split parts have been manufactured from micro-alloyed fine-grained steel of tensile strength up to 800 N/mm$^2$ without material failure to a total splitting depth of 20 mm per side [7]. Also standard steels like DD11 (StW22), stainless steel X6Cr17, Aluminium AlMg3, H480LA and other fine-grained steels have been split successfully.

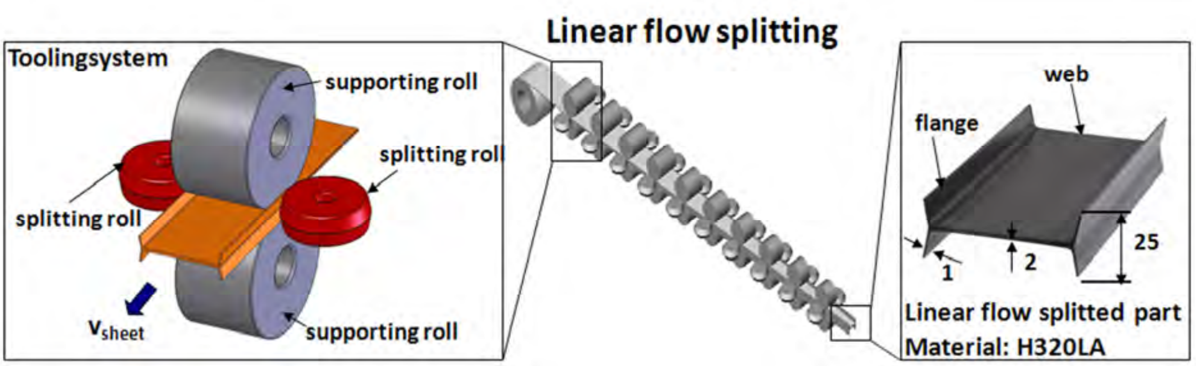


Figure 1: Tool arrangement (left) and manufactured prototype (right)

The linear flow splitting process is limited to the production of bifurcations originating from the bend edge. For the production of bifurcations at nearly any place in the sheet metal the new bulk forming process linear bend splitting was developed. The essential difference compared to linear flow splitting is the semi-finished part. For bend splitting the plane sheet metal strip first is formed for instance into a U-profile by a conventional roll forming process (figure 2). The splitting rolls then target the bending edges of the U-Profile. Thus it is possible to create a bifurcation in the place of the bended edge with the existing splitting stands. After the splitting process the parts can be processed by roll forming to a desired cross-section. Continuously produced parts are shown in figure 2. Especially stringers are in focus for the use in load carrying surface structures.

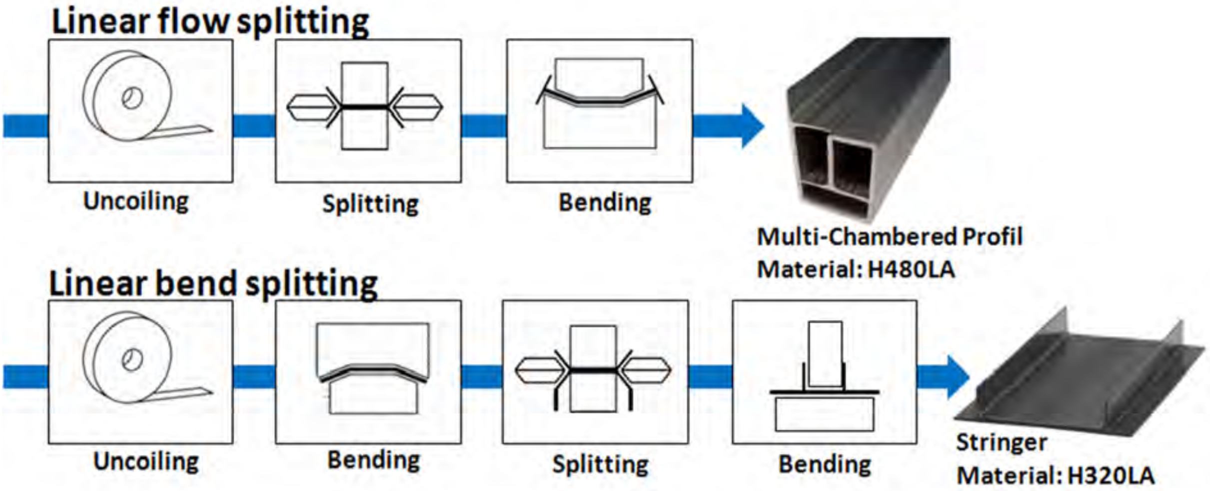


Figure 2: Process chain linear flow splitting (upper) and linear bend splitting (lower) with preprocessing by roll forming to different target geometries

The presented linear flow and linear bend splitting processes have a variety of benefits in comparison with other possible manufacturing processes. In general, profiles made of sheet metal with bifurcations (e.g. double T-profiles) have to be manufactured by lamination of sheet and entail a considerable amount of work for tool design. Also the lamination leads to greater amount of material, which has to be used. Furthermore the linear flow splitting process runs at ambient temperature. It is not necessary to preheat the semi-finished part like it is, if double T-Profiles are produced by hot rolling. The amount of energy needed is significantly less than producing by hot rolling. These advantages lead to considerable resource and energy savings. Another benefit of the process can be seen by looking at the resulting material properties. Because of the high natural strain in the deformed zone under superposed compressive stresses, the grain structure changes during the process [7]. An ultra-fine grained structure is obtained. The special characteristics of this grain structure are a good ductility and a concomitant high tensile strength. The tensile strength is raised by the process in comparison to the base material up to over 60% [8]. Again a better resource efficiency of this process can be claimed.

## 2.2 Deep Drawing of Blanks with bifurcated Cross-sections

A bend split metal strip can be cut into blanks at the end of a splitting line. These blanks serve as wrought material for a subsequent deep drawing process in which they are formed to their final spatially curved shape.

Deep drawing is a wide-spread and well known forming technology. It is used whenever sheet metal parts with complex geometries (e.g. car body parts) are to be manufactured in large numbers. The maximum size of deep drawn parts depends on the target geometry and the machinery used and varies from a few square millimeters to a few square meters.

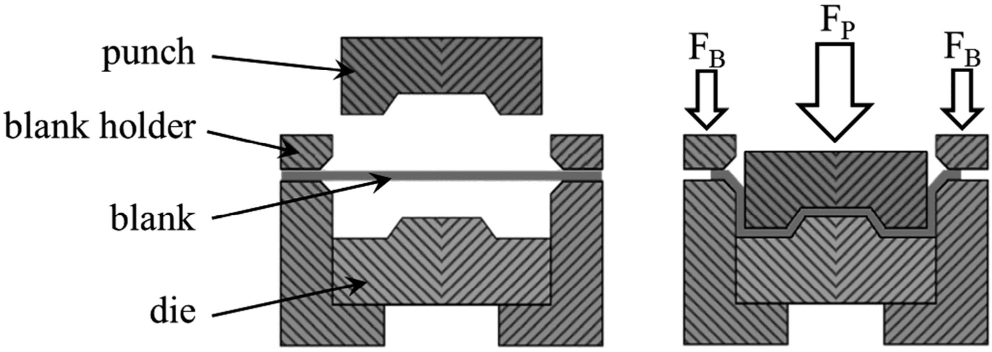


Figure 3: Deep drawing

A classical deep drawing tool consists of a punch, a die and a blank holder (see figure 3). The blank is positioned between the die and the punch, whose surfaces correspond to the target surfaces of the finished part. By closing the gap between punch and die their shape is reproduced in the work piece. The blank holder holds the blank in position. The adjustment of the blank holder force controls the material flow into the gap and is a key parameter of the deep drawing process. It influences the stress and strain distributions in the workpiece, the resulting sheet thickness at the end of the process and is also used to prevent wrinkling in regions of the work piece which are under compressive stress during the process.

Since within the context of deep drawing the term ‘flange’ is used for the outer regions of a workpiece (see figure 4) the flanges that result from the splitting process are referred to as ‘stringers’ from here on. Sheets with bend split bifurcations will be referred to as ‘stringer sheets’.

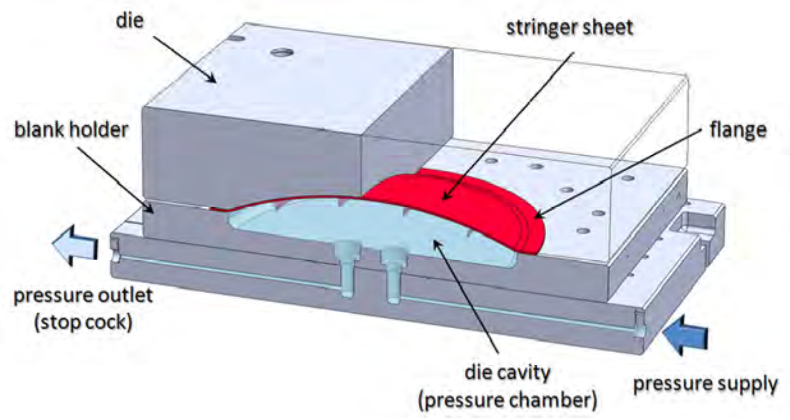


Figure 4: Sheet metal hydroforming of a stringer sheet (section few of a tool)

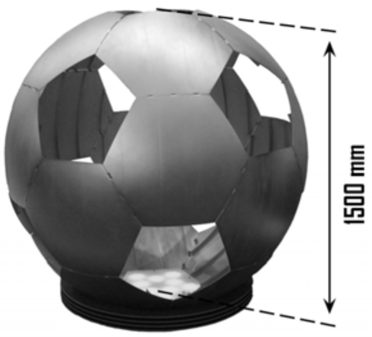


Figure 5: Demonstrator sheet structure made of hydroformed stringer sheets

Deep drawing as described above cannot be applied to stringer sheets, simply because there is no room for the stringers between the punch and the die. A variant of the process however replaces the punch by a pressurized liquid medium. This pressure medium pushes the blank into the die as a punch would do, but does not cause any collision of the stringers with solid parts of the tool. This variant of deep drawing is referred to as sheet metal hydroforming. A detailed description is given in [9]. Figure 4 shows the schematic of a sheet metal hydroforming process.

It is noticeable that in hydroforming the stringers have to be on the inside of the ‘global’ curvature of the part. A replacement with a pressurized medium not of the punch but of the die allows for stringers to be on the outside of a global curvature. This variant of deep drawing is referred to as hydro-mechanical deep drawing, described e.g. in [10].

Hydroforming of stringer sheets was first introduced in [11] using a rectangular cup as the target geometry. A number of process limitations originating from the use of stringer sheets were identified:

- The sudden change of the cross-section at the end of stringers causes high local stress concentrations. In some cases this leads to necking or even cracking of the sheet.
- High tensile stresses at the free edge of stringers (as may occur e.g. when a stringer is formed across a concave edge) may result in collapsing stringers or sometimes rupture.
- High compressive stresses in the free edge of a stringer cause them to buckle. Two kinds of stringer buckling can be observed: global buckling occurs during free expansion when the sheet is not yet in contact with the die but a dome with the stringers on the inside is formed by bending. Then compressive stresses at the free edge of the stringers are induced. Local buckling is a consequence of the part being formed into form features of the die with strong convex curvatures inducing compressive stresses.
- An uneven material draw in from the flange into the die cavity affects the positioning tolerances of the stringers.

Strategies to overcome these challenges have been developed over the past few years. Results of this development as well as the successful manufacture of the demonstrator shown in figure 5 are described in [12].

## 3 Geometric Figures and their Modularization

As a basis for the gain in knowledge about the modularization of freeform geometries, it is first important to examine the modularization of rule geometries. Three component families can be defined: single-curved, double-curved in the same direction (synclastic) and double-curved in opposite directions (anticlastic) [13]. To analyze possibilities of general modularization, below selected geometries of these component families are examined.

### 3.1 Single-Curved Geometries

Single-curved geometries can be divided into two sub-groups. The first sub-group has a constant curvature. Geometries of the second sub-group have a partially constant curvature and can be assembled out of several constant sections. The more the curvature becomes non-constant, the more components are needed for its modularization. In its extreme form this means that a fully non-constant geometry can be composed of unique modules only.

**Single-Curved Constant Geometries**

As figure 6 shows, a single-curved constant geometry can be build just out of one repeated component. In the idea of modularization both equilateral triangles and right-angle triangles were in use. In the further investigation the approach of the right-angled triangles is pursued.

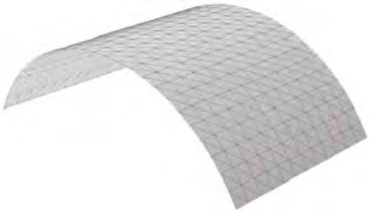


Figure 6: Constant single-curved geometry

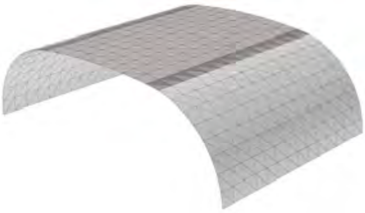


Figure 7: Partially constant single-curved geometry

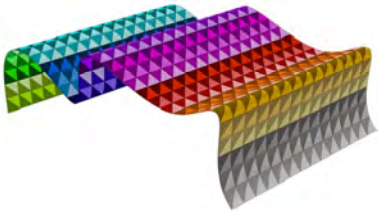


Figure 8: Non-constant single-curved geometry

### Single-Curved Non-constant Geometries

As figure 7 shows, a single-curved partially constant geometry can be assembled from a few components, because it is composed of a few constant curvatures. In addition there are some more special components which are needed in the transition region. The more irregularly the curvature becomes (as seen in figure 8), the more components are necessary for its production. The complete geometry consists of unique components exclusively.

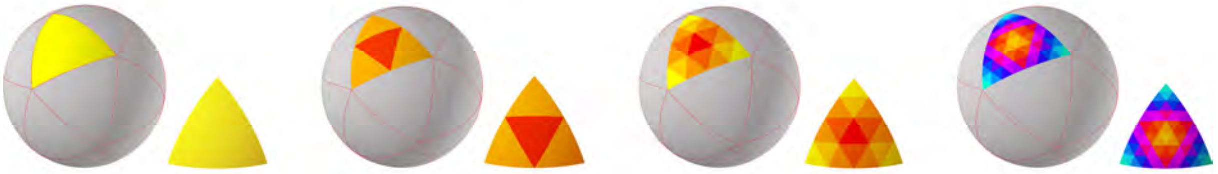
## 3.2 Double-Curved Synclastic Geometries

Double-curved synclastic geometries have three sub-groups. The first sub-group is at the same time the special geometry of the sphere. The second sub-group is the ellipsoid of revolution (spheroid) and the third sub-group is the triaxial ellipsoid. Consecutively all three sub-groups will be analyzed.

### Special Geometry of the Sphere

The sphere is a special geometry, because it is curved double in the same direction with the same constant curvature. For the modularization of spheres both can be used Platonic or Archimedean solids, because the edges are part of the circumscribed sphere. If using the platonic solid with the largest volume, the sphere can be build up with the Icosahedron, which exists out of 20 triangles. The Archimedean solid truncated Icosahedron has a higher volume and exists out of 20 hexagons and 12 pentagons. The advantage of the truncated Icosahedron over the Icosahedron is its smaller single component. This means that the buildable size of the sphere with a maximum of producible single component is bigger. If the sphere is supposed to be bigger than possible with starting from a truncated Icosahedron, the origin geometry of the Icosahedron has to be used as basis.

Richard Buckminster Fuller developed the principle of the geodesic dome [14]. The geodesic dome uses the basic geometry of the Icosahedron and divides the 20 triangles into more component sections [14]. Then the component sections are projected on the circumscribed sphere. With this strategy the triangles on the circumscribed sphere are indeed similar, but not identical. If we focus however on the Icosahedron and divide the triangles on the circumscribed sphere into smaller parts we are able to reduce the number of different items. Figure 9 shows the different subdivision order of the sphere. All component sections have the same curvature but not the same pre-cut.



| First Subdivision order: | Second Subdivision order: | Third Subdivision order: | Fourth Subdivision order: |
|---|---|---|---|
| 20 Component sections | 80 Component sections | 320 Component sections | 1280 Component sections |
| All identical | 60 Identical at the borders<br>20 Identical in the middle | 6x60 Identical at the borders<br>1x20 Identical in the middle | 21x60Identical at the borders<br>1x20 Identical in the middle |

Figure 9: Subdivision orders of a sphere

**Ellipsoid of Revolution (Spheroid)**

An ellipsoid of revolution is a comparatively constant geometry. It needs a comparatively low amount of component sections, because it is both in horizontal and vertical direction axially symmetric (figure 10). As the name suggests, the ellipsoid of revolution can be produced due to the revolution of the longitudinal curve in the x-axis. All components contained in the z- and y-axis are identical because of the rotation. Furthermore, all of these components are mirrored in the x-axes.

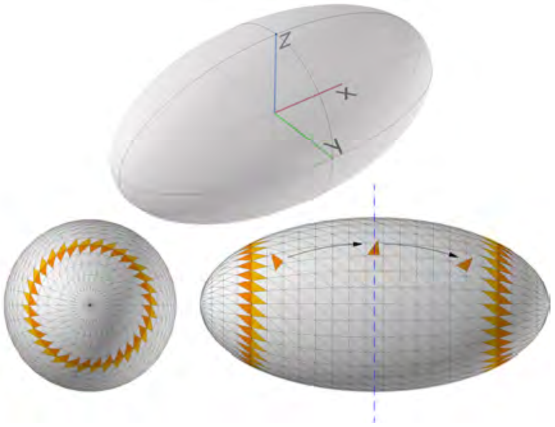


Figure 10: Ellipsoid of revolution

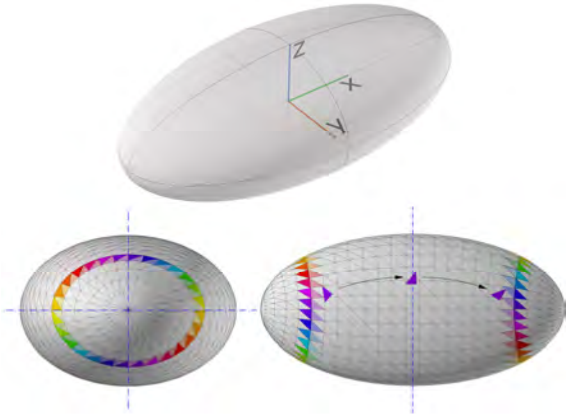


Figure 11: Triaxial Ellipsoid

**Triaxial Ellipsoid**

The triaxial ellipsoid can be produced only with a large number of individual parts, because there are different curvatures in all three axes (figure 11). Nevertheless, the triaxial ellipsoid is both in the y- and z-axis symmetrical. In addition, just like the ellipsoid of revolution, through the axial symmetry in the x-axis, all components in the y- and z-axis are mirrored.

## 3.3 Double-Curved Anticlastic Geometries

A double-curved anticlastic geometry can be identified for example in the geometry of a hyperbolic paraboloid (figure 12).

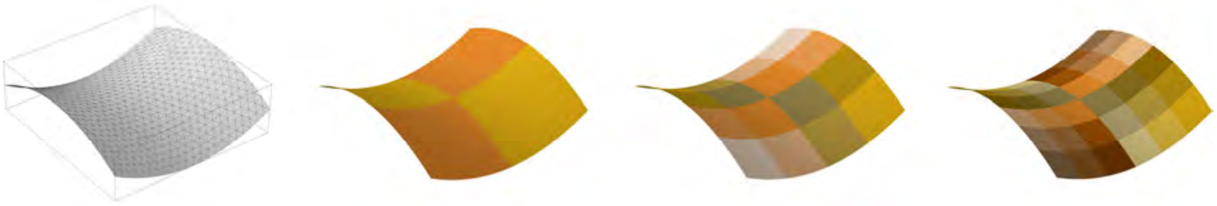


Figure 12: Double in the opposite direction curved Geometry

This can be manufactured either with only one component or it is composed of several components. The geometry is axial symmetric to the center point. Thus, the geometry can produce two identical components or modular systems (depending on meshing) with the second part being a mirror of the first part (figure 12). However, this principle can only be applied if the geometry is curved constantly in both axes.

## 3.4 Conclusion of the Modularization of rule Geometries

It is not possible to define a modular component system and to create different freeform geometries out of this. If a freeform geometry with the correct degree of curvature is to be split in a component system, it needs to be divided into its own modular set of components. It is also assumed that no component is similar to a segment of a different geometry. If freeform geometries are modularized in modular component systems, other computer-based tools will have to be used.

# 4 Freeform Geometries and their Modularization

Freeforms can be modularized with a number of different approaches, most of which are derived from construction practice requirements. In doing so, individual solutions for specific projects were developed. The Yas Island Marina Hotel serves as an example, in which the panelization and steel beam layout for the gridshell were optimized [15]. In contrast, there are approaches based on algorithmic solutions for the optimization of the aesthetical and manufacturing requirements. In [16] freeform geometries were approximated by strips of ruled surfaces. The modularization of double-curved geometries into planar quadrangles is described in [17]. In [18] Eigensatz et al. demonstrated modularization possibilities of freeform geometries into curved components using as many planar or single-curved components as possible. Double-curved components should differ only in their pre-cut but not in their curvature. This way the required tools can be reused as much as possible. These approaches are already used in construction practice. They generally optimize the single components according to aesthetical or manufacturing requirements and lead to individual solutions for individual freeform geometries.

The idea of using the advantages of contentious production as provided by the technology of the CRC 666 calls for a definition of a more general modular component system. This should contain as few parts as possible but at the same time be usable for different freeform geometries.

## 4.1 Composite Rule Geometries

A first approach to the modularization of freeform geometries is the assembling with well known and already modularized geometries. The disadvantages are the limitated design options which can only rely on a given geometry catalog (figure 13).

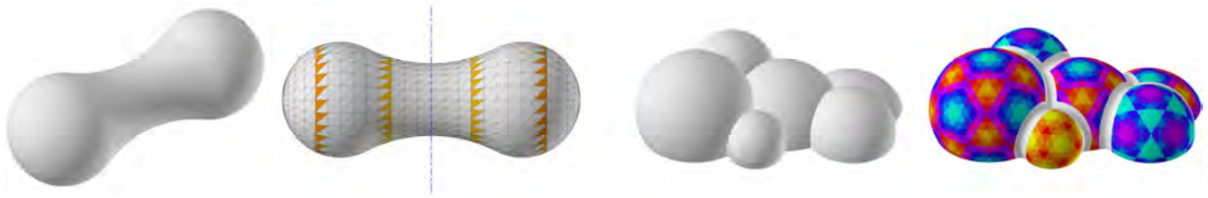


Figure 13: Composite rule geometry

## 4.2 Identification of Rule Geometries in Freeform Geometries

A slightly more liberal approach is to identify already known rule geometries in a freeform geometry. This can be done in three ways. In the first approach it is required to operate with a known geometry catalogue and use it for the special interim piece parts (figure 14). However, attention needs to be paid to the transition between the different rule geometries in order to assure that the modular component systems fit together and meet aesthetic demands.

In the second approach using computer-based tools the existing geometry has to be adjusted to the known geometry catalog. Regions in the geometry, which can be generated from segments of the geometry catalog, can be identified. Then these sections can be deformed, so that the existing freeform geometry is to be build ‘better’ with the known geometry catalog. Another approach is to incorporate these restrictions in the software for the geometry creation. Therefore a degree of meshing can be identified before and the possible geometries are based on it.

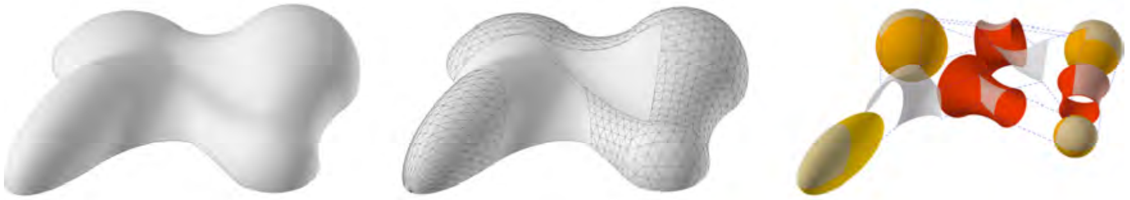


Figure 14: Identification of rule geometries in freeform geometries

### 4.3 Creation of Modular Component Systems for Freeform Geometries using Planar Components

Modularizing freeform geometries into modular component systems result in deviations from the original geometry. The more deviation is allowed the potential for creating modular component systems arises. One current approach is to map a given geometry with a limited number of planar components.

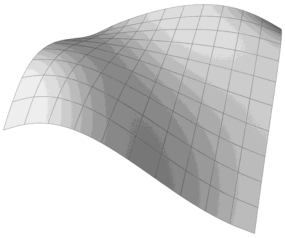


Figure 15: Origin geometry with the ideal curvature

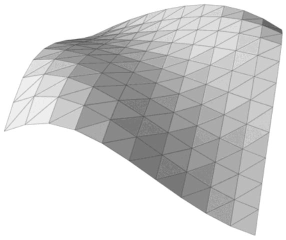


Figure 16: Origin geometry with 200 planar triangles

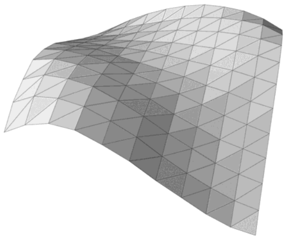


Figure 17: Abstracted geometry with 101 planar triangles

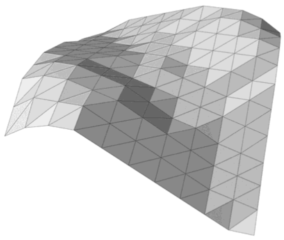


Figure 18: Abstracted geometry with 21 planar triangles

As figure 15 shows, a grid is projected from one direction of projection onto the geometry and the geometry is subdivided correspondingly. If the surface is divided into planar triangles, 200 unique triangles are needed (figure 16). Then the edges of the triangles were positioned in a vertical grid to avoid later the fracturing of the surface. Next, two modular component systems with triangles are determined. The modular component systems are defined by a section through a prism of a triangle. The number of components of the modular system is based on the defined edges in the X direction times the gradations in the Y direction. The large modular system has 399 and the small one has 43 components. Next, the area on the grid of the predetermined geometry is compared to the possible previously defined components and replaced with the most similar component from the predefined building blocks. In order to avoid extensive manual processing, a script has been programmed. Depending on the size of the predefined modular component system, the original geometry is shown nearly ideal or abstracted. The programmed script uses from the available modular component system just the needed components. Figure 17 shows how the large modular component system (399 pieces) was used to build the geometry with 101 different components. Similarly, figure 18 shows how the small modular component system (43 pieces) was used to build the geometry with 21 different components.

### 4.4 Future Prospects on New Approaches

Products manufactured with the technology of the CRC 666 are qualified excellently for the usage in building skins. They fulfill the requirements of both structural and structural-physical properties. Due to the technology of hydroforming of stringer sheets aesthetic requirements of non-planar surface-structure components are also met. Every freeform geometry can be modularized in a modular component system by using digital tools. Due to this possibility the advantage of serial production can be used in addition. Parametric and algorithmic based methods can improve modularization. This includes, among other things, the ability to abstract an existing geometry by a modular component system with a limited number of curved components. Another option in contrast is to already incorporate these constraints into the geometry creation software. With software like this only such freeforms can be generated which are suited for modularization.

Future investigations will include the question of how the flexibility of modules as well as module connections limits the number of components of a modular component system.

## 5 Acknowledgements

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# The Inner Skin of the Ventilated Facade

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## Summary

Two highly distinct building systems live side by side in conventional ventilated façades. Even though outer skins have reached a high level of technological sophistication, inner walls are mostly shackled to tradition.

This study focuses on the development of a prefabricated panel to meet the functional needs and specifications of the inner skins of ventilated façades. Panel design depends on the grouping of the basic inner skin functions.

The most interesting solution is a concrete sandwich panel with two very thin exterior layers made of UHPCFR with an XPS core. This proposal offers all the required functions and can be optimized for each situation through the specific design of the materials.

**Keywords:** ventilated façade, prefabricated, sandwich, building skins.

## 1 State of the Art

### 1.1 Ventilated Façades

Ventilated façades are all those enclosures that resolve the issue of waterproofing by providing a continuous drainage cavity that underlies the entire skin of the building. By definition, these drainage cavities are encapsulated between two membranes: an outer skin, which typically exhibits open seams, and an inner skin.

Given that the enclosure must ensure a baseline level of comfort, which cannot be compromised, numerous functionalities are required of each of these two skins.

Other than waterproofing, some level of sound attenuation and the ability to dissipate direct radiation via convection inside the cavity, the remaining requirements are delegated to the inner skin of the façade.

### 1.2 Empiricism and Rationalization

Two highly distinct building systems live side by side in conventional ventilated façades. Thus, even though outer membranes and the mechanisms used to attach them have evolved greatly in recent years and have reached a high level of technological sophistication when dry-assembled by specialists, inner membranes are still shackled to tradition.

Masonry, either in the form of ceramic units or concrete blocks, is the technique typically used for this inner skin. It requires a specialized tradesman: a skilled, experienced mason capable of joining masonry units with mortar in such a way that they form a solid wall. Whether the façade functions correctly depends on this being carried out properly.

Here, two highly different techniques live side by side in one unique architectural element. While the first is shaped by ongoing developments in architectural technology, the second depends on the skill of the workforce used to put it together. One is clean and dry, while the other generates a significant amount of rubble and requires the use of binding agents that require curing time.

This coexistence would not entail any problem were one able to conceive of the façade as a single, whole element. However, the lack of methods to guarantee the stability and flatness of the inner skin means that one cannot count on it as support. The outer skin is designed in an autonomous way, by observing the edges of the slab and incorporating more or less complex mechanisms to ensure verticality.

Therefore, the design process for the outer skin cannot gain from the benefits of having a properly planned inner skin.

Figure 1: Two different techniques in one element.

Ventilated façades entail significant advantages over traditional façades, even though they have yet to reach an optimal state of development. We are at an intermediate point in the evolutionary process, and only by conceiving of the system as a whole can it be optimized.

Not only is the inner skin highly unreliable in terms of its execution due to the increasing scarcity of skilled masons, but one must provide solutions to multiple functionalities without the benefit of having analyzed the mechanisms available for satisfying them, a priori.

Though ventilated façades incorporate a specific mechanism to make them waterproof, and in most cases they also provide thermal insulation, the remaining functionalities of the enclosure are provided by brick work. There has not been an analysis of how this brick work fulfills all those functions.

Thus, it is important that we carry out a functional analysis of the façade – as a whole – so as to determine where and how these functionalities should be resolved in the section of the enclosure.

### 1.3 Initial Proposals for Rationalizing the Façade as a Whole

Teams of architects and researchers from different companies specialized in areas related to the enclosure of façades have made proposals illustrating how far this development could evolve. The plethora of initiatives (such as drywall, metal sheets, and precast and sandwich panels) reflects the lack of systematic criteria.

The simplest solution supposes the inner skin of the ventilated façade to be a drywall construction made up of a traditional framework of galvanized steel studs girded with cement boards or ribbed panels made of steel. In these cases, the outer membrane is disconnected from the inner skin, which would hardly be able to withstand the pressure of the wind. For this reason, there is a trend towards prefabricating the inner skin, by which the concept of the façade as a whole continues to be ignored.

The quest for a maximum optimization of this framework explains the proliferation of other systems that can enable it to bear the weight of the façade. Some are based on well-known stick-type curtain wall technology.

Figure 2: Not wind load bearing inner skin.

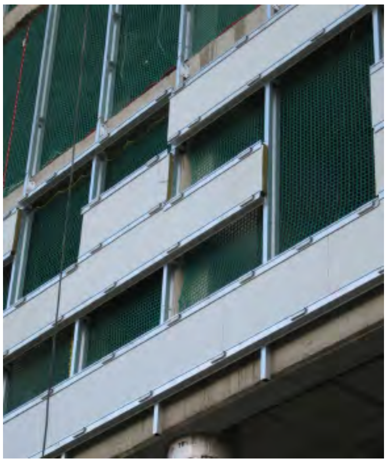


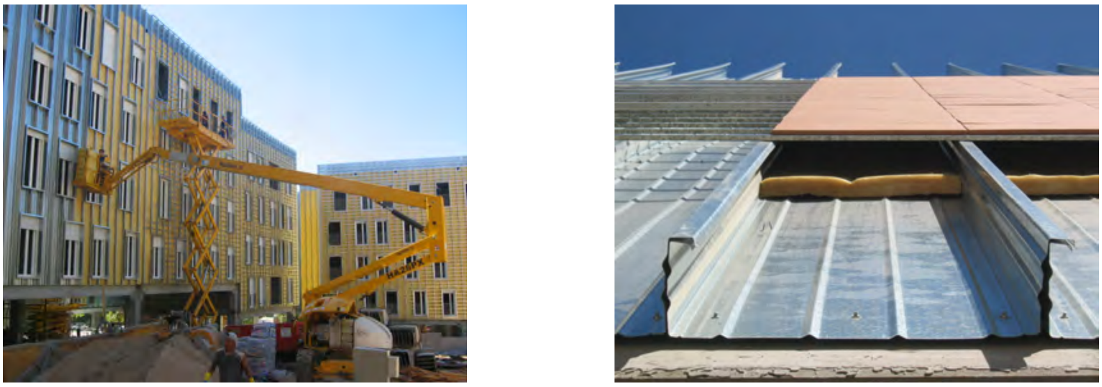
Figure 3: Wind load bearing inner skin.

Though these systems conceive of the façade as a whole, they still are frameworks that must be assembled on site. Nevertheless, the assembly process could easily be shifted to a workshop and the component panels could be brought to the construction site.

The panel format seems to be the best choice. Thus, any sort of panel can be used in this new application, from solid monolithic panels, to lightweight ribbed ones.

The façade of Renzo Piano’s building on the Rue des Meaux in Paris has come to represent a historical paradigm, as it represent one of the first known instances in which a prefabricated inner skin was used to support the weight of the totality of a façade.

Its opening was closed off with a G.R.C. sheet that was high enough, wide enough and thick enough to be affixed directly to the main structure of the building, though this could have alternately been resolved using any other kind of interlocking paneling.



Figures 4 and 5: Steel folded plate as inner skin.

The new Spanish building codes, encapsulated in the publication “Código Técnico de la Edificación” (“Technical Building Codes”, henceforth referred to as CTE), have been an obstacle to the evolution of the conventional ventilated façade, as they require any alternative building solutions not included within its guidelines to seek approval via a “Documento Reconocido” (“Recognized Document”) that guarantees that it will comply with whichever functionalities they are meant to provide. Any innovative proposal not sponsored by a company able to take this extra step is thus rendered economically unfeasible.

Most of the solutions cited do not conform to the building solutions compiled in the CTE, which entails that they must be backed up by a “Recognized Document”.

What is apparently negative for technological innovation in the field of construction should be understood as a catalyst for a process for change, whereby future development depends on an effective management of the issue by organizations representing architects’ interests.

# 2 The Search for Alternatives to Masonry for the Inner Skin

## 2.1 Objective

This thesis focuses on the development of a panel aimed at resolving the inner skin of ventilated façades so as to provide a rigorous solution to the functionalities and requirements that these façades necessitate. Such a panel will also support the weight of the façade without actually forming part of the main structure of the building.

## 2.2 Hypothesis

The inner skins of ventilated façades must be resolved with a semi-product or multifunctional component panel that is optimized so as to meet the functionalities required of it. These panels are large in format and make use of dry-set, reversible methods of attachment.

## 2.3 Strategy: The Reassigning of Functionalities as a Criterion of Panel Design

The type of panels that arise from this study will vary depending on the range of functionalities they are designed to fulfill.

The panels studied herein can be based on semi-products as well as component pieces; in other words, some will be highly prefabricated products that in certain cases will admit dimensional variations on site (semi-products), while in other cases these will not be possible (as in the case of components).

Whether a panel makes use of semi-products or components entails that one analyzing it will do so based on whichever functionalities are already incorporated when the panel is brought to the construction site.

Elements added on site to complete the façade system do not form part of the panel.

The functionalities that the inner skin of a façade must fulfill are those which are vital to making the space inside habitable; providing thermal comfort and acoustical insulation and creating an airtight interior. Fire prevention and load-bearing requirements, insofar as they relate to the forces that act on the enclosure, are also basic functionalities.

The remaining requirements are not taken into account when defining the proposals for the inner skin, though they will play a determining role when evaluating these proposals.

## 2.4 Defining the Functionality of the Panel: Load-bearing Capacity versus Horizontal Deflection

There are many functionalities that can be provided by the panels of a façade, but there is only one that is common to every combination of requirements: that of bearing the façade weight and wind load.

Out of the different layers that can make up the inner skin of the ventilated façade, the panels focused on in this study satisfy the functionality of bearing the load of the façade system.

In any system, not just those used in construction, once the skeleton has been identified, any other requirement can be resolved by adding a functionality to that framework or by incorporating a new element to it. If the framework has not been defined, the system will lack an underlying structure, which means that the remaining elements that make it up will neither be able to maintain their position nor be held in place.

# 3 The Identification of Functionalities and the Requirements of the Inner Skin

## 3.1 The Functionalities of Conditioning and Service

The appropriateness of the different inner skin panel proposals for ventilated façades depends on how well these proposals satisfy the essential functionalities needed to guarantee an adequate level of comfort and conditions of use, in addition to how well they fulfill a series of requirements necessitated by issues such as installation and economics.

A panel proposal’s characteristics should be such that these requirements are met in a satisfactory manner, meaning that they are not proposed as exigencies but rather, if they fulfill the functionality or requirement it is understood that the necessary characteristics for this to are present.

Of the two basic types of functionalities, conditioning and service, only those related to conditioning imply regulation of energy and material flows through the façade. These functionalities play the largest role in the design and definition of the materials that make up the enclosure.
Service-related functionalities have little relevance when choosing materials, although they do play a role in the exterior finishes. They should also be taken into account when designing the assembly of layers that make up the enclosure, although normally these will not imply considerable variations to a design aimed at conditioning in- and outflows.

<u>Functionalities of conditioning that can or should be resolved by the inner skin of the façade</u>

- Stability of the skin itself and of the façade as a whole
- Thermal comfort
- Fire resistance
- Acoustic insulation
- Airtightness

<u>Service functionalities that can or should be resolved by the inner skin of the façade</u>

Though service functionalities cannot be assigned quantifiable values, they do have an impact on the design of the enclosure. The installation of utilities can influence the superimposition of layers while also favoring given geometries for the panel.

- Providing a finished interior surface
- Providing a space for service utilities

<u>Other requirements demanded of the inner skin of the façade</u>

There is no limit nowadays to the non-functional requirements demanded of panels that withstand wind load; specifically, these arise from consideration of the issues of slenderness and light weight, which are factors that condition the development of façade solutions.
Panel thickness is reduced to the minimum possible value, as this entails an optimized relationship between the built and useable surfaces.
The advantages of a lightweight panel – in terms of diminishing the possibility of overloading and simplifying on-site manipulation and transportation – are counteracted by the inverse relationship between acoustic buffering and mass.
In order to make use of lightweight panels without undergoing an extreme reduction in acoustical response, panel weight has been set to the maximum established by the CTE for lightweight façades in the document “Protección frente al ruido” (“Protection against noise”); in other words, 200 kg/m².

- Slenderness
- Light weight

# 4 Taxonomy of Panels for an Inner Self-bearing Skin Based on Criteria of Functionality

## 4.1 Relevance of the Criterion of Functionality

To choose an organizational criterion, it is important that one have a clear notion of the element to be analyzed; in this case, it is the inner skin of the ventilated façade. Likewise, one must know the context in which the desired results can be met.

- Objective: To satisfy the functionalities necessary such that the façade – as a whole – provides an acceptable level of comfort inside the space it surrounds.
- Context: Development of building systems.

The design of a panel for the inner skin of the ventilated façade depends on the functionalities it must provide a solution to. Its typically null presence in the finished building gives it a purely functional character, which is not conditioned by formalism or other subjective variables.

As was stated at the beginning, ventilated façades are those enclosures characterized by a specialization in waterproofing, while the remainder of the functions are entrusted to an inner skin of prefabricated paneling that recalls traditional construction techniques. Regarding this inner skin, however, there have been few occasions on which specialists have reflected on what these functionalities are and what the best way to satisfy them is. For this reason, it is precisely such a functional analysis that we are interested in, and which will serve us as a guide vis-à-vis the taxonomy.

### 4.2 Separation of the Functionalities from the Inner Skin

The objective of this taxonomy is to categorize the possible solutions for load-bearing inner skins in ventilated façades based on the remaining functionalities they must fulfill.

The maximum concentration supposes the satisfaction of five basic functionalities, subsequently to which these functionalities are separated into specialized layers. These layers are themselves resolved by specific elements designed for precisely such a purpose, whereby the resolution of these functionalities ceases to be the responsibility of the load-bearing element.

It is possible that as the number of functionalities separated from the load-bearing skin increases, they end up being resolved by a single layer adjacent to the latter. In such a case, separation would not be accompanied by specialization, but would instead have produced a regrouping of functionalities around a different element than the one focused on in this study. Insofar as what concerns us in this study, these would be functionalities that had been “expelled” from the panel and would thus have no impact on the definition of the latter.

### 4.3 Sequence of Separation

The progressive separation of functionalities does not automatically yield functional types. Instead, these depend on the range of possible combinations in which the functionalities can be grouped in the panel. A panel can satisfy the functionality of thermal insulation without being fireproof, or vice versa. There is no a priori determined order to which functionalities should be separated first.

Despite the fact that five functionalities have been taken into account in developing the taxonomy, the possible combinations should not include them all.

Load bearing

The load bearing functionality is indispensable, as it is a characteristic of the element being studied.

This functionality is the only one that can be resolved by means of a discontinuous panel. This discontinuity can yield a variation in the thickness in section or an alternation of solids and voids.

The load bearing functionality is not always located in the inner skin. Wind load can be deflected by the outer skin, by resorting to supports of a lesser mechanical capacity to make up the structure of the inner skin. There is also the possibility that this breaking down of the load bearing element can be carried to an extreme, whereby by substructures appear for the different layers forming the enclosure.

Still, breaking the load bearing functionality down into substructures, or even relocating it to the inner skin does not simplify the design of the enclosure. As has been stated above, this has been taken as a defining characteristic of the inner skin panel in this study.

Airtightness

Airtightness is a basic condition for achieving thermal insulation, fire retention and acoustical reduction. As such, it cannot be separated unless all three of these have already been delegated to another element beforehand.

Acoustical

The acoustical functionality requires a minimum value for the massing. If this is not met, a discontinuity must be established between whatever sheets make up the panel. If the panel has an adequate section so as to satisfy the functionalities of thermal insulation and fire retention, it will typically also provide for the necessary degree of acoustical reduction, either by dint of its mass or the succession of layers.

According to the Law of Mass and as is stipulated in the CTE, a mass of 43 kg/m² is sufficient to provide the necessary 32 dBA of insulation. This mass can be achieved with a 3-cm-thick material of a density of 1,433 kg/m³, 5 cm if the density is 860 kg/m³ or 8 cm for 538 kg/m³. These densities could correspond to a lightweight concrete or even wood or aerated concrete. Fulfilling the load bearing functionality could possibly lead to an increase in density or thickness, but even so the thermal and fire retention properties would not be resolved.

<u>Thermal insulation and fire retention</u>

A material that is a poor conductor and is not highly combustible satisfies the functionality of thermal insulation but not that of fire retention. By increasing the thickness, it is possible to improve the response to the latter by slowing its loss of integrity.
In this case, the thickness is conditioned by fire retention and not by thermal insulation.
If a material is sufficiently conductive, the thickness required to provide thermal insulation will surely be greater than that needed to avoid fire propagation.
For instance, the combustion speed (0.76 mm/min) of KLH plywood requires the use of a 117-mm-thick panel to satisfy the fire retention property. This thickness is increased to 200 mm to fulfill the required transmittance.
This same thickness of aerated concrete is capable of withstanding fire for six hours but it barely is able to fulfill the transmittance required in the harshest climatic zone, E1.
In combustible materials of a thermal conductivity of around 0.035 W/mK, that is, all those thermal insulators not included in category A1, the increase in thickness is justified by the materials' satisfying fire retention requirements.
In a steel sandwich panel with a polyisocyanurate (Polyiso) core, less thickness is required to satisfy the thermal functionality (80 mm) than for satisfying the needs for fire retention (175 mm).
The combination of separating these two functionalities from the panel gives rise to the definition of two types that each fulfill four functionalities, depending on whether the fourth functionality included is that of thermal insulation or fire retention, respectively.

## 5 The Morphological Diversity of Load-bearing Inner Skins of Panels

### 5.1 Morphologies Definition

There are six alternate morphologies, distinguished by two characteristics: geometry and structure. The first of these focuses on the external shape of the panel, while the second contemplates alterations to the thickness of the section. If the sheets that make up the panel have been cut in opposite directions (transversally or longitudinally), the result will be different sections and a heterogeneous plate.

Table 1: Morphological possibilities

| SECTION GEOMETRY | STRUCTURE | MORPHOLOGY |
|---|---|---|
| Rectangular | Homogeneous | Homogeneous |
| | Heterogeneous | Sandwich |
| | | Hollow |
| Non-rectangular | Heterogeneous | Ribbed |
| | | Nervate |
| | | Stud |

### 5.2 Morphological Alternatives per Each Functional Type

When changing from a rectangular geometry to a corrugated, ribbed or framework panel, the panel will lose functionalities. Obviously, this is the case whenever one maintains a thickness that is not excessive for a ribbed or corrugated panel.
Panels that have a constant transversal section throughout their width and length typically display a better behavior as they always react in the same way to incidents. They are typically suitable for satisfying many functions.

It does not make much sense to apply panels of a complex structure to functional types that provide responses to only a few functionalities.

The different shapes lead one to work with a diverse array of materials depending on the typical processes used to craft these materials.

Ribbed structures typically bring to mind folds, laminates or extrusion, which in turn favor the use of wide variety of metals, among which one finds steel. Steel's high thermal conductivity and mechanical capacity confirm the non-multifunctional character of the solution, which is instead focused on the stability and airtightness of the façade.

Hollow corrugated panels are benefited by the monolithic nature of the amorphous materials made by molding or extrusion. These same materials allow one to insert connectors between the strips of the sandwiches prior to assembling them.

## 6 Resulting Functional Types Related with Different Morphologies

The possibilities resulting from this combination of functional types and morphologies are summarized in the array accompanying this text. Obviously some morphologies fit better to a specific functional type than to another.

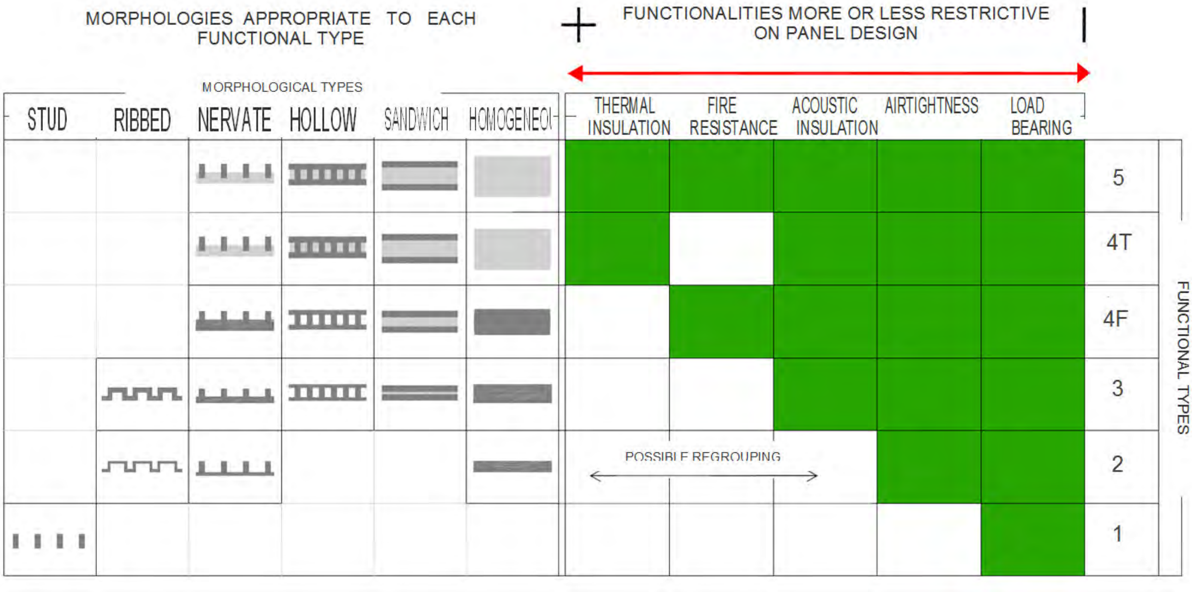


Figure 6: Array of possibilities for the inner wall of the ventilated façade.

## 7 Prospects for the Future

The resulting array raises several possibilities for the development of prefabricated inner wall solutions for the ventilated façade. After a detailed analysis of the advantages and disadvantages of each of them, included in the complete document of the doctoral thesis *"The inner skin of the ventilated façade. Analysis, taxonomy and prospects for the future"*, the next step has been the development of one of those solutions.

In collaboration with iMat – Construction Technology Centre - we are working in the implementation of this inner wall for ventilated façade based on a sandwich panel made with two thin exterior layers of UHPCFR (15 mm each one) and a XPS core material which is the only responsible for the solidarity between layers.

All the essays conducted so far have been very successful from the point of view of solidarity between layers without the inclusion of specific connections. The panel is able to easily support wind loads up to 200 $kg/m^3$.

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# Beyond Parametric Design – New Approach to Robotic Employment for Freeformed Surfaces and Shell Structures

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## Summary

This paper describes the first steps of the realization of a resource efficient, process-controlled, on prefabricated parts based construction method for shells and freeform geometries in concrete and ultra high performance concrete. Fundamental idea is a parametrical computerized fabrication method, which is characterized by its potential to enable the achievement for almost every essential work step by one industrial 7-axis robot minimizing the required machine outfit.

An adaptive reusable formwork for prefabricated segments is the core area of our research project, which is also carried by the Institute for Structure Concrete, the Institute of Technology and Testing of Building Materials and the Laboratory for Structural Engineering.

**Keywords:** Shell, freeform, form finding, UHPC, FRP-reinforcement, parametric, robotic

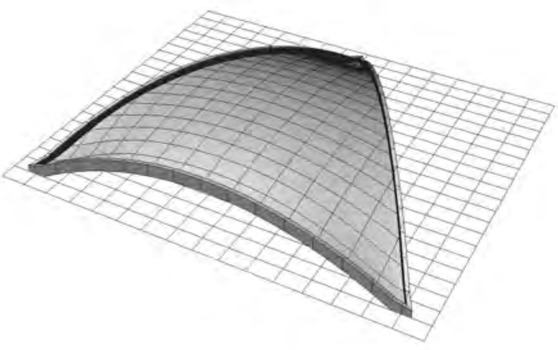


Figure 1: First rendering of a segmented shell

# 1 Shells in UHPC – Renaissance of a Structural Shape?

The idea of modern architecture, irrelevant if you think about trivial architecture or landmark projects, is connected to the questions of sustainability and energy efficiency. In today's discourse an essential contribution to resource efficiency is the economization of construction materials for building structures and envelopes, as well as an optimization of the energetic production expenditure. This can be reached by consequent use of lightweight design and lightweight materials, which have an influence on the whole material usage from the building envelope to the foundation. The research project presented in this paper is based on the lightweight design of shell structures in UHPC (Ultra High Performance Concrete).

## 1.1 Shells – Inspiring Structures for Architects and Engineers

Shells as single- or double-curved surfaces are lightweight load-bearing structures, and because of their special geometry they have a favorably load bearing behavior which causes the immanent low material consumption. In addition to that they fascinate by their elegance and a logical combination of form and distribution of forces. Like no other principle shells combine the load carrying structure and the building skin to a unique architectural entity. Referring to this, Heinz Isler ones wrote that the thin walled shell might be the most efficient construction method in material universe [1].

## 1.2 Material and Production

Concrete, because of its properties like its compression strength and being castable, is an ideal material to manufacture this kind of structure. That's why concrete shells where produced for many years, not just for landmark projects (e.g "L`Oceanografic", TWA Terminal) using the iconic character, but also for functional industrial buildings.

Many works and patents for construction methods document the diversity that resulted from the ideas of architects and engineers, especially during the first half of the twentieth century, and which had one ambition: increasing the efficiency of shells. New developments like on-site production methods, like they were realized by Wallace Neff or Dante Bini, and their special concepts for membrane formworks, or the segmentation in semi-precast elements that coined Pier Luigi Nervi life´s work, enhanced the idea gradually. Nervi resumed after 30 years of work that prefabrication still seemed to be that kind of building technique, offering most potential to free concrete structures from the "slavery" of timber formwork [2].

## 1.3 State of the Technology

Even if these developments show a still incompletely exploit potential, the height of the concrete shells ended during the 1970´s. Except a few examples, shell and freeform geometries are realized using glass, steel, or membrane structures today. Increasing technical complexity is accepted for this.

Often named reason for the explained paradigm change is the proportionately expensive formwork in comparison with the cheap material reinforced concrete [3]. But labour costs for formwork and falsework cause this problem. Moulds (especially for double curved elements) still are milled from a solid component, or in bigger scale made by a multitude of planar or single curved elements [4, 5].

Adaptive formworks are in demand to react on this deficit. That means formworks that are able to reproduce many different geometries based on a reversible system. First ideas can be found in actual research reports. In Axel Kilians dissertation from 2006 "experiment 10" showed a model controlled using 9 motorized threaded rods, and "ADAPA-Adapting Architecture" presented a similar looking project for the fabrication of thin concrete panels at the "Computational design modeling" in Berlin 2011 [6, 7].

# 2 Application to the Own Approach

The chapter "State of technology" has shown the hidden potential, lying in the use of the new digital tools, not just for form generation but for production. A direct transmission of these techniques, and their application on new high performance materials, could help to realize a production process as efficient as the geometrical structure.

## 2.1 Methodology and Hardware

Important unique feature of the development is the holistic approach of a total fabrication that can be managed by one single robot. The adaptive formwork can be driven just as well as the finishing, like trimming or drilling the connecting points, can be done by changing the die heads.
The plant that is installed and that is used for practical testing and realization is an ABB IRB 6660 6-Axis industrial robot mounted on a high precision track. The whole of the facility is designed for wet conditions. A 12 kW milling spindle can carry the special tool for wet machining.

## 2.2 Digital Process Chain

A digital process chain that is broken down in eleven steps integrates every work step and transfers the required information. The organigram [Figure 2: Organigram of the digital process chain] shows the production sequence and how the different work steps are connected to each other. Another distinctiveness is the abdication of electronic or hydraulic parts by a pure mechanical drive. Because the robot can achieve all these work steps, quantity of the required components can be reduced and the costs decrease. That allows an economical production of a whole series of formworks that are simple, cheap, robust, transportable and universal applicable in different environments (autoclave, factories).
The work steps can be categorized in 3 topics: digital formfinding and generating, production, finishing and post production.

The three subjects of the current investigations are the adaptive formwork, high performance materials and connecting methods and will be explained more precisely in the chapters 3, 4 and 5.

## 2.3 Digital Formfinding and Generating

Shell structures are mainly stressed by membrane forces. This feature that causes their high efficiency, refers to a simple geometrical formfinding process: The reverse of catenaries and suspended models. The resulting structures are characterized by the correlation between the flux of force, bearings and geometry.
Even before the computer age allowed numerical methods, complex structures where realized using this method, like the “Multihalle Mannheim” by Frei Otto or the “Sagrada Familia” by Antoni Gaudí.
At the Institute for Structural Design digital tools like “Rhinceros 4.0” in combination with plug-ins like “KangarooPhysics” allow designing digital based free forms and suspended net models. That enables a direct transfer of a generated model into FE-simulation (A.1).

## 2.4 Production

After the geometry is found, it is loaded in another Rhino-plug-in “Grasshopper” that cuts the model into segments according the boundary values of the adaptive formwork (A.2). The boundary values depend on the size, curvature and the demand of the surface quality. In addition the aspects of prefabrication and assembling are taken in account.
The originated elements are sorted in two categories: Elements that can be mould by the adaptive formwork (A.3a, A.4a), and segments with a special geometry like the abutments or border elements (A.3b). After the reinforcement for both types is planned (A.5), the robot drives the adaptive formwork and mills the mould construction (A.6a, A6b) to prepare them for concreting (A.7).

## 2.5 Finishing and Post Production

Both segment types need a special finishing. The element made by the adaptive formwork has to be cut exactly on size (A.8), and to maximize the surfaces contact for the “dry joint” connection, contact faces are grinded (A.9). Depending on the connection that was chosen, connection points are drilled and fasteners or anchors are placed, and the structure can be built up by assembling all segments on a falsework (A.10).
Final part of the project is the analysis of the structures load bearing behavior (A.11).

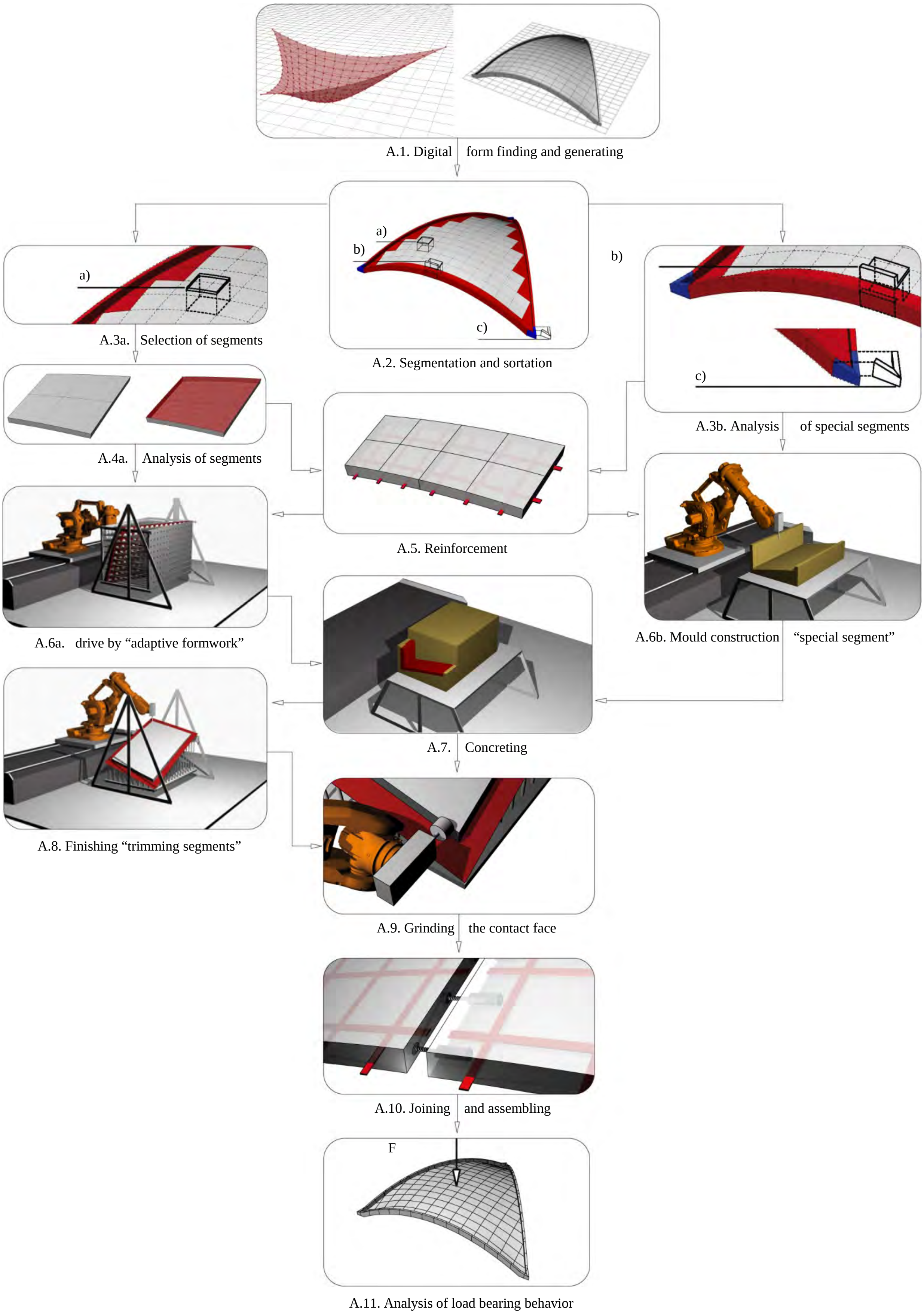


Figure 2: Organigram of the digital process chain

## 3 Adaptive Formwork

The adaptive formwork [Fig. 3] (mentioned in the organigram as A.6a) is built up of a rotatable frame that is rasterized in orthogonal field of pins on both sides. These pins can be axial adjusted and fixed serially by an industrial robot. A formwork facing that is connected to the pins covers the field and flexible layered battens proof the border area.

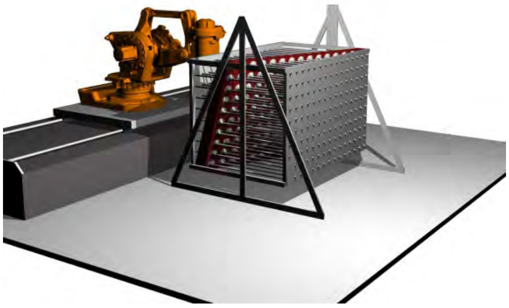


Figure 3: Adjusting the pins

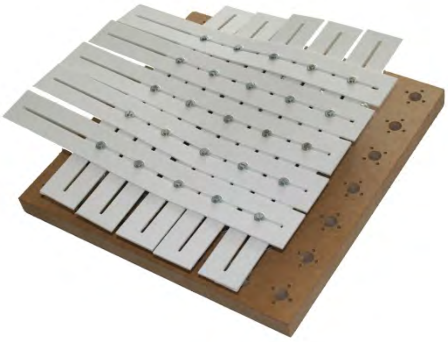


Figure 4: Adjusted field of the first model

### 3.1 Digital Transformation into Physical Construction

To adjust the pins and realize the computer generated form, the geometrical information of any segment has to be transferred. For this a script in “Rhinoceros-Grasshopper” was written [Fig. 5]. It analyzes both surfaces, the top side and rear side, and breaks them up and rasterizes suitable for the pin field. Then it calculates the traveling distance of every single pin and exports it as a vector in a list [Fig. 7]. These vector files are transferred into a work step file for the robot. Because the current model works on a thread based system, the file needs a number of revolutions to drive the formwork. To avoid overstretching, a maximal accepted travelling distance per work step is specified, depending on the flexibility of the form facing. Therefore another script controls the working cycle.

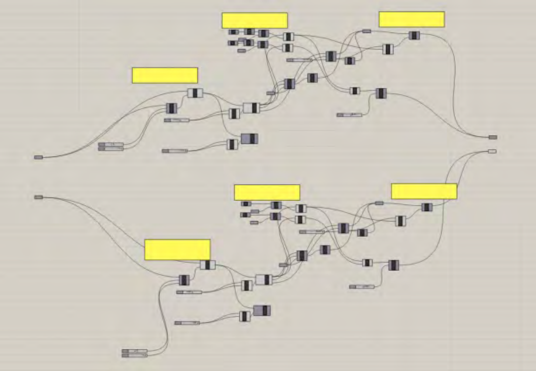


Figure 5: Grasshopper-file

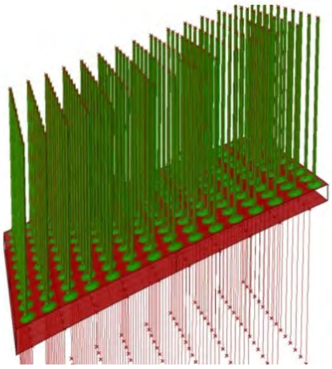
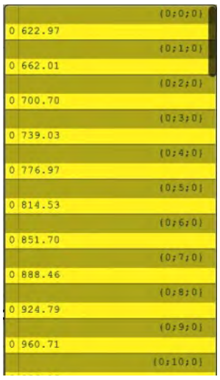


Figure 6: Implementation on a segment



```
                {0;0;0}
0 622.97
                {0;1;0}
0 662.01
                {0;2;0}
0 700.70
                {0;3;0}
0 739.03
                {0;4;0}
0 776.97
                {0;5;0}
0 814.53
                {0;6;0}
0 851.70
                {0;7;0}
0 888.46
                {0;8;0}
0 924.79
                {0;9;0}
0 960.71
               {0;10;0}
```

Figure 7: Resulting list

## 4 High Performance Materials for Shell Structures

Additional to the development of new analysing tools and production processes, materials technology has evolved too. Concrete technology as well as reinforcement provides new materials with a lot of potential. So as a logical consequence in this project steel reinforced concrete is substituted by UHPC (with or without steelfibres) and CFPR (Carbonfiber-Reinforced Polymers).
To prove their combined material performance, first tests were conducted and several are following.

### 4.1 Material Properties

Ultra-High Performance Concrete (UHPC) is characterized by enormous compressive strengths up to over 200 N/mm² and allows the design of extremely slim structural elements under compressive stress that were reserved to steel constructions until now. Unfortunately, its tensile strength does not increase at the same rate and reaches values not much over 15 N/mm² even when short steel fibers are added. This fundamental problem makes it difficult to use UHPC efficiently under bending load and reach the lightness and slenderness the material deserves.

In accordance with normal concrete, there are actually three ways to deal with tensile stresses in UHPC constructions: reinforcing the tensile stressed areas, pre-stressing the construction to suppress tensile stresses or choosing a construction with low bending stresses. But even by using efficient structures like shells, bending stress can´t be avoided completely.

So in this study the first approach is followed, by reinforcing the UHPC with Fiber-Reinforced Polymers (FRP). The reason behind the decision is that this method is technically simple and does not have a strong influence on the structure´s form. The aim of this study is the development of efficient UHPC-FRP composite structures with a balanced ratio between compressive and tensile strength, which are able to utilize the high resistance of both materials. [9, 10].

### 4.2 Bond Behavior

In October 2011 pull-out tests were carried out at the Laboratory for Structural Engineering at the University of Technology Graz with the research target to investigate bond behavior of UHPC and CFRP-lamellae in principle and to find out the influences of surface roughening. The tests were carried out with three varyingly rough lamellae surfaces: smooth (test series 1), fine sanded (test series 2) and coarsely sanded (test series 3). The smooth lamellae did not have any after-treatment, whereas the surface of the fine and coarsely sanded lamellae was manually coated with epoxy resin and covered with quartz sand. The fine sanded variant had an approximate resin thickness of 0,1 mm and the surface was only partially covered with sand grains. The coarsely sanded lamellae had an approximate resin thickness of 0,4 mm and the surface was fully covered with sand grains.

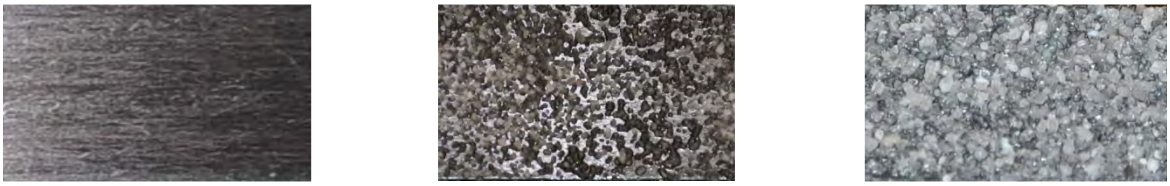


Figure 8: Investigated surface characteristics: smooth, fine sanded and coarsely sanded lamellae

The test results showed that fine sanded surface (test series 1) achieved the best bond strength results by far with an average maximum bond stress of 8,30 N/mm². The smooth and coarsely sanded surface achieved an average of 2,51 N/mm² (test series 1) and 1,99 N/mm² (test series 3), which demonstrates that the surface roughening does not necessarily lead to bond strength improvement.

The test series 1 with fine sanded lamellae reached a maximum pull-out force of approximately 20 kN with a bond length of 8 cm. On the assumption, that the maximum chargeable bond stress remains constant when the bond length is enlarged, the projected anchorage length of the investigated CFRP lamellae is 25 cm.

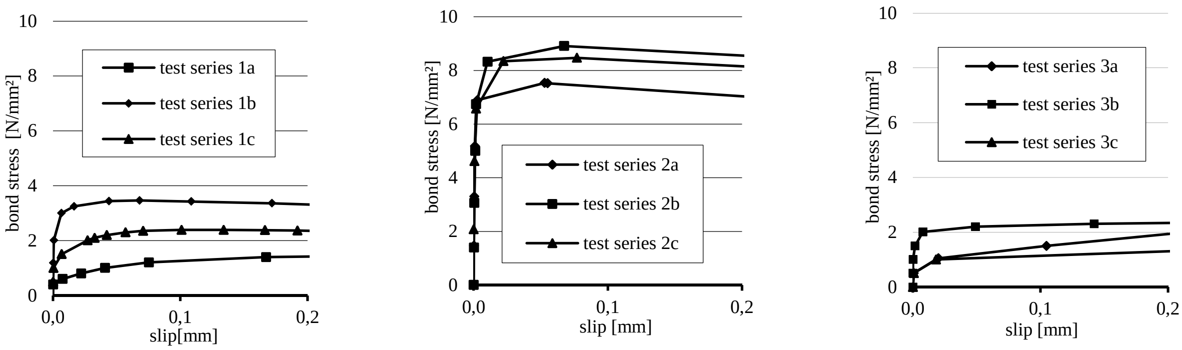


Figure 9: Bond stress-slip relationship of test series 1-3

## 4.3 Bending Behavior

For the investigation of principle bending behavior of thin walled UHPC plates with steel-fibers and centric CFRP lamellae, 4-point bending tests were carried out in February 2012 at the Laboratory for Structural Engineering. The plate elements had a thickness of 2,5 cm and spanned a length of 60 cm. The CFRP surface was roughened with fine sand, as described before.
In order to get comparison values, the tests were carried out with two different types of reinforcement: UHPC plates with steel fibers and 3 centric CFRP-lamellae (test series 1), and UHPC plates with steel fiber reinforcement only (test series 2). The test´s intention was to investigate the influence of centric CFRP-reinforcement on stiffness, crack formation and maximum load capacity of thin UHPC plates.

Figure 10: Cross section of the UHPC plate used for test series

The test results show that UHPC plates with centric CFRP reinforcement (test series 1) had an almost 8 times higher breaking load than those without (test series 2). Consequently, the reinforcement causes a significant increase of load bearing capacity. The bending stiffness $EJ^I$ in the non-cracked condition was 150.000 (test series 1) and 120.000 kNcm$^2$ (test series 2), the concrete cracked at a moment of 35 kNcm (test series 1) and 31 kNcm (test series 2). Thus, the centric CFRP reinforcement did not increase bending stiffness in non-cracked condition and crack moment substantially.

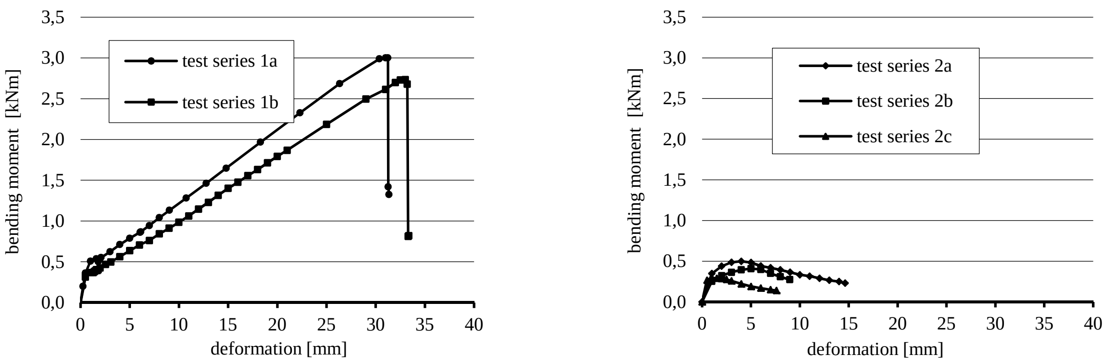


Figure 11: Bending moment-deformation relationship of test series 1 and 2

# 5 Connecting Methods

One of the core issues of prefabrication is the connection of the segments. In a loadbearing shell made of prefabricated elements, the joint primarily has to carry membrane forces, but also bending moments and transverse forces. Just a few examples using joining technologies that can fulfil the requirements were realized.

a) Wet joints - Subsequent cast of the joints with overlapping reinforcement [10].
b) Use of semi-precast parts, which are casted with a second external concrete layer. Prominent example is the "Palazetto dello Sport" in Rome by Pier Luigi Nervi [11].
c) Carry of the internal forces by high precision, subsequent finished "dry joints" in combination with reversible fasteners, eventually used for prestressing. Realized example is the "Wildbrücke" in Völkermarkt [12].

## 5.1 Methodology

The method that is brought into focus is the "dry joint". Idea of this technique is to maximize the surface contact and thereby the static friction. The segments can be connected by reversible fasteners. This technique requires high precision grinding of the contact faces.
According to these requirements the tools and the grinding material were developed in close cooperation with Rappold Winterthur Technology GmbH. They are available for first tests. The specification was defined as following:

a) Material: Steel fibre reinforced UHPC
b) Precision: 2/10 mm measured at the outline
c) Minimize forces in the tool

The process scheme is known from the typical milling process and is divided in two stages. In the first step the tool roughs down the concrete. In the second step the abrasive disc cuts the steel fibre reinforcement. The first tests attest the strategy fulfilling all demands. On-going research focuses on questions of speed and the rate of removal.

Figure 12: First attempt of wet machining

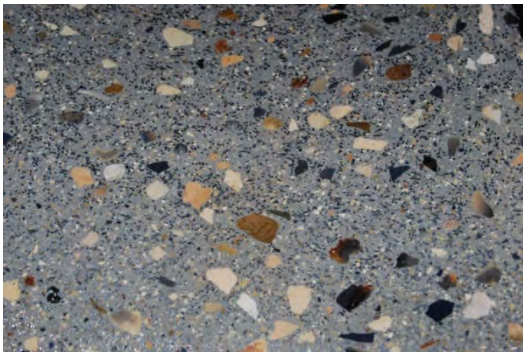


Figure 13: Grinded contact face

A transfer of this strategy for the application on double curved elements is aim of the next steps.
Arising questions to solve are:

- Get knowledge about the tool material interaction using thin elements made from UHPC
- Questions of measurement systems to align the elements and to verify the results of machining

## 6 Preview

Previous results of our research demonstrate the potential of the new developed procedure. The interacting of the three topics: “form/geometry”, “material” and “assembly/fabrication” have become a key issue at the Institute for Structural Design.
In the next 4 years to come the realization of a big scale prototype of a parametrical designed and prefabricated UHPC-shellstructure will be the aim of our research.

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# Breathable Glass Facade

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## Summary

This paper describes a research project initiated by MArch student Andrei Gheorghe in collaboration with engineers (Werner Sobek, TimMacFarlane) at the Graduate School of Design (GSD) Harvard. The project explores degrees of visual and climatic permeability by using glass. It introduces glass fins, which are twisted in order to allow for cross-ventilation and dichroic effects.

The torsion capability of glass is analyzed with the aim to create a porous, air permeable façade prototype. Further aspects are identifying the effect of twisting on the bending capacity of glass and corresponding deflection measurements. The project attempts to identify the technical limits of this application through FE analysis and small scale model building.

Design aspects and material qualities of dichroic glass are investigated. Through layers of metal oxide, visible light is split in beams of different wavelenghts (colors). The color changes at different viewpoints. Details and alternative solutions of joints and gaskets are developed and discussed.

**Keywords:** twisted glass, dichroic effects, permeable glass facade, kinetic facade

## 1 General Approach

With fast developments currently occurring in structural design techniques, technology and ecotechnology, one of the most fascinating and interesting frontiers in architecture takes place during collaborations of designers with open-minded engineers ‘Sobek et al. [1]’. The research project was conducted by MArch student Andrei Gheorghe in collaboration with the engineers Werner Sobek and Tim Macfarlane at the Graduate School of Design (GSD) Harvard. The project explores degrees of visual and climatic permeability by using glass. It introduces glass fins, which are twisted in order to allow for cross-ventilation and dichroic effects.

### 1.1 Main Question

The torsion capability of glass is analyzed with the aim to create a porous, air permeable façade prototype. Further aspects are identifying the effect of twisting on the bending capacity of glass and corresponding deflection measurements. The project attempts to identify the technical limits of this application through FE analysis and small scale model building. Design aspects and material qualities of dichroic glass are investigated. The glass color changes at different view points and perspectives. Details and alternative solutions of joints and gaskets are developed and discussed.

## 2 Aesthetics

### 2.1 Light in Architecture

According to Ed Carpenter ‘[2]’, the manipulation of light in architecture becomes a game of layering and texturing, obscuring and revealing, and allowing the movement of shadows and light patterns to animate a room, wall or courtyard. A building acts as the stable vessel into which sublime forces may be projected. Good architects all understand this. Le Corbusier’s chapel at Ronchamp, Aalto’s libraries and Ando’s pierced structures are obvious examples. Furthermore, light has most emotional power when it is filtered, or reflected, or intensified by mediating elements ‘[2]’.

### 2.2 Dichroic Glass

The affective qualities of light are accentuated by motion of the mediating elements. Natural light becomes transcendent when it is being squeezed through small openings, or broken into patterns, or filtered into colors while coming from a hidden source ‘Carpenter [2]’. Kinetic effects may be transmitted which bring into a building a mysterious living pulse. Multicolored projections of light patterns in the Oregon Institute of Technology are created by sun passing through strips of dichroic glass. The visual display changes color depending upon the angle of entrance or reflection of light ‘[3]’.

Figure 1: Dichroic effects © Carpenter, © Blazy, through metal oxide layers

In this research project, design aspects and material qualities of dichroic glass are investigated. Through layers of metal oxide applicated on the glass, visible light is split in beams of different wavelenghts (colors) ‘[4],[14]’. The color changes at different view points. Figure 1 displays reference examples by James Carpenter and John Blazy.

## 3 Sustainability

### 3.1 Overheating

With the increasing use of glass in facades the realization of the disadvantages became visible: overheating and heat loss ‘[5]’. In 1969, in “The Architecture of Well-Tempered Environment” Reyner Banham spoke against the high energy requirements of artificial air conditioning systems ‘[6]’. People like Mike Davies ‘[6]’ started to propose the development of multiple performance glazing which could dynamically regulate the energy flow from outside to inside and vice versa.

The “Breathable Glass Façade” project explores degrees of climatic permeability by using glass. Glass fins are twisted in order to allow for cross-ventilation and reduce overheating.

## 4 Kinetic Architecture

An “intelligent” glass façade can adapt in a dynamic, almost “living” way to changing light and weather conditions using self-regulating thermal protection and solar control measures ‘[5]’. According to Andrea Compagno, the “intelligence” of a façade is not measured primarily by how much it is driven by technology, but how it makes use of natural, renewable energy sources, such as solar radiation, air flows and the ground heat in as environmentally compatible way as possible ‘Compagno [5]’.

The “Breathable Glass Façade” project uses twisted glass fins. This research attempts to identify the technical limits of this application through FE analysis and testing through small scale kinetic models. Figure 2 displays the kinetic concept.

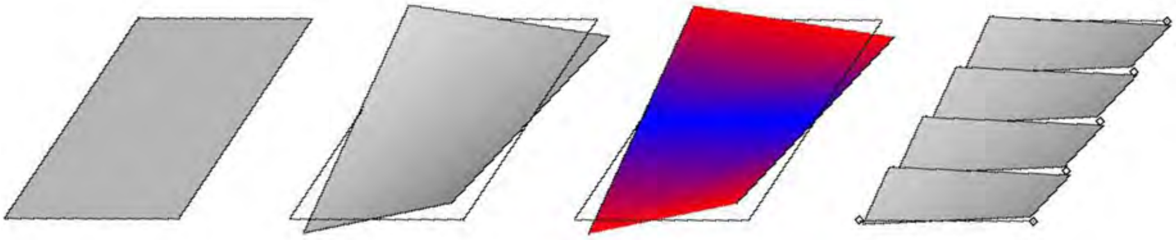

Figure 2: Kinetic principle

# 5 Innovative Material Use

## 5.1 Structural Glazing

Recent research used glass as a structural element to withstand vertical loads. According to analysis by Dewhurst '[7]', glass is about a third as stiff as steel, which means it will stretch, 3 times more than steel for any given tensile stress. Youngs Modulus for Elasticity for glass is 70,000 N/mm2, compared with 210,000 N/mm2 for steel. Steel copes with high stresses by first yielding or undergoing plastic flow then if high levels of stress are maintained will, after considerable deformation, fail. In steel structures this plastic deformation allows high concentrated loads to be distributed to other parts of the structure preventing sudden or brittle failure of the member. Glass does not exhibit plastic flow and will break as soon as its tensile limit is reached.

The failure stress for Fully Heat Tempered (HT) Glass is 150 N/mm2, for Heat Strengthened (HS) Glass 120N/mm2, and for Chemically Toughened Glass 300N/mm2 '[8],[9]', and it is generally accepted in the industry that a safety factor of 3 for all glass types is appropriate '[7]'. For glass structures designed for wind loading a figure of 70/3 = 23N/mm2 and for all other glass structures a figure of 40/3 = 13N/mm2 is recommended '[7]'. The Apple Store in New York shows a fully structural staircase of vertical loaded glass that has been built by using HT Glass '[10]'.

## 5.2 Twisted Glazing

This project follows an alternative approach. It aims to develop a porous facade system of operable lamellas by twisting glass. Glass has a certain ability to twist before it breaks. Longitudinal shaped glass fins are fixed in position at their endpoints and are twisted in their midpoints. This creates openings that can be beneficial for climatic or visual effects. Through the twisting operation, the glass fins become stiffer and withstand higher horizontal (wind) loads. Figure 3 shows the effect of twisting on the bending capacity of glass and corresponding deflection measurements. The torsion capability of glass is therefore used with the aim to create a porous, air permeable façade prototype.

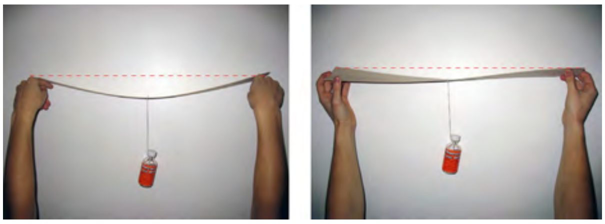

Figure 3: Reduced deflection behavior of lamella after torsion is applied.

# 6 Structural & Constructional Requirements

## 6.1 Structural System

The glass façade in the Netherlands Architecture Institute consists of frameless glass panes with silicone joints held in place by a pre-tensioned 3D framework of cables. These are connected with point fixtures to the glass panes. Minimal deflections are taken into considerations and can be absorbed with the flexible cable sub-structure '[11]'.
For the "Breathable Glass Façade" project setup (Fig.4), longitudinal glass fins (ratio approx. 1:10) have been arranged vertically. Due to maximum fabrication limits and functional requirements (transportation, handling, etc) stripes of 400 mm width and 6000 mm length have been chosen for structural testing.

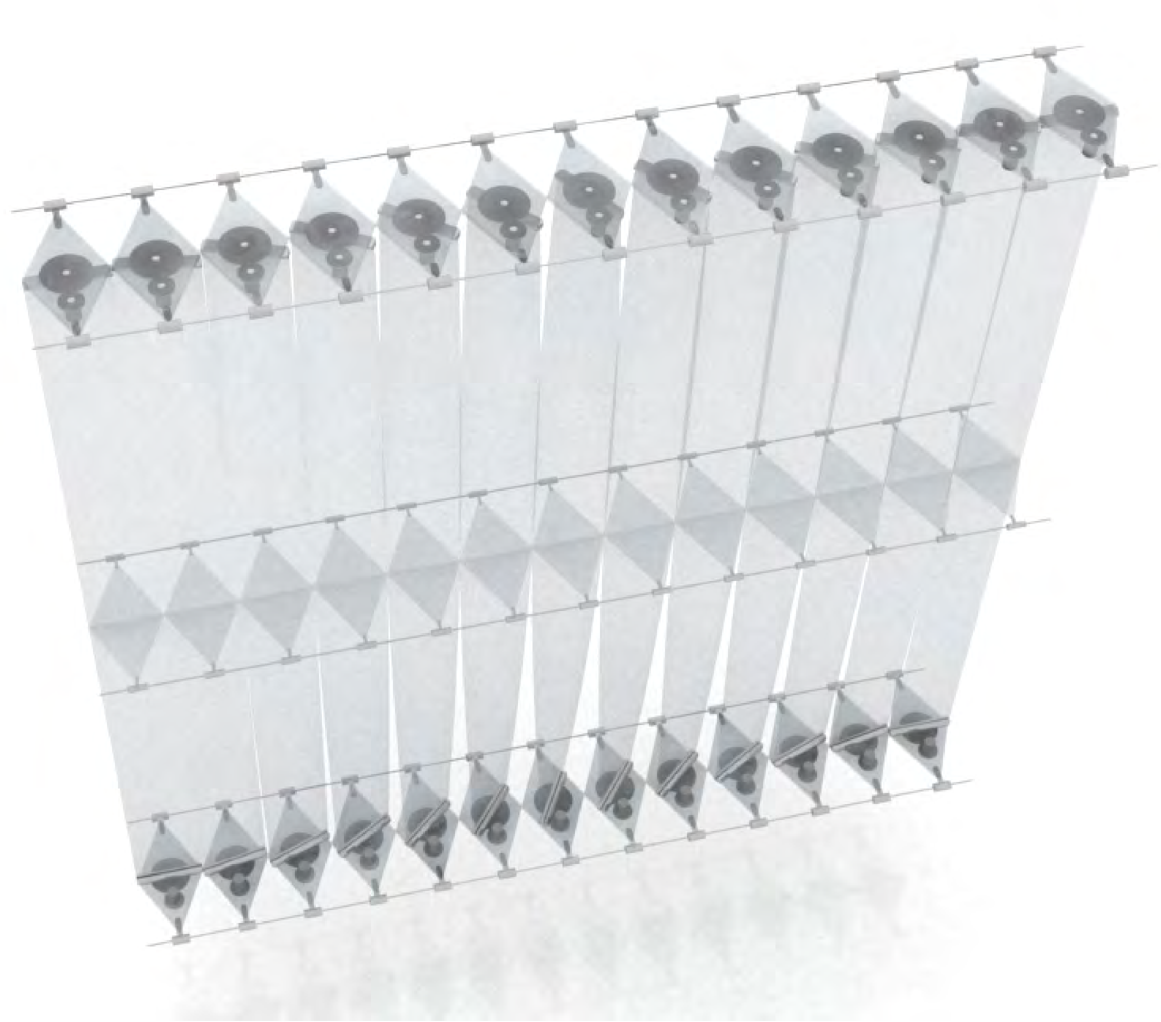

Figure 4: Façade System

The lamellas are fixed on their lower and upper endpoints through a horizontal truss system. Horizontal tension cables apply torsion at the midpoint of the glass lamella (Fig. 5,6).

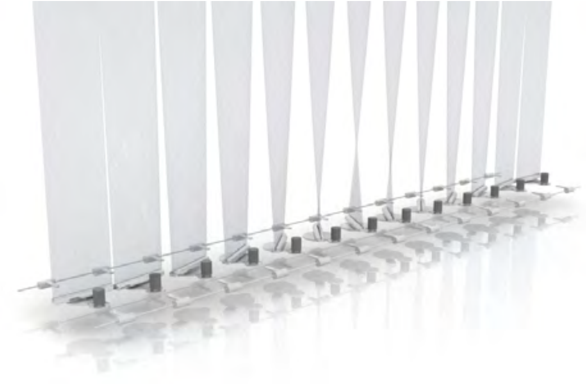

Figure 5: Structural System

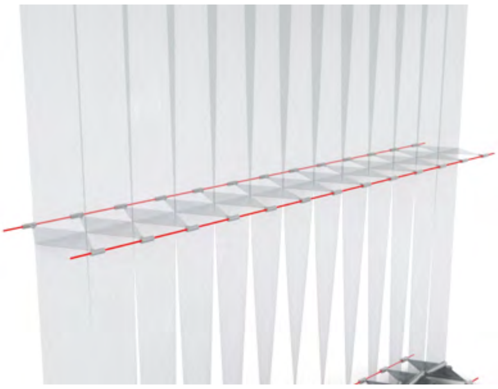

Figure 6: Tension cables of horizontal truss.

The performance calculations and analysis has been conducted in collaboration with Tim Macfarlane / Dewhurst and Martin Bechtold / GSD Harvard - Solid works 2008 (non-linear FE analysis). Torsion has been applied to assess the maximum twisting angle before failure.

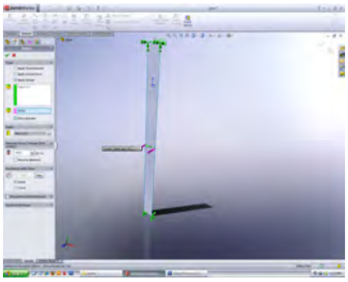

Figure 7: Force Load

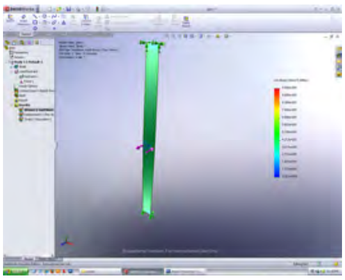

Figure 8: Stress

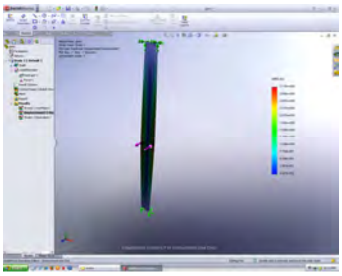

Figure 9: Deformation

The maximum opening angle for the glass fins (6000 x 400 x 6 mm) figured approx. 50 degree. This results in a maximum porosity (relation of open to total glass surface) of 56.3 % (Fig. 10,11).

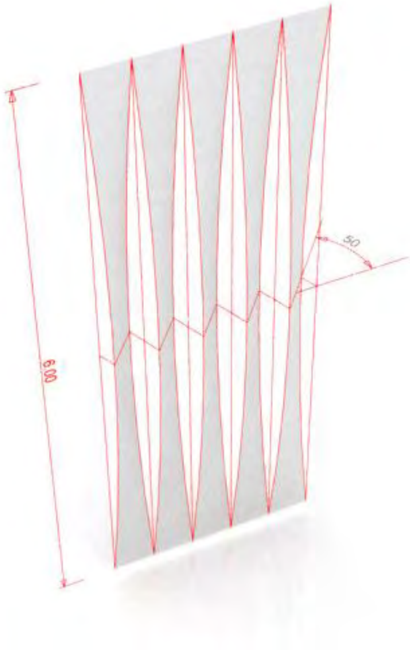

Figure 10: max. torsion angle 50°

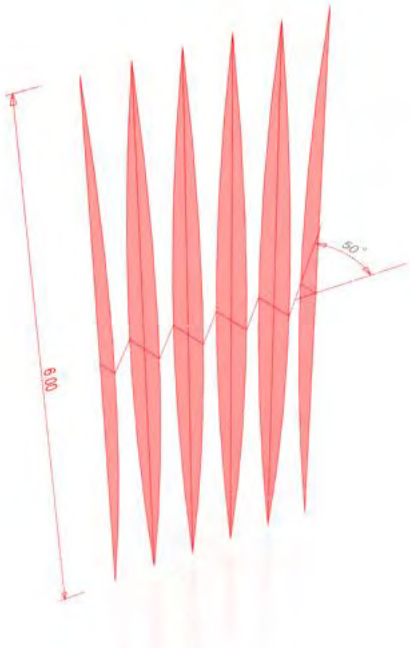

Figure 11: max. porosity achieved 56.3%

### 6.2 Joints

The Elbphilharmonie building by Herzog & deMeuron, sliced and opened the massive glass skin to provide natural ventilation, as well as to draw in the smells and sounds of the environment '[12]'. According to Herzog & deMeuron '[12]', the formal deformation of the glass creates openings in the façade and generates a rich play of reflections that transforms according to the location, weather and perspective.

In the "Breathable Glass Façade" project, the glass fins are in their initial position while the façade is closed. In this position, the joints have to guarantee water and wind tightness. After analyzing reference examples '[13],[15]', details and alternative solutions of joints and gaskets (single glazing, double glazing, laminated glass ) were developed and discussed in collaboration with Timo Schmidt and Werner Sobek. Figure 12 shows different detailing options for single and double-glazing.

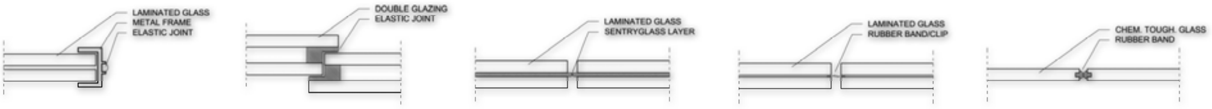

Figure 12: Joint details

## 7 Prototype Model

### 7.1 Kinetic Prototype Model

A prototype of the façade was produced in a scale of 1:10. To simulate the bending of the lamellas in the corresponding material thickness, acrylic sheets have been used as a substitute for glass. The fins are fixed a their ends, and a horizontal truss system with tension cables enables the functional operability. Servo motors are linked with arduino and controlled over the a processing control board directly from a laptop computer. Figure 13 displays the experimental setup.

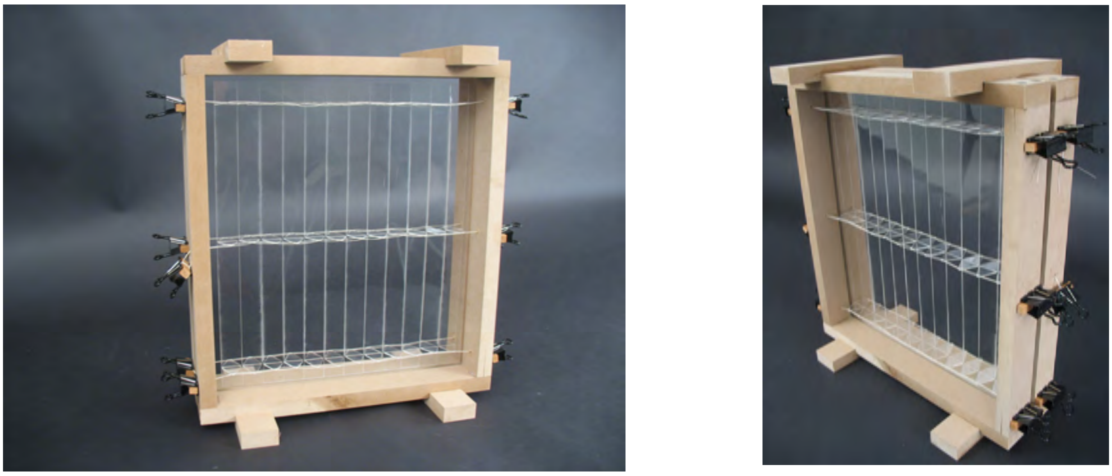

Figure 13: Kinetic Model Setup

### 7.2 Kinetic Model Analysis

The tests have been satisfactory. A considerable amount of tension force has been applied to allow for the opening of the lamellas. The software could easily be updated with a wind or temperature sensor to activate the opening procedure not manually, but interactively according to the prevailing climatic and environmental parameters. Figures 14 and 15 display the opening capability and different opening scenarios of the kinetic model.

Figure 14: Closed Position

Figure 15: Open Position

## 8 Conclusion

This project suggests a radical new approach towards using glass. Usually, twisting is avoided, due to the brittle behavior of glass. The author claims that applying torsion below certain limits will allow to create openable glass façade systems. This will help reduce mechanical ventilation by allowing natural ventilation when needed. Through the use of dichroic glass visual color effects can be achieved through the twisting motion. This project attempts to apply kinetic principles to combine technological knowhow and aesthetic effects while offering a new experimental approach on glass façade systems.

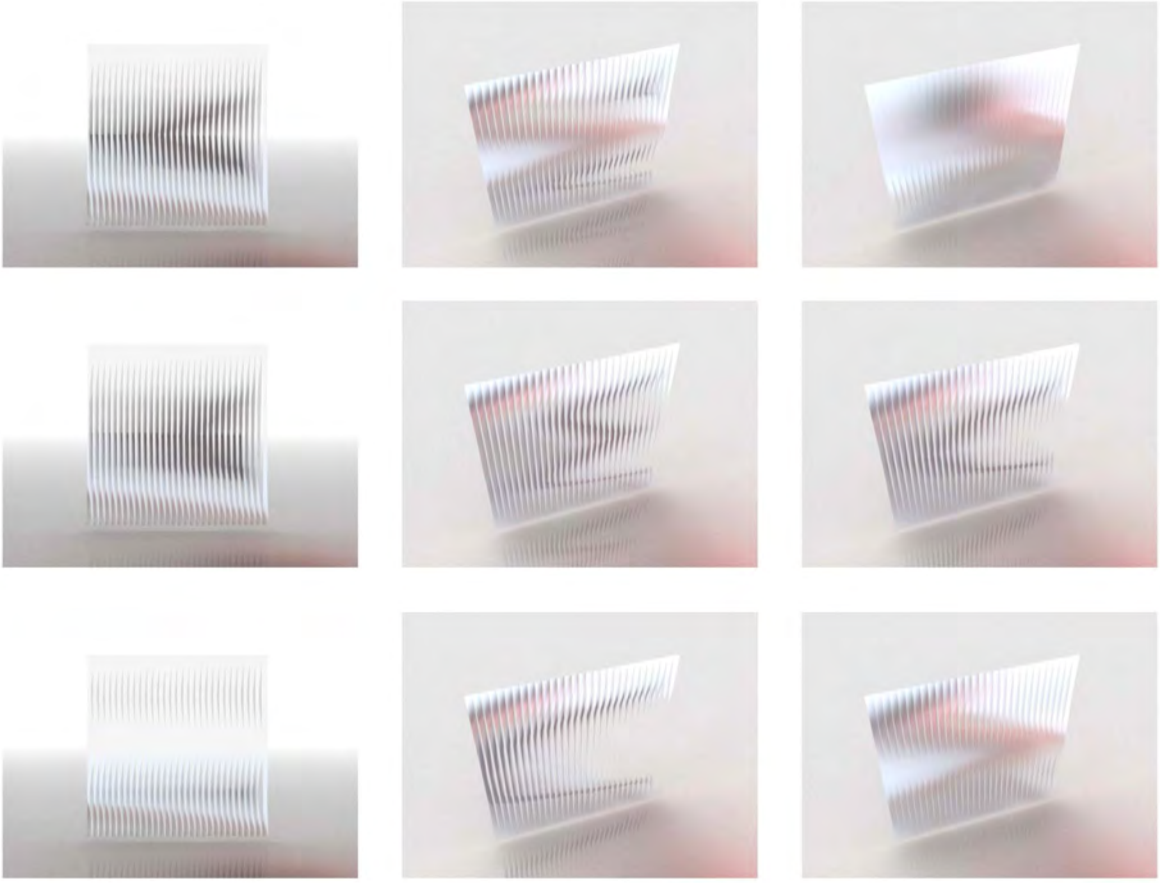

Figure 16: Simulated Dichroic Effects during Opening Operation

## 9 Acknowledgements

The author would like to thank Samina Gheorghe for the support in creating and editing this paper.

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# Numerical and Experimental Analysis of Suspended Glass Fins

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## Summary

Transparency is a characteristic, which is often requested for the facades of banks, shopping malls, office buildings or other public constructions. One possibility to increase the transparency of the facade is to use glass not only to separate the interior of the building from the exterior, but also as structural elements in the form of glass fins. In this paper a rectangular and a trapezoidal geometry for glass fins are analysed and compared. Additionally, grout and thermoplastic blocks are used as contact materials for both geometries in order to apply the loads into the glass edges. The results of numerical simulations and experimental tests are discussed and conclusions about which glass fin type behaves the best are formulated.

**Keywords:** Transparent Facades, Glass Fins, Structural Glass, Load Application into Glass Edges, Contact Materials, Grout, Thermoplastics

## 1 Introduction

The recent developments in the design of transparent building skins involve a maximal reduction of the ‘visible’ structure. To achieve this purpose architects either plan cable facade systems or use glass as structural elements. In the second case the glass facade can be designed to bear loads by itself (*Figure 1 left*) or glass fins can be used to stiffen the facade (*Figure 1 right*). For glass fins there are several standard solutions, but there is still room for optimisation.

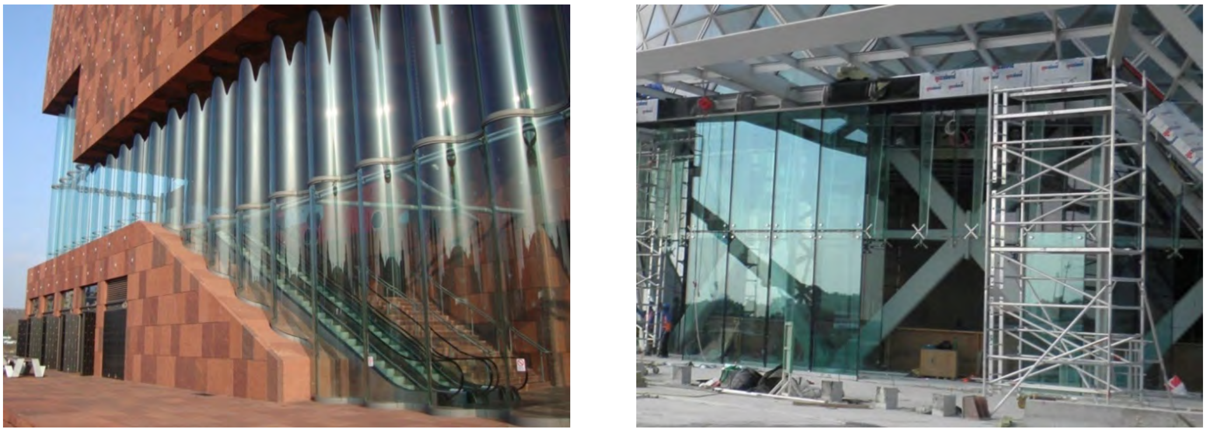

Figure 1: Curved glass facade at the MAS (Museum aan de Stroom) in Antwerp, Belgium (left); Glass fins at the Main Entrance Canopy of the ADNEC Capital Gate in Abu Dhabi (right) [by courtesy of Waagner-Biro]

The main problem in the design of glass fins is the development of the connection between the glass part and the supporting (steel) structure. Usually bolted connections in combination with grout, resin or thermoplastic blocks (POM, PA 6) are used [1]. Disadvantages of this type of connection are the boreholes in the glass, which have to be realised before the heat strengthening process and which bring extra costs and imperfections (for example an offset of the glass edges in the case of laminated glass).

## 2 Analysed Types of Glass Fins

The aim of the research was the optimisation of suspended glass fins, focusing on the load application from the fin into the steel supporting structure [2]. This interesting research topic was proposed by Waagner-Biro Stahlbau AG. Two different geometries were analysed, a rectangular one and a trapezoidal one. As contact materials the grout Hilti HIT-HY70 and the thermoplastic material polyoxymethylene (POM) were used and compared for both geometries. This resulted in four different types of glass fins, which were analysed in this research. In all cases laminated glass formed of three sheets of fully tempered glass and polyvinylbutyral (PVB) as an interlayer was used. The fins had a length of 2,8 m and the support area was 0,5 m long. Other dimensions are shown in *Figure 2*. In the numerical model the glass was simulated as one sheet with shell elements with a thickness of 24 mm. The effect of the lamination was not important, since the fins were loaded in the plane of the glass sheets and stability problems were not analysed in this research project. For the experimental tests a stability failure was also excluded.

### 2.1 Geometries

First, the more common rectangular geometry (*Figure 2 left*) has been analysed. In this case the dead load is transferred by a bolted connection with one bolt. Horizontal loads (e.g. wind load) are transferred by contact at the glass edges. In the case of the second analysed geometry (*Figure 2 right*), due to the inclined edge, all the loads can be transferred by contact at the glass edges. The big advantage is that no boreholes and no bolts are needed anymore.

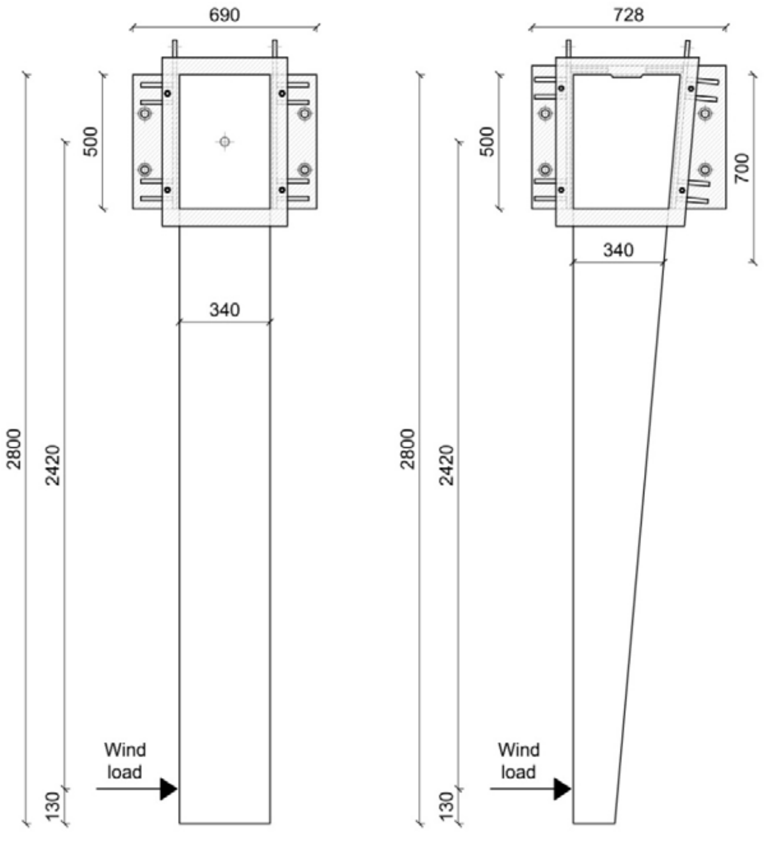

Figure 2: Rectangular (left) and trapezoidal (right) geometry of the analysed glass fins

## 2.2 Contact Materials

As contact materials both the two-component grout Hilti HIT-HY70 and the thermoplastic material POM were analysed in the numerical and experimental studies. For the numerical modelling pressure spring elements were used for both contact materials. The length of the thermoplastic blocks and the distance to the upper glass edge were determined in parameter studies. Results on the mechanical values for the thermoplastic materials POM and PA 6 can be found in [4]. The problems which occur in the case of load application into glass edges are summarized in [3]. The *Figures 3* and *4* show the location of the contact materials in the supporting area for the rectangular and the trapezoidal glass fins.

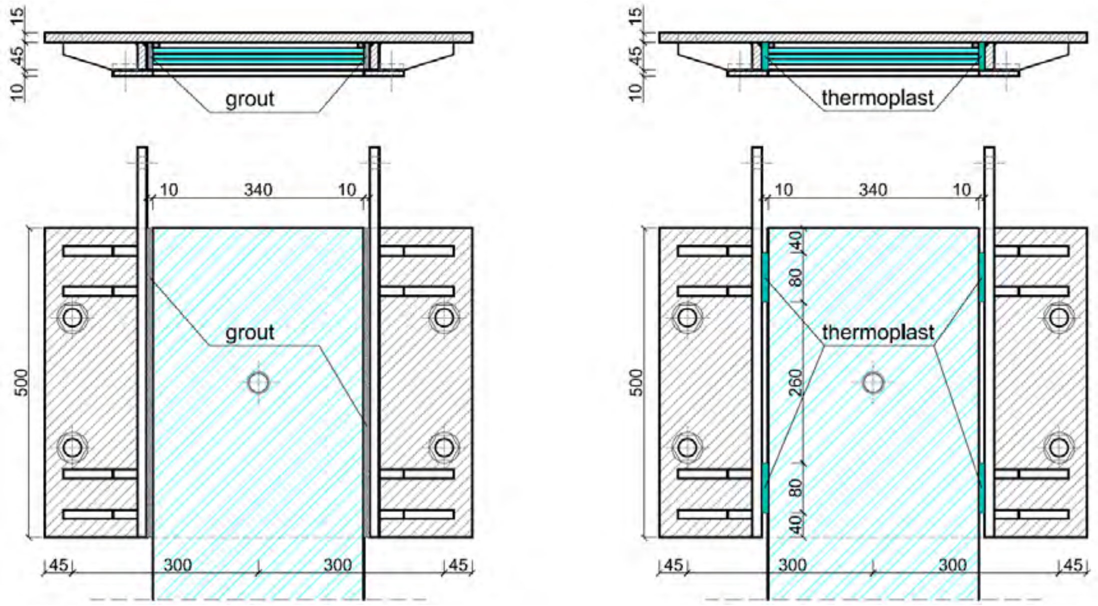

Figure 3: Supporting area of the rectangular glass fins with grout (left) and with thermoplastic blocks (right)

In the case of a horizontal load (wind) on the edge of the trapezoidal glass fin the reaction force at the inclined edge includes a vertical component. To reach an equilibrium state it is necessary to transfer loads also at the upper edge of the glass fin. This is the reason why contact materials were arranged also at this edge (*Figure 4*).

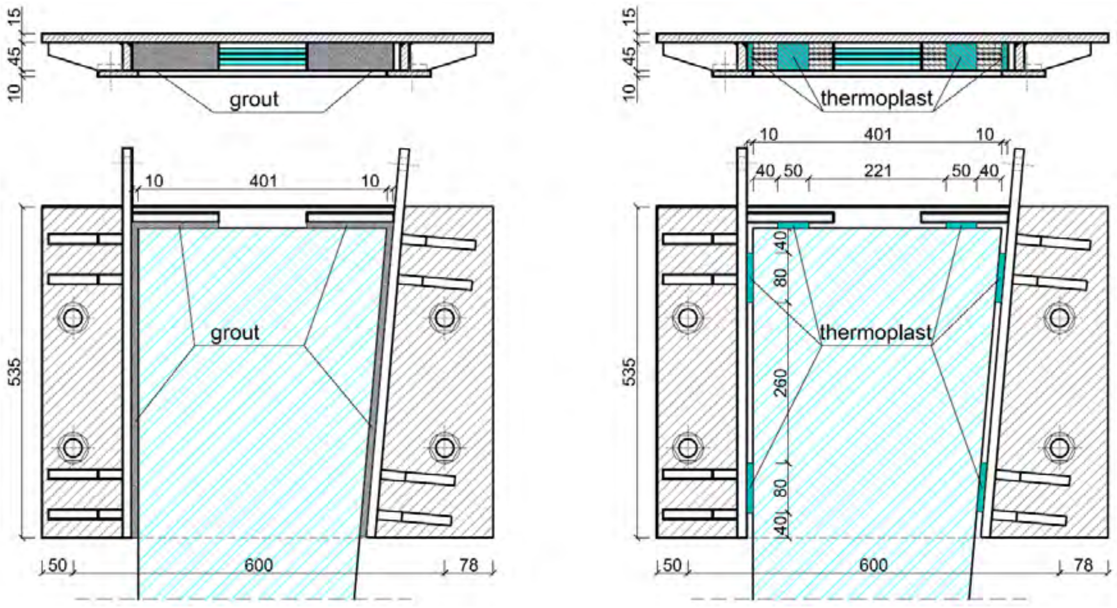

Figure 4: Supporting area of the trapezoidal glass fins with grout (left) and with thermoplastic blocks (right)

## 3 Results of the Analysis

In this chapter the results of the numerical and the experimental analysis are shown and compared. For the experimental tests (financed by the Waagner-Biro Stahlbau AG and performed at the Institute of Structural Engineering/Steel Structures of the Vienna University of Technology) different measurement techniques were used:

- Inductive displacement transducers - to measure the relative displacement between the glass fin and the testing frame (displacement 1), the relative displacement between the glass fin and the supporting steel bracket (displacement 2) and a potential displacement of the glass fin out of plane;
- Strain gauges – to measure the maximal tensile and compressive strain below the supporting area;
- Photogrammetric measuring system ARAMIS [5] – to measure the strain distribution in the supporting area.

First some measured parameters from the experimental tests are shown in *Table 1*. The highest failure loads were reached in the case of the trapezoidal glass fins with grout as contact material. The maximal measured tensile stress of 147 N/mm$^2$ is 1,25 times higher than the characteristic tensile strength for glass of 120 N/mm$^2$ mentioned in standards.

Table 1: Measured parameters for the different experimental analysed glass fins

| Test specimen | Failure load [kN] | Maximal strain [%] | Maximal tensile stress [N/mm$^2$] |
|---|---|---|---|
| Test run – trapezoidal glass fins with grout as contact material | | | |
| V1M | 33,9 | 0,19 | 133 |
| V2M | 35,3 | 0,21 | 147 |
| V3M | 29,8 | 0,17 | 119 |
| Test run – trapezoidal glass fins with thermoplastic blocks as contact material | | | |
| V4K | 29,5 | 0,19 | 133 |
| V5K | 33,0 | 0,21 | 147 |
| V6K | 25,4 | 0,20 | 140 |
| Test run – rectangular glass fins with grout as contact material | | | |
| R7M | 30,2 | 0,18 | 126 |
| R8M | 30,4 | 0,18 | 126 |
| R9M | 31,1 | 0,20 | 140 |
| Test run – rectangular glass fins with thermoplastic blocks as contact material | | | |
| R10K | 24,2 | 0,16 | 112 |
| R11K | 24,8 | 0,17 | 119 |
| R12K | 23,4 | 0,15 | 105 |

In the next two sub-chapters the results of the analysis are separately treated for the rectangular and the trapezoidal fins. Load-displacement diagrams, stress/strain distributions and some pictures of the test specimens are shown.

## 3.1 Rectangular Glass Fins

In the *Figure 5* two load-displacement diagrams are shown. The load application during the experimental tests occurred displacement-controlled. The diagram in *Figure 5 left* shows the relative displacement of the glass fin to the testing frame for the three tested rectangular glass fins with thermoplastic blocks as contact materials. Beside the stiffness of the glass and of the contact materials, these curves also include the relative movement of the steel bracket to the testing frame, because of the play between bolts and boreholes. The diagram in *Figure 5 right* illustrates the relative displacement of the glass fin to the supporting steel bracket for the same test specimens. The black load-displacement line is the numerical determined one. A good agreement cannot be recognized, because the measured load-displacement curves do not coincide among each other. The buckles and the changes of direction in the curves can be explained by changes which happen in the system, for example the slipping of a thermoplastic block.

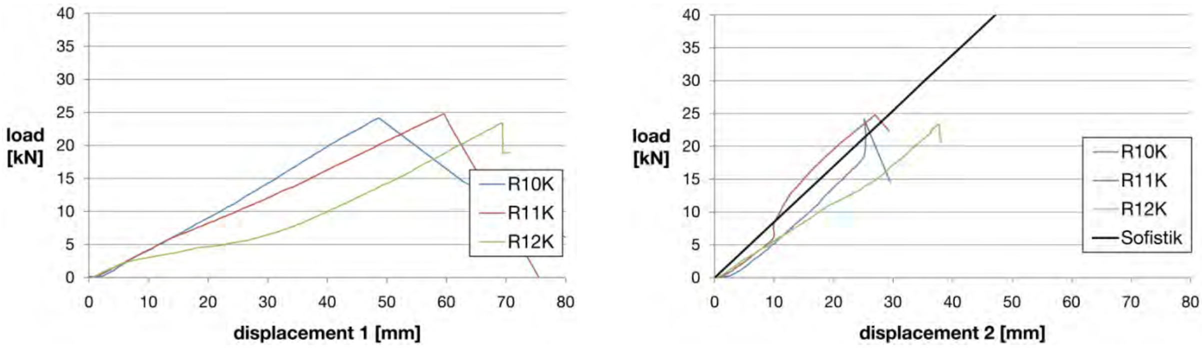

Figure 5: Load-displacement diagrams for the rectangular glass fin with thermoplastic blocks as contact material: relative displacement between glass fin and testing frame (left); relative displacement between glass fin and supporting steel bracket (right)

*Figure 6* shows the stress distribution from the numerical simulation (left) and the strain distribution measured with ARAMIS (right) for the test specimen R10K. For both pictures the load level before failure has been chosen. A very good qualitative similarity can be observed. Quantitative, single strain values were compared on failure load level and showed a good agreement. A more detailed evaluation of the photogrammetric measurement results is in progress.

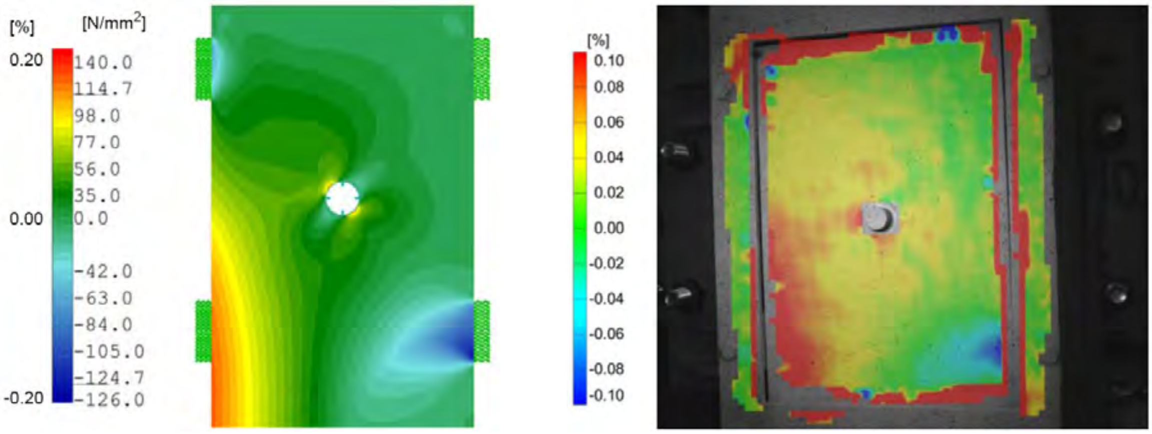

Figure 6: Rectangular glass fin with thermoplastic blocks as contact material: stress/strain distribution from the numerical simulation (left); strain distribution from the photogrammetric measurement (right)

An important aspect for using glass as structural elements is the residual load-bearing capacity after failure. Except for one test specimen, in the case of all other rectangular glass fins all three sheets broke at the same time. Due to the bolted connection and to the PVB-interlayer, the glass fin did not fall down from the steel support (*Figure 7 left*). Unfortunately, the glass fin loses its stiffness because of the breakage of all sheets at the same time (*Figure 7 middle*) and can't bear anymore loads. This is one of the reasons why a high redundancy is necessary, when structural glass elements are included in a facade design.

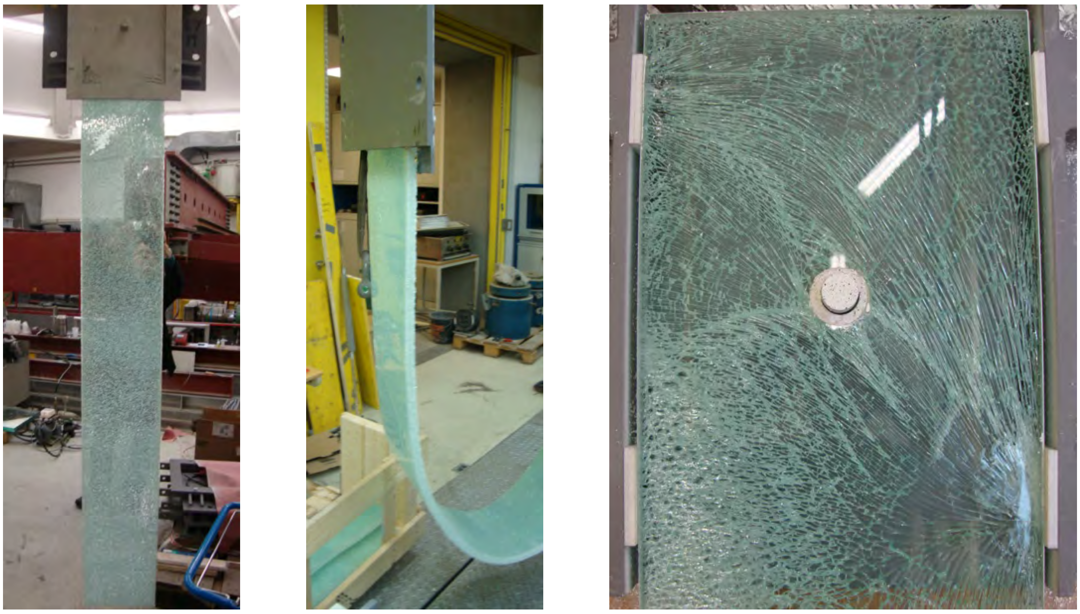

Figure 7: Rectangular glass fin: residual load-bearing capacity (left & middle) and fracture pattern (right)

*Figure 7 right* shows the fracture pattern for the test specimen R12K, the unique one for which only one glass sheet broke. This is advantageous for analysing the fracture pattern, because the stress trajectories can be clearly recognised. It is obvious that in the induced load scenario only the upper left and the lower right thermoplastic blocks are effective – only here loads are transferred from the glass fin into the supporting steel bracket. It can be also observed that a compression diagonal goes exactly through the borehole. This is the reason why the position of the borehole in the middle of the supporting area is not the most convenient.

## 3.2 Trapezoidal Glass Fins

*Figure 8* shows load-displacement diagrams for the trapezoidal glass fins with grout as contact material. The diagram in *Figure 8 left* illustrates the relative displacement of the glass fin to the testing frame, while that exhibited in *Figure 8 right* shows the relative displacement of the glass fin to the supporting steel bracket. The black line in the second diagram is numerical determined and shows a good agreement with the measured load-displacement curves. This proves that the grout can better adjust to imperfections in the steel surface or at the glass edges.

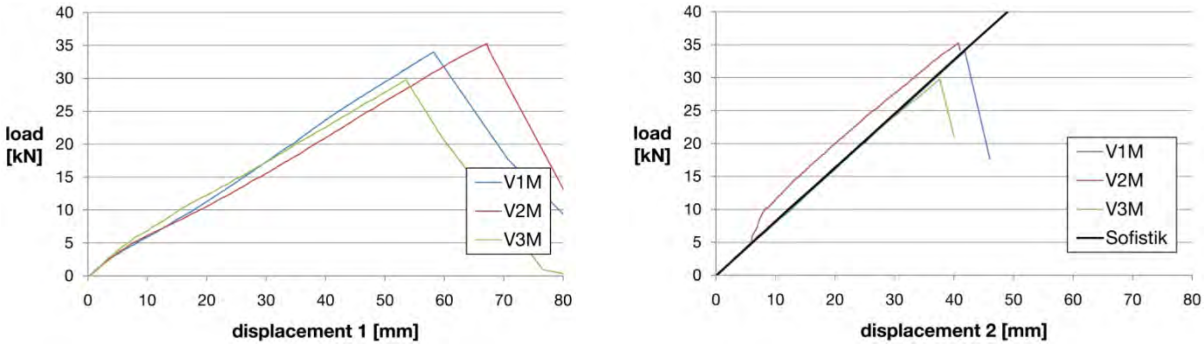

Figure 8: Load-displacement diagrams for the trapezoidal glass fin with grout as contact material: relative displacement between glass fin and testing frame (left); relative displacement between glass fin and supporting steel bracket (right)

*Figure 9* shows the stress distribution from the numerical simulation (left) and the strain distribution measured with ARAMIS (right) for the test specimen V1M. For both pictures the load level before failure has been chosen. As in the case of the rectangular glass fins with thermoplastic blocks shown in *Figure 6* a very good qualitative similarity can be observed. For this specimen, single strain values were also compared on failure load level and showed a good quantitative agreement.

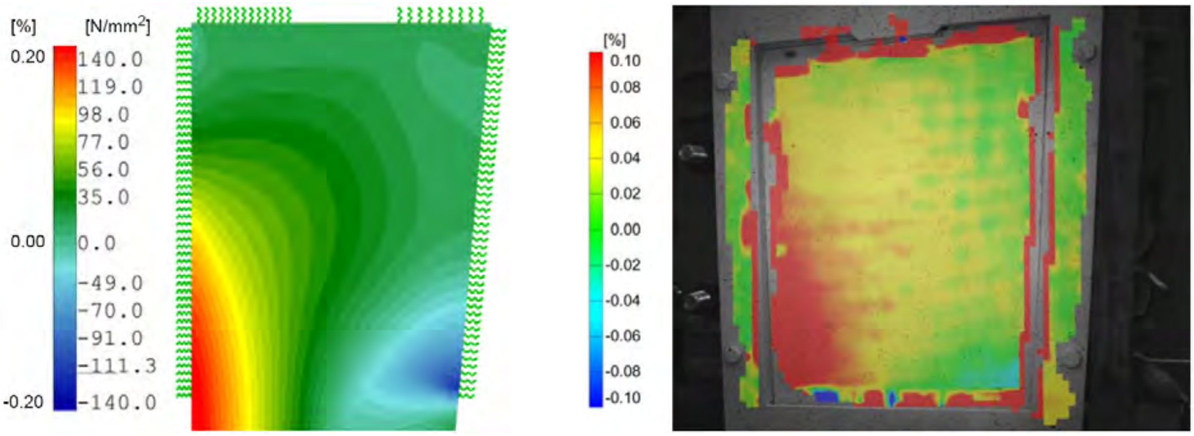

Figure 9: Trapezoidal glass fin with grout as contact material: stress/strain distribution from the numerical simulation (left); strain distribution from the photogrammetric measurement (right)

Concerning the residual load-bearing capacity the same observation as for the rectangular glass fins could be made. Even though there is no bolted connection from which the PVB-interlayer could hang, the glass fins remain in the steel brackets after failure (*Figure 10 left*). This happens because the broken glass fin clamps in the narrowing bracket. Because of the breakage of all three sheets, also the trapezoidal fins lose their stiffness (*Figure 10 middle*) and cannot bear anymore loads.

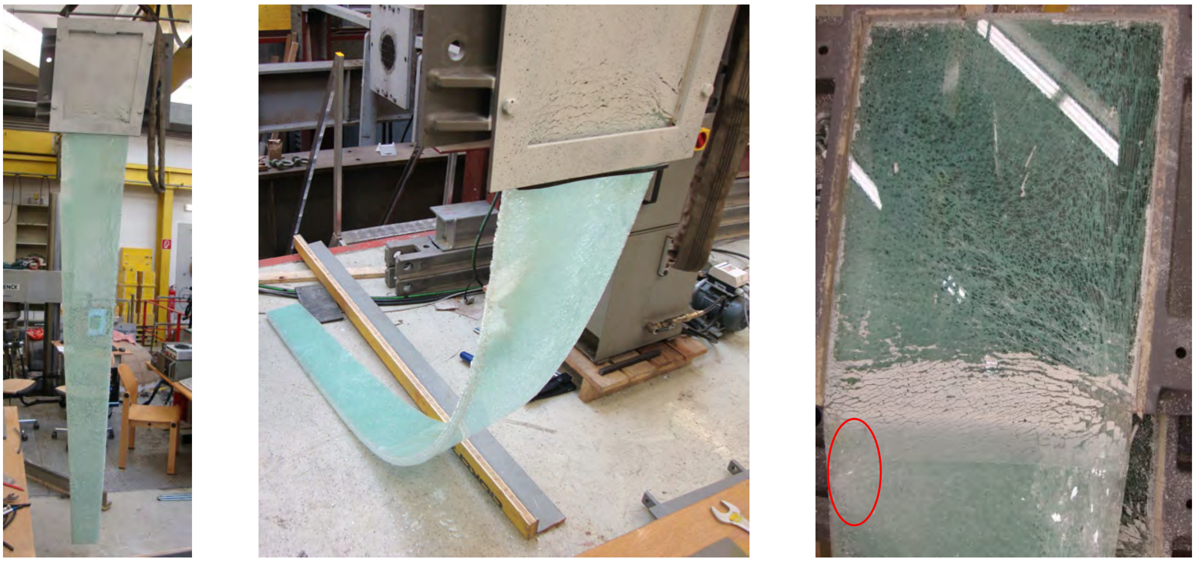

Figure 10: Trapezoidal glass fin: residual load-bearing capacity (left & middle) and fracture pattern (right)

*Figure 10 right* shows the fracture pattern for a trapezoidal glass fin with grout as contact material. The trajectories are not as clear as in the case of the rectangular fin shown in *Figure 7 right*, because all three sheets are broken and the fracture patterns are overlapped. However, it can be recognised that a compression trajectory goes to the upper edge, so the arrangement of contact materials in this area is justified. The initial fracture point can be observed at the left edge (tension).

## 4 Conclusions

In most cases the problem in the use of glass as a load-bearing structural element is the load application into the glass edges. To prevent the formation of stress peaks due to a contact between glass and steel, different contact materials, like grout or thermoplastic blocks, are used. In the performed analysis the grout showed a better behaviour than the thermoplastic blocks. On one hand the failure loads were higher for both the rectangular and the trapezoidal glass fin in the case of the grout. On the other hand the grout has the big advantage that it compensates the inaccuracies of the steel surface and possible offsets of the glass edges. In addition the grout is easier to assemble, because in the case of the thermoplastic blocks, they have to be cut in the right dimensions to fit perfectly between the steel bracket and the glass fin.

The experimental tests showed that the trapezoidal geometry of the glass fin and the steel bracket are enough to guarantee that the fin does not fall down from the supporting steel bracket after the fracture of all sheets. The big advantage of this design is that no boreholes are needed.

Finally, the use of the photogrammetric measurement system during the experimental tests showed that this technique is proper for the use on glass surfaces. However further applications of this technique have to be made on glass specimens and a more detailed analysis of the results has to be done. One of the disadvantages of such measurements is that only values for the surface of the test specimen, which is orientated to the two cameras, are collected.

## 5 Acknowledgements

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# Bearing Capacity of Thin Film Photovoltaic Modules – Differences in the Safety Levels

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## Summary

The increasing use of thin film photovoltaic modules and the increasing occurrence of damages raise the question about a sufficient safety level for the glass-glass-modules used at present. This paper compares the experimental determination of the load-bearing capacity used in the solar industry according to IEC 61646 and a calculative method according to the German structural design standard for glass structures (DIN 18008). Substantial differences in the safety level are pointed out. Moreover, the load case „temperature“ can become relevant for the structural design because of the high solar absorption of the modules. This influence is currently not regulated in the standards. For typical installation situations, a calculative consideration of this load case is discussed.

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**Keywords:** Photovoltaic, Safety level, Temperature

## 1 Introduction

The use of photovoltaic (PV) modules is growing more and more due to falling prices of the modules and governmental subventions. In 2010 Germany produced more than 11 billion kilowatt hours of electricity by photovoltaic systems according to the Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) [1]. This represents an increase by 77% compared to 2009.

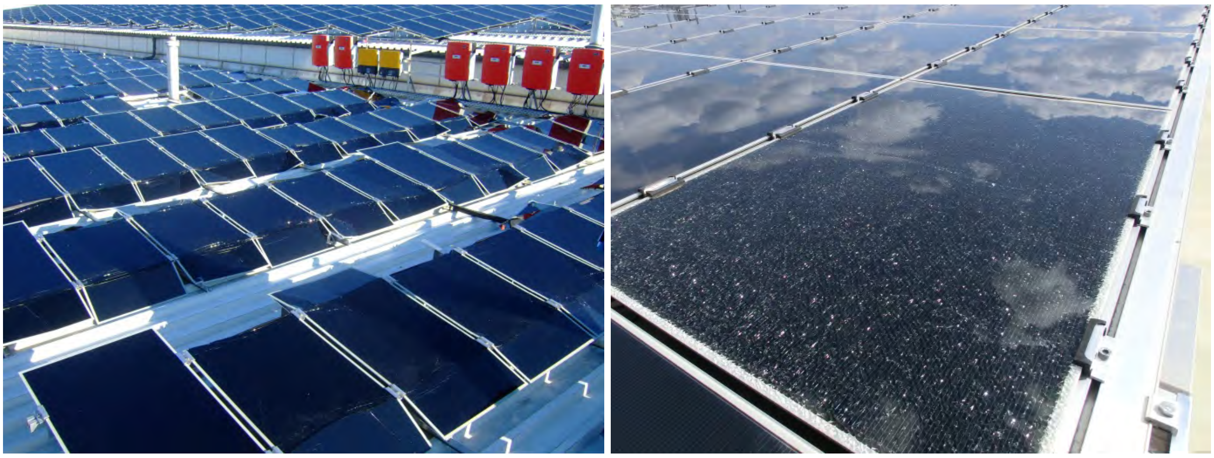

Figure 1: Damage pattern in thin-film PV modules with glass-glass assembly

This is accompanied by the rising occurrence of damages at installed modules (Figure 1). Especially in thin-film modules with glass-glass assembly (Figure 2) increased cases are noticed, where, due to glass breakage, the modules lose their function as a power supplier and also become problematic due to a reduced residual load-bearing capacity of the modules.

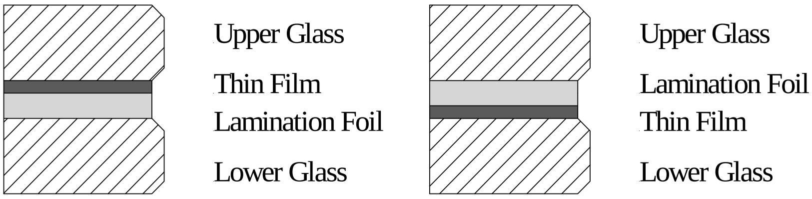

Figure 2: Systematic design of a thin-film module with glass-glass assembly

The solar industry is testing the performance of their products based on IEC 61646: “Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval” [2]. Herewith, the achieved safety level for the load-bearing capacity of PV modules that are currently in use is significantly below the usual safety level of the German structural design standards in glass structures “Technische Regeln für linienförmig gelagerte Verglasungen” (TRLV) or the new DIN 18008.

The draft standard to DIN VDE 0126-21: “Photovoltaik im Bauwesen – Photovoltaic in building” [3] provides that PV modules must meet the requirements of DIN 18008, depending on the application. In practice, however, the tests according to IEC 61646 are considered to be sufficient so far.

Apart from the discussion of the standards, this article illustrates by examples, which maximum load standard glass-glass PV modules can bear using computational design. It is shown that a consistent application of the German structural design standards in glass constructions would severe restrict the applicability of the already installed modules. Framed and clamp-supported modules and modules with back rail systems are compared.

## 2 Tests According to IEC 61646

In the solar industry, thin film photovoltaic modules are tested according to IEC 61646, which specifies the requirements for the testing of the modules. The term “type approval” used in the title does not imply that by meeting the requirements of the standard, a general technical approval for building constructions is achieved. The goal of the standard is to determine the electrical and thermal characteristics of the tested modules. However, the test series also include a mechanical load test, which is deemed to determine the ability of the module to withstand wind, snow, ice or static loads.

A complete test series of thin-film PV modules according to IEC 61646 contains a total of eight specimens. However, only one of these eight specimens is subjected to the mechanical load test. In this test, the module is loaded cyclically. The load corresponds to a constant surface load. The module is attached to a rigid support structure with the manufacturer's prescribed method of attachment.

Firstly, the module is subjected to a uniform distributed compressive load of 2.4 kN/m². This load is hold for an hour. Then, without dismounting the module from the substructure, the same load is applied as a suction load and also held over an hour. This pressure-suction-cycle is repeated for a total of three times.

If big snow and ice accumulations are to be expected, the pressure load must be increased to 5.4 kN/m² in accordance to IEC 61646. But the installation situations where this increased load is required are not defined. Moreover, it is pointed out that even tougher test may be necessary if the tested loading does not cover the installation situation. Therefore, theoretically a common design according to DIN 18008 or TRLV would have to be performed. In practice, however, the common belief is that with fulfilling the IEC 61646, the application range of any construction is covered.

In addition to the mechanical load test, IEC 61646 requires a thermic cycling test. However, this test is only deemed to ensure the electric functionality and does not consider sufficiently the glass-specific material behaviour under thermal loads.

## 3 Design Method According to DIN 18008 and TRLV

The new German structural design standard in glass constructions DIN 18008 with the already published parts [4], [5] describes the required analysis for the ultimate limit state and the serviceability limit state of glass components. In contrast to the currently valid German standard TRLV [6], where the concept of global safety factors is prescribed, for the analysis according to DIN 18008, the concept of partial safety factors is specified. The safety level aims at a failure probability of $p_f = 10^{-6}$ per year according to the common construction standards, e.g. [9].

The computational load bearing capacity of glass constructions is proven by the fact that the existing principal tensile stresses in the glass due to the loads according to DIN 1055 or EC 1 do not exceed the design strength of the glass. Generally, the design strength of the glass $R_d$ is determined by:

$$R_d = \frac{k_{\mathrm{mod}} \cdot k_c \cdot f_k}{\gamma_M} \tag{1}$$

with:

- $k_{mod}$: coefficient for consideration of the load duration of annealed float glass (0.7 for wind, 0.4 for snow and 0.25 for dead weight),
- $k_c$: coefficient for consideration the type of construction (1.0 or 1.8),
- $f_k$: characteristic bending tensile strength (45 N/mm² for annealed float glass, 70 N/mm² for heat-strengthened glass (HSG), 120 N/mm² for fully tempered glass (FTG)),
- $\gamma_M$: partial safety factor for resistance (1.8 for annealed float glass, 1.5 for HSG and FTG).

The strength of annealed float glass is highly dependent on the load duration due to the subcritical crack growth. In DIN 18008, this is explicitly taken into account by the coefficient $k_{mod}$.

If tensile stresses occur at the free edge of the glass, for annealed float glass only 80% of the glass strength can be applied due to the existing damage from the edge treatment.

If laminated glass (LG) or laminated safety glass (LSG) is used, the design value may be increased by 10% (Table 1).

Table 1: Design values of glass strength according to DIN 18008 [4].

| Type of Glass | Load duration | $k_{mod}$ | $R_d$ [N/mm$^2$] | | |
|---|---|---|---|---|---|
| | | | monolithic | + laminated | + edge stress |
| Annealed float | long | 0.25 | 6.3 | 6.9 | 5.5 |
| | middle | 0.4 | 10.0 | 11.0 | 8.8 |
| | short | 0.7 | 17.5 | 19.3 | 15.4 |
| HSG | - | - | 46.6 | 51.3 | 51.3 |
| FTG | - | - | 80.0 | 88.0 | 88.0 |

DIN 18008 prescribes $k_c = 1.0$, unless otherwise specified. Only for vertical annealed glazing with circumferential linear support $k_c = 1.8$ may be applied. Below, the general case $k_c = 1.0$ is assumed, since PV modules are mainly used as horizontal glazing (inclination to the vertical > 10°).

The determination of the design load values results from the respective valid standards (DIN 1055 and DIN EN 1991).

Older regulations like the TRLV are based on the concept of global safety factors. Here the load values are characteristic values. The resistance (glass strength) is reduced by a global safety factor (Table 2).

Table 2: Allowable bending stress according to TRLV [6].

| Type of Glass | $\sigma_{zul}$ [N/mm$^2$] | |
|---|---|---|
| | overhead | vertical |
| Annealed float | 12 | 18 |
| Laminated (Annealed) | 15 | 22.5 |
| FTG | 50 | 50 |

## 4 Comparison of the Safety Levels According to IEC 61646 and TRLV or DIN 18008

The IEC 61646 contains only the performance of *one* mechanical load test with a pressure or suction load of 2.4 kN/m². The standard explains in the comments the origin of this value with a wind pressure of 0.8 kN/m$^2$, corresponding to a wind speed of 130 km/h and a safety factor of $\gamma = 3$.

This relationship between wind velocity and pressure can be confirmed by DIN 1055-4 [7]. However, a characteristic wind pressure of 0.8 kN/m$^2$ is achieved already for a building in wind zone 2 at a building height of 10 m to 18 m. This does not yet include the $c_{pe}$-factor, which takes into account the geometry of the building, the mounting position in the building and the size of the loaded area.

Which actions (wind, dead weight, snow and ice loads, and combinations thereof) are associated with the increased pressure load of 5.4 kN/m$^2$ and which application should be covered with this load is not described in IEC 61646.

However, the specified global safety factor of $\gamma = 3$ for the wind pressure of 0.8 kN/m$^2$ is too low for a design based on only one test. A comparison with the safety level of the TRLV demonstrates this. For horizontally mounted laminated glass made of annealed glass, the global safety factor is determined by:

$$\gamma_{global} = \frac{f_k}{\sigma_{zul}} = \frac{45\frac{N}{mm^2}}{15\frac{N}{mm^2}} = 3.0 \tag{2}$$

This global safety factor is based on the characteristic value (5%-fractile) of the glass strength. According to IEC 61646, the safety factor is, however, based on a mechanical load test with only one test specimen. The (high) scattering of the glass strength is therefore not considered. If, in addition to the 5%-fractile value, the mean value of naturally aged annealed glass with $f_m$ = 80 N/mm² [8] and the 95%-fractile are estimated, this results in the global safety factors according to Table 3.

Table 3: Safety factors according to TRLV for horizontal mounted LSG made of annealed float glass.

| Strength of the tested glass [N/mm$^2$] | 5%-fractile value | mean value | 95%-fractile value |
|---|---|---|---|
| | 45 | 80 | 115 |
| Global safety factor | 3.0 | 5.3 | 7.7 |
| Comparison to IEC 61646 | 100% | 178% | 256% |

This comparison can also be made with the new DIN 18008 to take into account the concept of partial safety factors. For laminated safety glass made of annealed float glass, the design value for the resistance under wind load results in:

$$R_d = 1.1 \cdot \frac{k_{\text{mod}} \cdot k_c \cdot f_k}{\gamma_M} = 1.1 \cdot \frac{0.7 \cdot 1.0 \cdot 45\, N/mm^2}{1.8} = 19 \frac{N}{mm^2} \tag{3}$$

This only considers the resistance side. The partial safety factor for the load (wind) according to DIN 1055-100 [9] is $\gamma_Q = 1.5$. This must be multiplied with the partial safety factor for resistance to allow a comparison with the global safety factor. Taking into account the scattering of the glass strength, the required safety factors are shown in Table 4.

Table 4: Safety factors according to DIN 18008 for LSG made of annealed float glass under wind load.

| Strength of the tested glass [N/mm$^2$] | 5%-fractile value | mean value | 95%-fractile value |
|---|---|---|---|
| | 45 | 80 | 115 |
| partial safety factor | 2.4 | 4.2 | 6.1 |
| global safety factor | 3.6 | 6.3 | 9.1 |
| Comparison to IEC 61646 | 118% | 211% | 303% |

The comparisons for global and partial safety concept show similar results. The performance of one mechanical load test according to IEC 61646 with the stated global safety factor of $\gamma = 3$ does not provide a comparable level of safety to TRLV or DIN 18008. If a glass with a high strength (e.g. 95%-fractile) would be tested, a global factor of $\gamma = 9.1$ would be needed to meet the safety level of DIN 18008.

Moreover, the IEC 61646 does not consider sufficiently the time-dependent behaviour of the strength of annealed float glass. The load duration for the mechanical load test is longer than the short-term load (wind, 10 minutes) but well below the middle-term load (snow, 30 days). Moreover, as the tests are carried out at room temperature, a certain shear transfer between the upper and the lower glass is active due to the lamination foil. This shear transfer does not exist in the real installation situation under solar radiation with the usual viscoelastic lamination foils (PVB, EVA).

Basically, a proof of the bearing capacity with mechanical load tests is possible, but should be based on the fundamentals of structural design. DIN EN 1990 [10] describes in Appendix D how to perform a test-based design of construction elements. Thereafter, with a test sequence which includes the real actions (storage conditions, load type and duration, temperature, etc.) and a sufficient number of specimens, the design value of the resistance can be determined. This can subsequently compared with the actions for the particular installation situation.

## 5 Load-bearing Capacity According to DIN 18008 for Typical Module Assemblies

Photovoltaic modules are offered in different designs. Mostly, framed modules are used. Here, the glass-glass module is held by a circumferential aluminium frame which is fixed to the support structure. Unframed modules can be held either locally by clamping brackets or linearly by using a back rail system which is glued to the rear glass of the modules. The systems, each with typical dimensions, are shown in Figure 3.

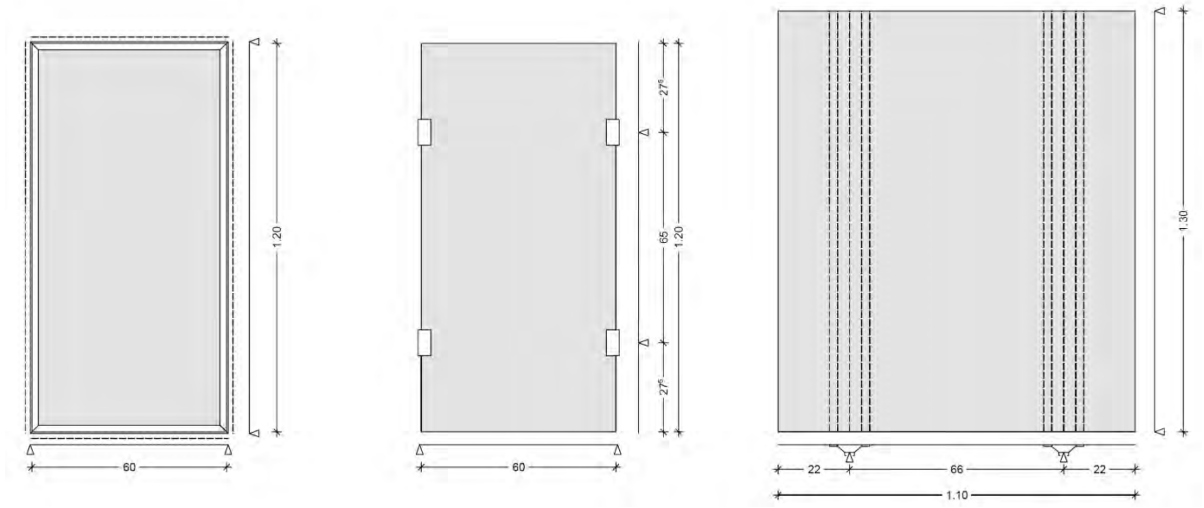

Figure 3: Typical support structures of glass-glass modules, a: framed, b: clamped , c: back rail supported

A laminated glass with 2 x 3.2 mm float glass is used for the calculation below, which is usual in the market. Thus, these types of modules represent assemblies, which have passed in identical or similar design the tests according to IEC 61646 and are currently used in construction industry.

According to DIN 18008, the positive effect of shear resistance is not taken into account in the calculations. The design value of resistance $R_d$ is given by Table 1.

The aluminium back rail profile, which is shown in Fig. 4, is glued to the rear glass of the module by an adhesive tape. The adhesive tape has been simplified to a linear-elastic material model (Young’s modulus $E = 1.0\ \text{N/mm}^2$; Poisson's ratio $\nu = 0.4$). The calculation takes into account geometrically nonlinear behaviour of the glass-glass laminate (Figure 4).

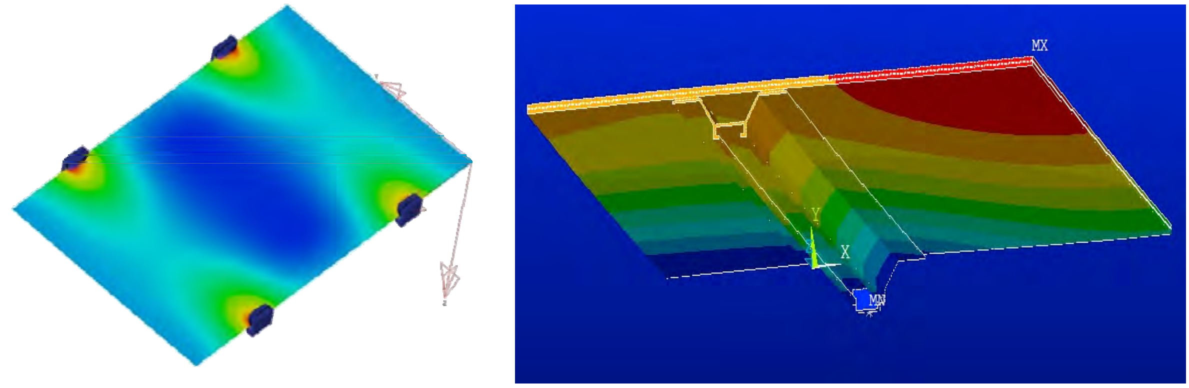

Figure 4: Finite Element Model for glass-glass modules,
a: clamped (SJ MEPLA), b: back rail supported (ANSYS 13)

The calculation gives the load capacity at which the glass strength $R_d$ is reached. This load corresponds to the design value of the action load $E_d$ in the ultimate limit state:

$$E_d \le R_d \tag{4}$$

In order to obtain the characteristic load capacity $E_k$, the pre-determined design values are divided by the partial safety factor according to the load duration for permanent loads (e.g. dead weight) $\gamma_G = 1.35$ and for short and medium loads (e.g. snow, wind) $\gamma_Q = 1.5$. In accordance to DIN 18008, the higher value of $k_{mod}$ is used when considering load combinations. For example, in the combination of dead weight plus wind, $k_{mod}$ is set to 0.7. The results for the determined characteristic loads $E_k$ are shown in Figure 5.

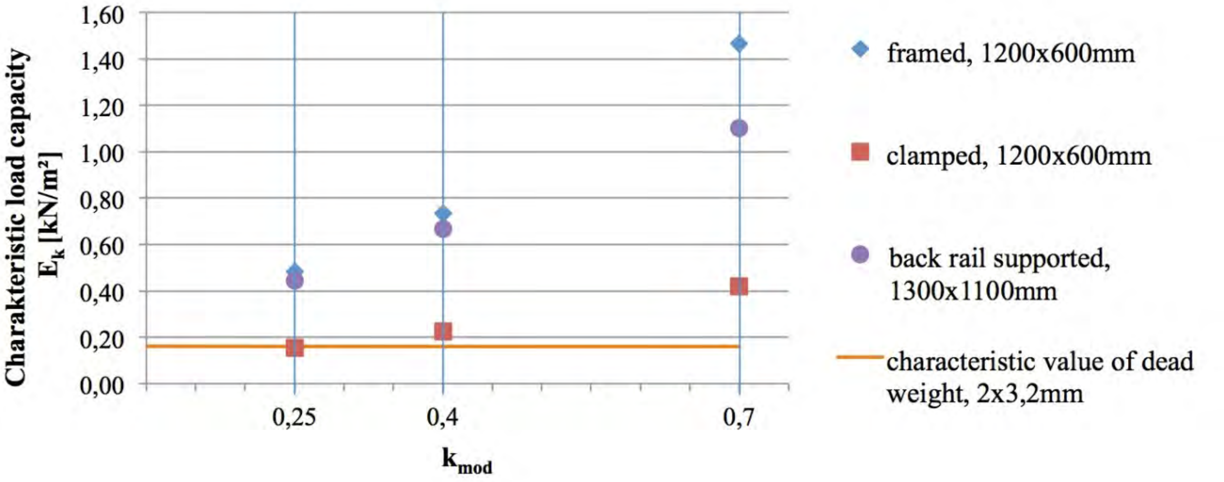

Figure 5: Characteristic load capacity of typical PV modules

The comparison of the characteristic load capacity in buildings with usual wind and snow loads shows, that the application of these modules is highly limited.

The framed module can bear about 0.6 kN/m$^2$ in addition to its dead weight for a medium load duration (snow) and about 1.3 kN/m² for a short load duration (wind). A comparison of these values to the characteristic loads in accordance to DIN 1055 demonstrates the limited application possibilities of these modules. For example, a building in snow load zone 2 (about 80% of Germany) with a roof slope of up to 30° must withstand a characteristic minimum snow load on the roof of $s_1$ = 0.7 kN/m² according to DIN 1055-5 [11]. This already exceeds the characteristic load capacity of the module.

The module which is clamped at four points reaches its full bearing capacity already under its dead weight. With the approach of the lower value for $k_{mod}$ for combined loads (dead weight plus snow or wind) after DIN 18008, the additional load capacity is so low that it is hard to find a possible application.

The back rail supported system shows the best structural behaviour of the presented systems. Despite the larger dimensions of the module, the load bearing capacity is only slightly below the framed system.

A neglected aspect in the examples is the position of the connection socket. This can be located at the edge or on the surface area of the module. In an assembly on the surface area, a hole in the rear glass is required. This hole reduces, depending on its location, the load capacity of the modules again significantly. According to DIN 18008, holes in annealed float glass are not permitted, so the drilled rear glass would have to be thermally toughened.
Furthermore, it has to be discussed, whether an increased coefficient for consideration the type of construction $k_c$ may be applied for framed PV modules in conjunction with a proof of sufficient residual load-bearing capacity. This would reflect the fact that the PV modules are often mounted on existing roof structures or on a field and thus not directly provide a risk on persons if they have sufficient residual load-bearing capacity after glass berakage.

## 6 Load Case Temperature

The influence of solar radiation on photovoltaic modules compared to transparent façade glazing is much higher due to the fact that the absorption coefficient increases. Uncoated glasses have a solar absorption of approximately 8-20 % depending on the glass thickness [12]. A thin film photovoltaic module (ASI), however, has an absorbance between 60 % and 90 %.

The solar absorption basically leads to two superposed temperature profiles over the module thickness. A constant temperature load can be superimposed with a variable temperature profile over the cross section (Fig. 6).

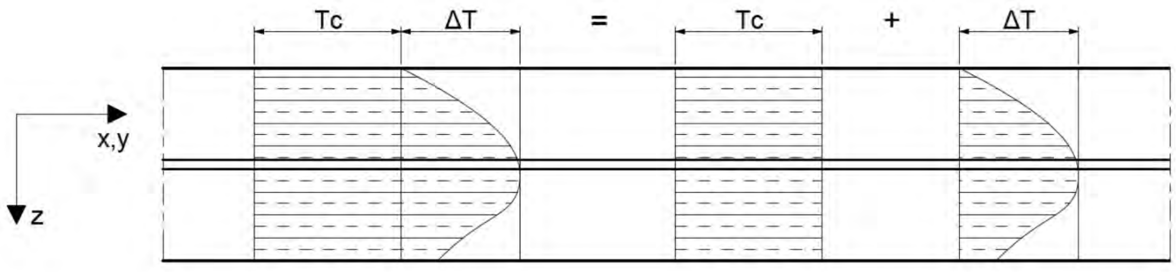

Figure 6: Separation of the thermal stress in a constant and variable part

The constant temperature Tc only leads to compressive stress in the glass for framed modules with an idealized system (constant linear horizontal support of the edges).

For locally clamped modules and temperatures up to 50 °C (compare [13]) with a 2 mm elastic support of the glass edge and soft contact materials (Young's modulus $E = 5 – 200$ N/mm², $\nu = 0.5$, e.g. EPDM), no design-relevant tensile stresses occur, too. Only for very stiff contact materials (Young's modulus $E = 1\,000 – 3\,000$ N/mm², $\nu = 0.3 - 0.4$, e.g. POM), the principal tensile stresses would be in a design-relevant dimension.

For back rail supported modules, no significant tensile stresses are caused by constant heating of the glass sheets due to the flexibility of the overall system.

With a variable temperature profile, the (suppressed) bending of the glass panes leads to tensile stresses, which may be relevant to structural design.
A parametric study using the above framed module with two types of a variable temperature profile shows this clearly. In the first variant (symmetric temperature distribution), the upper and lower sides of the laminate are cooler than the thin film and the lamination foil in the middle due to the ambient atmosphere. In the second variant (asymmetric temperature distribution), a reduced cooling of the lower glass panel was taken into account and therefore a constant temperature distribution assumed (Figure 7).

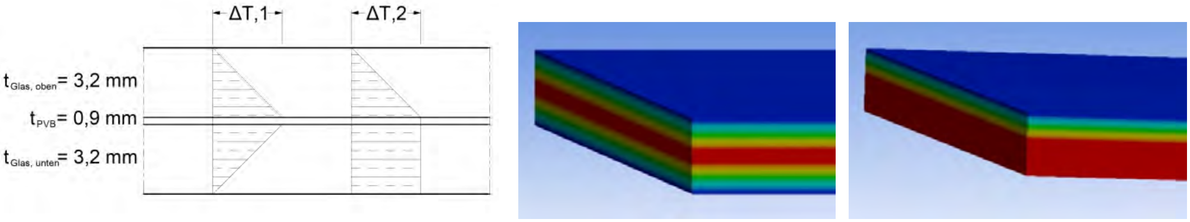

Figure 7: Investigated temperature distributions (symmetrical and asymmetrical)

For the frame, the limits "soft" and "rigid" were investigated. Here "soft" means free glass edges (x, y- and z-direction), "rigid" means simply supported edges of both glass panes in z-direction.
The interlayer is modelled with a Young's modulus of 1.0 N/mm² and a Poisson's ratio of $\nu = 0.499$. The temperature difference $\Delta T$ was increased progressively up to 20°C (e.g. rain cooling). Figure 8 shows the stress distribution of the finite-element calculations which takes into account geometrical nonlinearity.

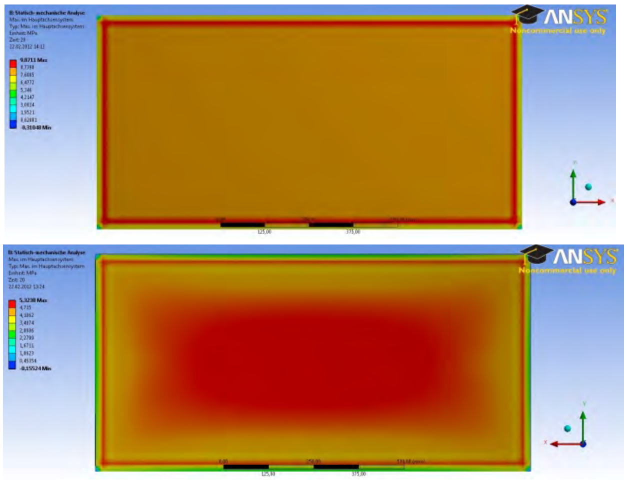

Figure 8: Principle tensile stresses on the outer surface of the upper glass pane with symmetrical (left) and asymmetrical (right) temperature distribution and soft frame

The maximum principal tensile stresses occur under symmetrical load $\Delta T{,}1$ at the outer surfaces. With the asymmetrical load $\Delta T{,}2$ these are located on the outer surface of the upper glass pane (Figure 9).

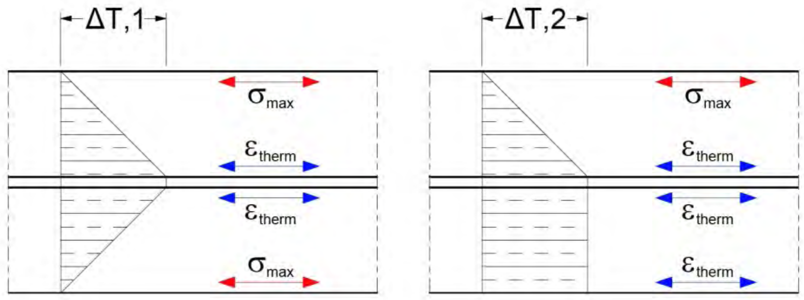

Figure 9: Thermal expansion ($\varepsilon_{therm}$) and tensile stresses ($\sigma_{max}$) for symmetrical (left) and asymmetrical (right) temperature distribution

Figure 10 shows an almost linear relation between temperature difference and the glass stresses. The small differences arise from the geometrically nonlinear analysis. Furthermore, it indicates that the consideration of the load case temperature can be quite relevant for structural design, especially if the capacity of the modules is already reached with other loads.

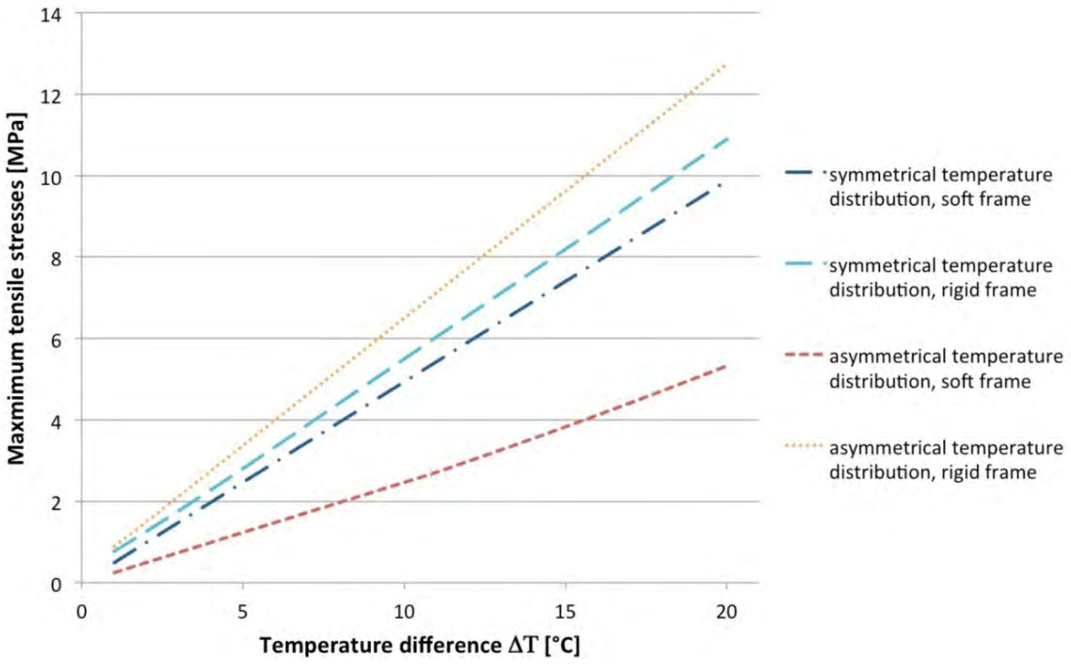

Figure 10: Principal tensile stresses on the glass surface as a function of the temperature distribution and the stiffness of the frame

## 7 Summary and Outlook

The mechanical load test according to IEC 61646 with only one specimen leads to a much lower safety level than the application of the structural design standards for glass constructions (TRLV, DIN 18008).

To consider the scattering of the glass strength, the number of specimens should be increased significantly to reach a comparable safety level to DIN 18008 (see Table 3 and 4). Instead, according to IEC 61646, only a safety factor of $\gamma = 3$ is taken into account referenced to a characteristic wind load of 0.8 kN/m². Thus, the allowable installation and application situations that may be covered by the staggered test load according to IEC 61646 with 2.4 kN/m² and 5.4 kN/m² have to be discussed.

Nevertheless, it is common practice to install PV-modules, which were tested according to IEC 61646 without any additional structural calculations. The consequences are already evident in numerous cases of damages. Only the positive post-breakage behaviour of laminated glass ensures that the damages did not cause greater hazards to people so far.

It was shown that temperature loads and especially variable temperature profiles over the cross-section can lead to design relevant principal tensile stresses.

For the future, besides the need of a suitable structural design method for PV-modules, the post-breakage behaviour of laminated glass has to be analysed systematically to develop appropriate mechanical models. Moreover, specific loads on PV-modules, such as thermal stresses due to the high solar absorbance of the thin film and the associated thermal stresses in the glass, have to be investigated further.

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# Daylight Concept with Cones Made of Glass

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## Summary

A recently finished and very interesting project is the new entrance of the museum quarter ´Joanneumsviertel´ in the center of Graz in Austria. The complex of the museum's buildings consists of two wings of the existing structure. For the connection of those old parts of the museum the architects designed the new entrance with two basement levels between them. The architectural challenge of this project was to bring daylight into these two lower floors. The concept of the architects was to let natural daylight flow in via vertical funnels in the form of small round courtyards with a diameter of up to approx. 16 m into the basement. Laminated and insulated glass was used for the cladding of these conically-shaped funnels.

**Keywords:** conically-curved laminated glass, conically-curved insulated glass

## 1 Introduction

A very interesting project, finished at the end of 2011, is the new entrance situation of the museum quarter ´Joanneumsviertel´ in the center of Graz in Austria. The complex the museum's buildings consists of two wings (museum of natural science and the museum of modern art) of the existing structure. For the connection of those old parts of the museum the architects - eep architects, Graz/A; Nieto Sobejano Arquitectos, Madrid/E - designed the new entrance between them. The visitors of the museum can reach the biggest cone designed as the museum entrance via a specially designed public place. The picture below shows this cone with an escalator. (see figure 1 bottom left).

Figure 1: New Entrance Situation - ´Joanneumsviertel´ [1]

The basement with a depth of approx. 10 m was excavated and the two levels were covered with wide spanned reinforced concrete slabs. An architectural challenge of this project was to bring daylight into these two lower floors (see in the model in figure 1 above). The concept of the architects was to let natural daylight flow in via vertical funnels into the basement. These funnels have the form of small

round courtyards with different diameters of up to approx. 16 m. Laminated safety glass and insulated glass were used for the cladding of these conically-shaped funnels.
The cones have a central axis which are inclined up to 15° from the vertical and for this reason the inclination of the glass panes vary from the vertical position to a position of up to 30° from the vertical. Two of the six cones interpenetrate and another one is posed on its top and situated in the center of a larger one.

## 2 Cones 1 & 2

Cones 1&2 are the cones with an interpenetration located on the northern part of the public place. Cone 1, with a diameter of approx. 9 m, extends into the first basement level and Cone 2, with a diameter of approx. 6 m, extends into the second basement level (see figure 2 below). For the balustrade, laminated safety glass with a thickness of 24 mm which consists of 2 x 12 mm conically-curved glass panes was used. The cladding in the basement levels consists of insulated glass with conically-curved 12 mm glass on the outer side, a 16 mm space and laminated safety glass which consists of 2 x 8 mm conically-curved glass on the inner side.

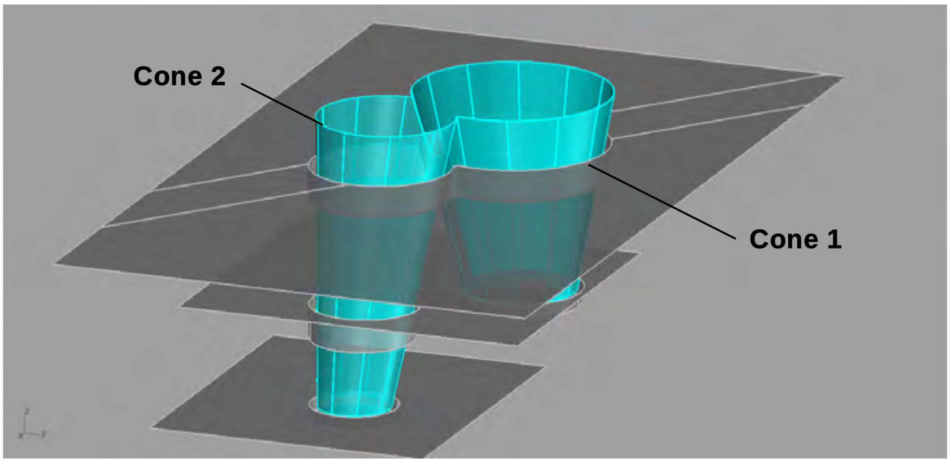

Figure 2: Principle of Cones 1&2 [2]

The guaranty of the tightness against the rain for the parabolic curve (see figure 3 below) of the interpenetration was a difficult part, as was the geometrical challenge which had to be solved. The gap between the glass panes of the different cones was covered with a specially formed stainless steel profile with approximately the same cross section as the stainless steel handrails of the balustrade.

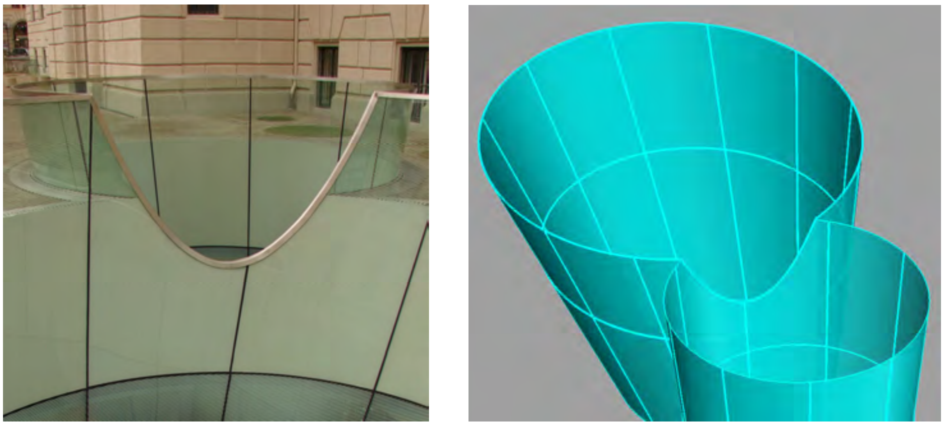

Figure 3: Interpenetration of Cones 1&2 [2]

## 3 Cone 3 & 4

Cone 3 has its larger diameter on the upper side in comparison with cone 4 which was posed on its top and has the larger radius on its bottom edge. Smaller cone number 4 is situated in the center of cone 3 which is larger. For the balustrade, laminated glass with a thickness of 24 mm which consists of two 12 mm conically-curved glass panes was used. The cladding in the first basement levels was made for both cones of insulated glass with conically- curved 12 mm glass on the outer side, a 16 mm space and a laminated safety glass which consists of 2 x 8 mm conically-curved glass on the inner side. The glazing in the second basement level, which is used as a depot for the exhibits, was designed to be laminated glass. Cone 6 is equal to Cone 3.

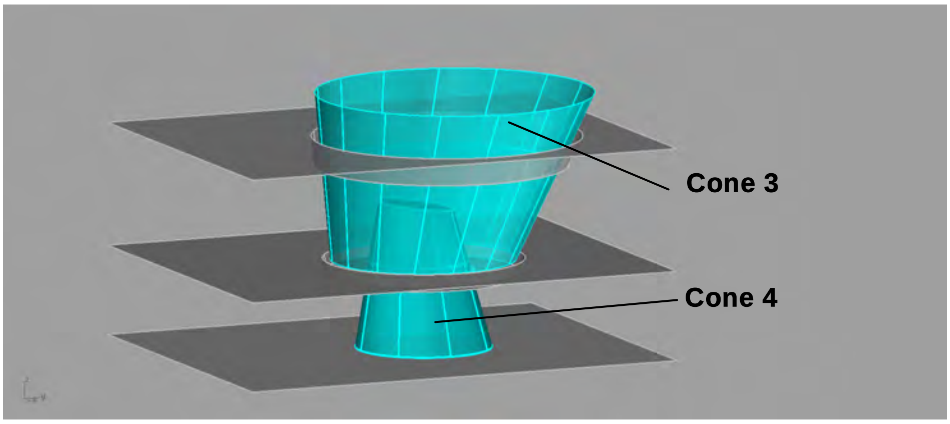

Figure 4: Principle of Cones 3&4 [2]

The picture in figure 5 (see below) shows the view from the inner of the museum in the first basement level through the insulated glass unit of the cone 3 to top of the insulated glass of the cone 4. The top of Cone 4 is covered with an elliptical, flat, insulated glass. A very slender steel construction positioned in the gaps between the conical glass units carries this insulated glass of the top and is supported on the concrete slab.

Figure 5: Cone 3&4 – View from the inner

## 4 Cone 5 – The New Entrance of the Museum

The biggest cone - Cone 5 - with a diameter of approximately 16 m was designed as the new entrance for the visitors of the museum. Via an escalator the people reach the first basement level and can enter the museum through a sliding door. The central axis of this cone is inclined at approximately 15° from the vertical and for this reason the inclination of the glass panes vary from a vertical position up to an angle of 30° from the vertical (near to the escalator). For the balustrade, laminated safety glass with a thickness of 24 mm which consists of two 12 mm conically-curved glass panes was used. In the balustrade, a gap for installation of the escalator was positioned (see figure 7 below).
The upper edge of the laminated safety glass was covered with a stainless steel handrail and this profile protects the glass against damage.
The cladding in the basement level was made of insulated glass with conically-curved laminated safety glass consists of a 2 x 8 mm glass on the inner and the outer side and a 16 mm space between. The horizontal and the vertical (inclined) gaps between the glass units were sealed.

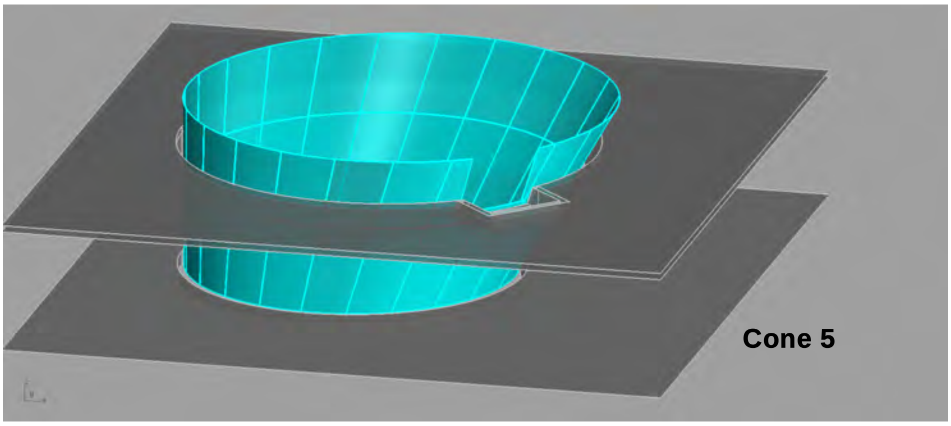

Figure 6: Principle of Cone 5 [2]

Figure 7: Cone 5 – View from the interior

## 5 Principle Concept of the Glazing

The special boundary condition of the great deformation of the wide span concrete slabs of more than 30 mm (for the long-term deformation) causes the special structural system of all the cladding. The glass panes of the balustrade had to be staked on the insulated glass of the level below. This means that the lower glass has to carry the dead load of the glass above. To keep the distance between the upper and the lower glass level synthetic blocks were used. The calculations made during the design process showed that the additional stresses due to the dead load of the upper glass were not very high and in this case acceptable. At the lower edge of the insulated glass pane the dead load is supported by steel consoles, which were mounted on the concrete slab.

For the horizontal loads, the glass panes were glued to stiff stainless steel ring sections and those were discretely supported at their ends. These hinged supported systems transfer the horizontal loads (e.g. wind or human impact) to the concrete slabs and guarantee the freedom of vertical movements of the concrete slabs (see figure 8).

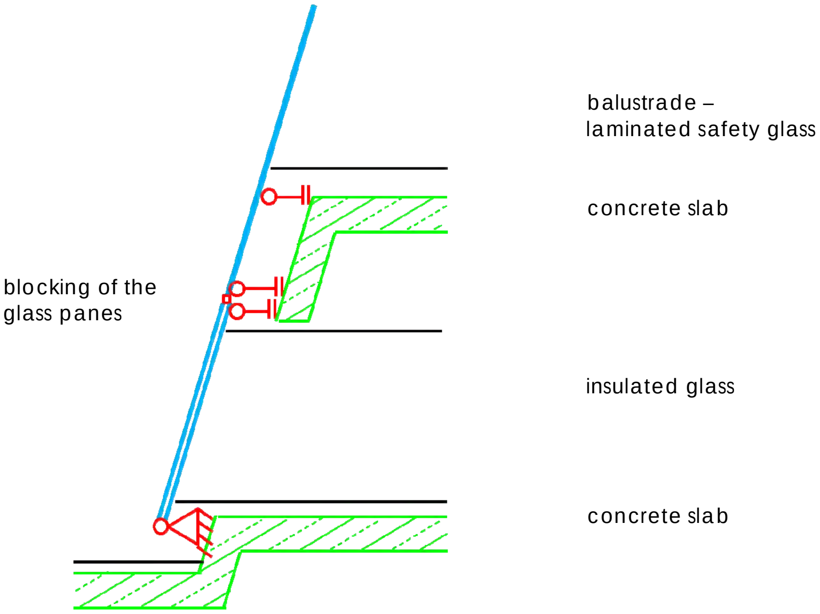

Figure 8: Cross section – principle of the structural system of the cones

## 6 Design of the Cones

All the different cones were designed with a finite element model which covers all glass panes. The loads were defined with dead loads, wind loads and horizontal loads due to human impact. For the design of the balustrade in the public are a horizontal load of h=3.0 kN/m was used. This level of the load is based on the possibility of a big gathering. Beside these mechanical loads the climatic loads in the insulated glass units were taken into account. These climatic loads include the difference in temperature (summer and winter), the difference in the meteorological air pressure and the difference in the altitude (between the production site and the building site). All these internal and external loads were superposed in the finite element model.

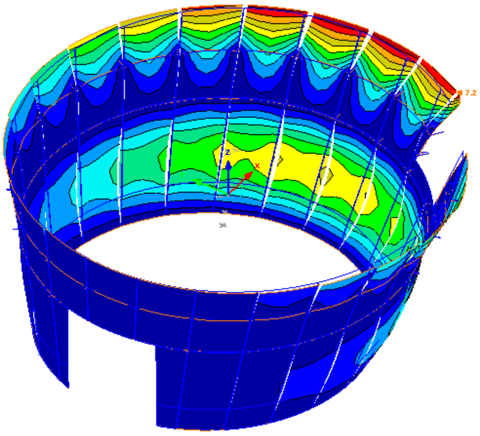

Figure 9: Cone 5 deflection results of the design with a finite element program

## 7 Pendulum Impact Test

For the laminated safety glass of the balustrade for dynamic loads in particular a pendulum impact test was demanded. This test was carried out directly on the site for real boundary conditions. As required, a 50 kilogram steel mass with the twin tires swung into the glass panes with a drop height of up to 900 mm (according to the standards). The test started with an impact located in the center of the glass pane with a drop height of 450 mm. After the test was successfully passed, the height of the fall was increased up to 900 mm. The impact located in the center of the glass causes no failure (no cracks). Only with an impact located near the vertical edges with a drop height of 900 mm did the glass pane on the side of the load break. The crack pattern after the pendulum impact test can be seen in the right picture in figure 10 below. The glass opposite was still intact and only a few small pieces of broken glass could be observed.

Figure 10: Glass before and after the pendulum impact test [2]

## 8 Acknowledgements

All these conically-curved laminated safety glass or insulated glass as well as the steel substructure were produced by the company SFL Technologies in Austria. The structural development and the structural design were made by the Research Center for Integral Construction Engineering “fibag”.

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# A Tool that Combines Building Information Modelling and Knowledge Based Engineering to Assess Facade Manufacturability

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## Summary

Modern façade design projects involve a wide range of materials whose manufacturing and installation impose many different constraints on the design. The façade engineer's role is to manage and apply these constraints to achieve an optimal design. The paper presents a tool to assist façade consultants in the capture, storage and use of 'downstream' design constraints. The aspect of the design process to be targeted by the tool is identified through two process mapping methodologies. The tool captures expert knowledge of the geometric constraints placed on façade panels due to the manufacturing processes. As a demonstration, the tool is applied to real-world façade projects, and is shown to identify areas of the design requiring modification to improve manufacturability.

**Keywords:** Knowledge, Facade, Manufacturability, BIM

## 1 Introduction

The façade sector is information intensive, and the development of a good façade design relies on the façade consultant's ability to gather and assimilate large quantities of information regarding the constraints on the design. Using this information, the consultant must identify and communicate the impact of these constraints to the design team. The task is made more challenging by the increasing complexity of façade designs. This complexity arises both from the geometry and from the materials and processes required to produce façade panels to increasingly high-performance specifications.

The primary benefits of  Building Information Modelling (BIM) include the efficient storage, access and transfer of design information, and increased collaborative working [1].  As a result BIM has been proposed as a tool to manage and communicate design information[1]. In recent years the construction industry as a whole has increased its use of BIM. However, BIM can be used to improve the end product as well as the design process. The availability of semantic digital design information provides the construction industry with the opportunity to employ knowledge-based engineering techniques[2].

Knowledge-based engineering techniques have previously been used successfully in manufacturing industries to improve manufacturability using Design for Manufacture (DFM) strategies [3]. This has relied partly on the availability of semantically rich digital design information. Fox et al.'s [4] review of DFM and its applicability to the construction industry places the façade sector in the group of sectors to with the potential to benefit most from cost reductions through DFM.

## 1.1 Knowledge

### Knowledge-based Engineering (KBE) in Façade Design

Little of the literature on the application of knowledge-based engineering (KBE) or knowledge management (KM) to the construction industry specifically addresses the façade sector. Much of the work that is available focuses on the service life performance of the façade, in particular thermal performance, moisture control and energy efficiency.

Early work in this area includes the presentation of BEADS (Building Envelope Analysis and Design System) by Fazio et al. [5], a knowledge based system approach to building envelope design. The outputs of the work included a software tool and a knowledge representation framework to hold attributes and values. Although drivers as broad as performance, cost, buildability and maintainability are discussed, the implementation covers performance only. Gowri's research covering the BEADS project suggests that a key area of further work would be to expand the knowledge base to cater for other design issues [6]. Iliescu continued the work on the application of KBE to building envelope design in Concordia University, however, the technique shifted from rule-based to case-based reasoning[7]. Iliesu's work also focuses on the energy efficiency of building envelope designs.

Fazio et al.'s [8] more recent work considers the application of BIM technology to building envelope design. The International Foundation Class (IFC) schema is used to store and transfer design information in a system that incorporates a database of bench mark values of façade performance. The system evaluates design alternatives, partly based on the values stored in the knowledge database. Again, the work only considers thermal and environmental design requirements.

Both Gowri [6] and Iliescu [7] highlight the information intensive nature of building envelope design and therefore the applicability of computers and KBE as information handling tools for the designer. However, the two pieces of work proposed different KBE techniques. Gowri uses rule-based design, and Iliescu a case-based approach, on the premise that the façade sector is a 'weak theory' domain, making elicitation of rules unmanageable. However, both conclude that the application of KBE to the façade sector is beneficial, particularly in the preliminary stages of design.

A key draw back of the case-based technique is the static nature of the database [7]; this indicates that a dynamic database that learns alongside the designer may be preferable. Although this work is not specific to the façade sector, live capture and use of knowledge has been proposed and developed in the CAPRIKON project [9], [10]. This refers to the capture of knowledge during a project in a format that can be used directly on the current project and on subsequent projects. Kamara et al.[9] suggest that 'live capture', as opposed to post-completion capture, increases the reuse of knowledge gained on a project and involves the supply chain with the capture of knowledge more efficiently. The paper also notes that live capture avoids the loss of knowledge when capture is coordinated through post project reviews. This work indicates that knowledge from the downstream supply chain is most effectively captured using a live capture methodology. Project knowledge so captured can be used on both the current project and future projects.

### Knowledge Based Engineering and Knowledge Management in the Construction Industry

Although the research community has developed and employed technologies in this area, industry itself has shown less progress. Robinson et al. [11] presents a review of the strategies and technologies used by large construction firms to capture and store knowledge. Those used by the consultancy sector included skills 'yellow pages', intranets, and communities of practice. These in general do not capture knowledge in a computer-interpretable format indicating that although research communities are automating (or semi automating) their capture and use of knowledge, industry is not and still relies on human interpretation.

## 1.2 Mapping

Façade design and construction is a relatively new sector of the construction industry, as is the role of the professional façade engineer, both in consulting and contracting [12]. In addition, the sector is complex in the of range of materials employed, geometries involved, performance requirements and its multidisciplinary nature. The youth and complexity of the sector suggest that a map of the design process would be a very useful aid to researchers in this field. The main benefits of process mapping suggested by literature include increasing understanding of actor's roles and activities [13], aiding identification of strategic, process and IT requirements [14], or forming the basis for IT systems [15].

The paper partly presents work based on two mapping methodologies. The maps have been used to select a scope for the proposed tool and to understand availability of design information.

### Mapping Design Influences

The Design Research Methodology developed by Blessing *et al*. [16] is a structured approach to design research projects. By mapping the influences on design project outcomes, it is possible to identify areas of the design process that could be targeted by the research project. In response, support tools can be developed and tested. This methodology has been employed in the initial phase of the research project to identify the scope of the design support tool.

### Mapping Design Processes

Previous work undertaken by the authors [17] include a map of the façade design processes. One benefit of process mapping suggested in the literature is that it form basis for IT systems [15]. For this research, the map has been used to identify packets of knowledge that are non-project-specific and can be captured, stored and re-used.

## 1.3 Paper Content

The following sections of this paper outline the research undertaken on the topic. Sections 2 and 3 present two maps of the façade design process, one showing the influences on design outcomes and the other depicting the processes themselves. These sections describe how the maps have been used to identify the aspects of the design process that a knowledge-based tool should target. Section 4 provides a description of the tool devised, and section 5 presents two case studies showing the use of the tool on real-world projects. Conclusions and areas for further work are discussed in sections 6 and 7.

# 2 Design Influence Map Production

The Design Influence map has been developed through an iterative process, drawing on the experience of façade engineers currently working in the façade sector. First an outline map was developed via a series of interviews with industry members. This was then reviewed in an interview with a façade engineering team director, whose comments and modifications were incorporated into the map. The final iteration consisted of a workshop to elicit knowledge from a team of façade engineers and produce the final map.

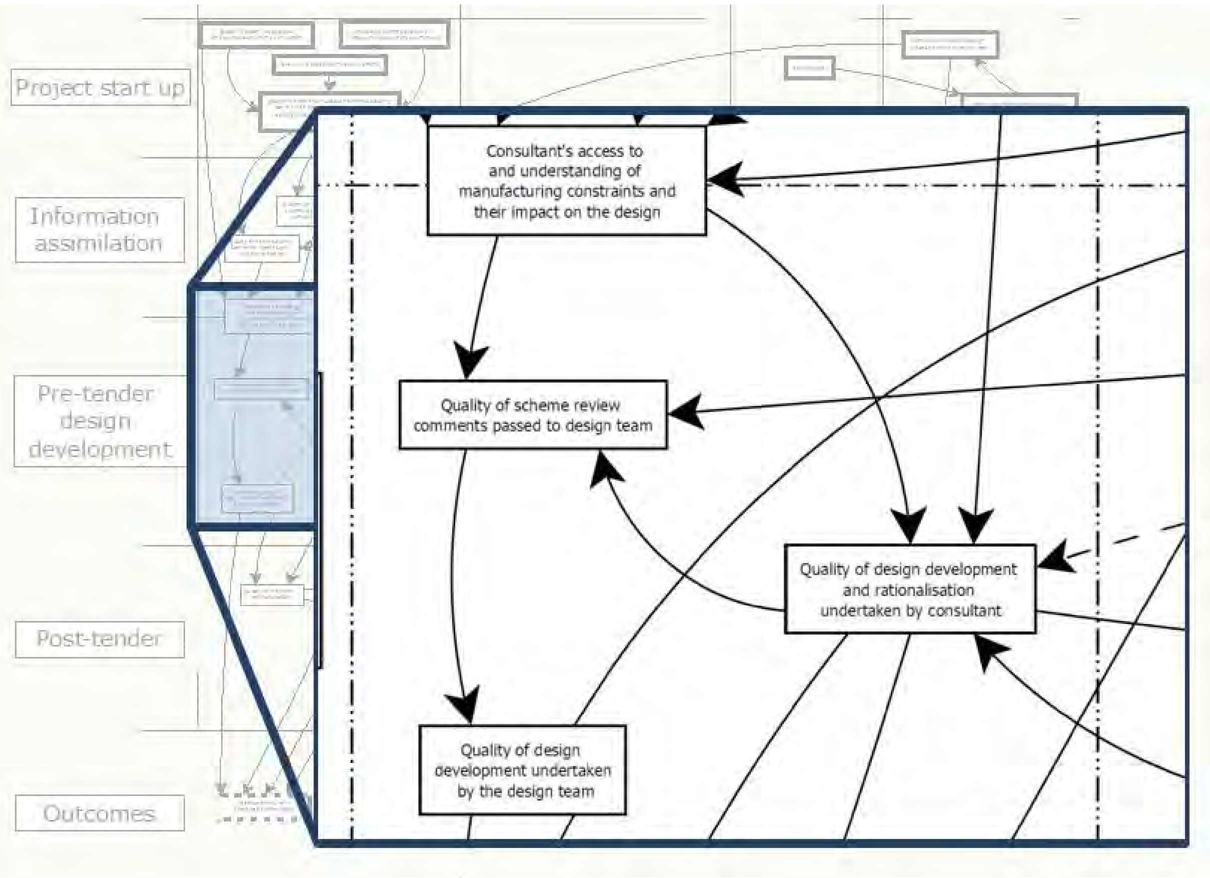

Figure 1: An expanded extract of the Façade Engineering Design Influence Map

Figure 1 shows an enlarged section of the map. Each bubble in the map describes either a design influence or a project outcome. For example, the quality of the scheme review comments passed to the design team influences the quality of the design development undertaken by the design team.

By using the DRM it was possible to identify which factors influence the overall construction cost, and the extent to which the final design conforms with the architect's and client's original design intent. One of the key factors identified was *the façade consultant's access to and understanding of manufacturing constraints and the impact of these constraints on the design at pre-tender design stages* (shown in Figure 1). As a result, capturing, storing, using and re-using manufacturing constraints is the focus of the tool.

## 3 Mapping Façade Design Processes

As part of previous work undertaken by the author [17], a full map of the façade design and construction process has been developed. For the research presented in this paper, the map was used to identify patterns of use of specific information or knowledge objects. For example, by identifying the repeated use of packets of knowledge that are not project-specific, a system can be developed to capture, store, and make accessible these elements for re-use in subsequent projects. In addition, by assessing when these information objects are re-used, the tool can be developed to encourage users to update the recycled information.

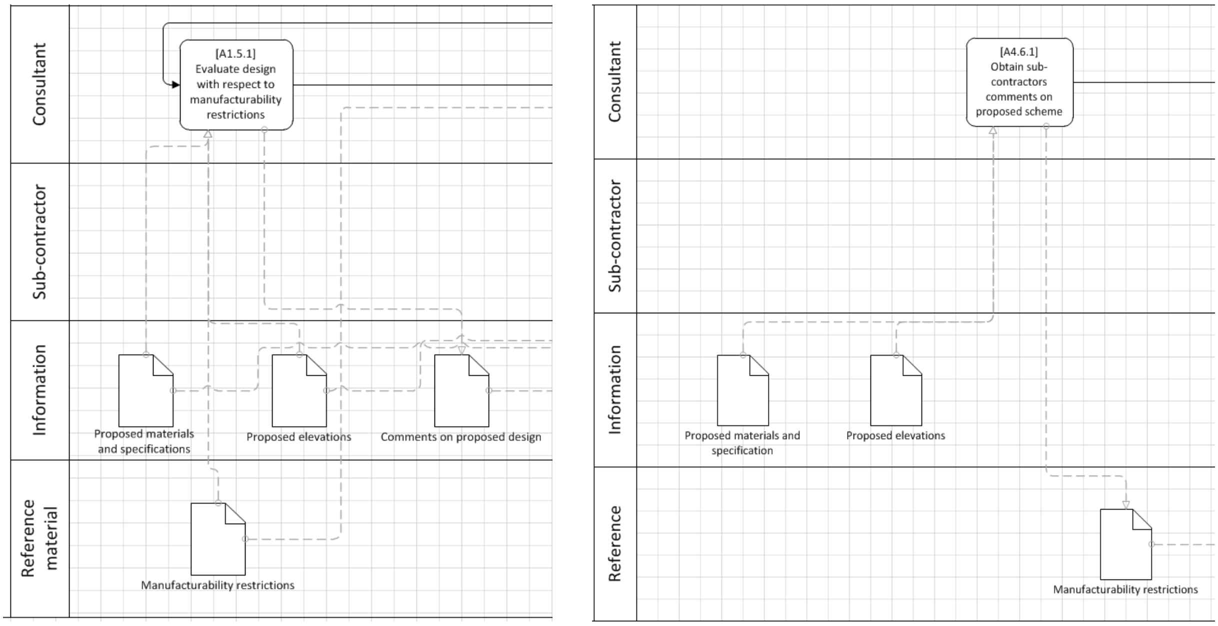

Figure 2: Activities A1.5.1 and A4.6.1

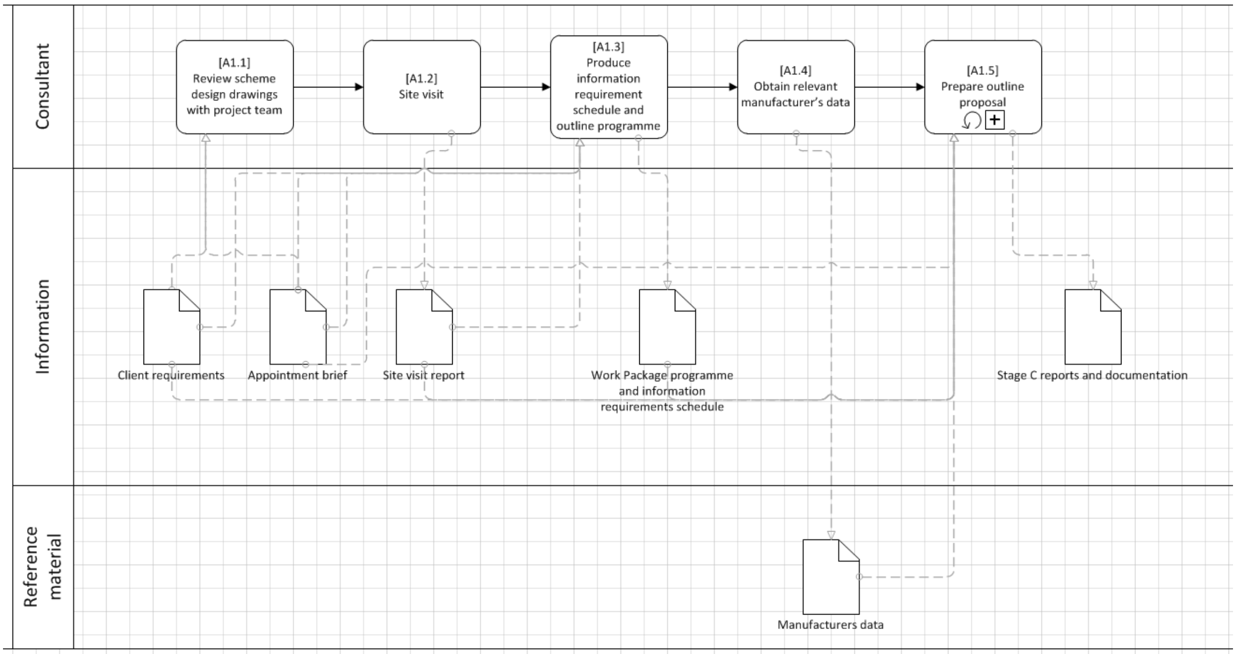

Figure 3: Activities A1.4 and A1.5

The map shows that activity A1.5.1 (Fig. 2) requires knowledge on size restrictions of facade panels to assess the panelisation scheme proposed by the project architect. This knowledge is owned by the consultant and is not specific to the project. Activity A1.5.3 uses the same information for a development rather than a review task. The consultant has the opportunity to update the knowledge during activity A4.6 (Fig. 3), when the same type of information, this time owned by the contractor, is used to review the design.

## 4 The Proposed Tool

The design outcome influence map discussed in section 2 suggests that both knowledge of manufacturing constraints, and the efficient and effective application of this knowledge by the façade consultant are key factors in determining the success of a project. The process map shown in section 3 indicates that this knowledge is not specific to a particular project and can be re-used. Therefore, the tool presented in this section has been developed to capture, store, use and re-use knowledge. The tool focuses on knowledge of the constraints manufacture imposes on the façade panelisation scheme.

The proposed system is in prototype form and consists of a series of modules. Geometric design information is stored in the Building Information Model (BIM) in IFC format (element (A) in Figure 4). Details of the extraction and analysis of design information from the IFC database are provided in [18].

The IFC schema is unable to store details of the materials and processes that make up the façade panels in a sufficiently structured manner. Therefore the panel materials are specified by the user using an spreadsheet-based tool developed for the project (element B on Figure 4). The two types of design data (geometric and material) are linked through a labelling system. For example, an attribute of the panel object in the BIM database is the façade type (A, B, B.1 etc.); this corresponds to a façade type specified in the tool. The material options are stored in the re-useable database (element (D) on Figure 4). This part of the database has been populated by extracting the required information from specifications for 30 real-world projects.

Alongside providing the knowledge-based tool with the information required to identify relevant design constraints, the tool generates and updates the project façade typology report, a key (paper-based deliverable) of the façade consulting team during the design stages (element (C) of Figure 4).

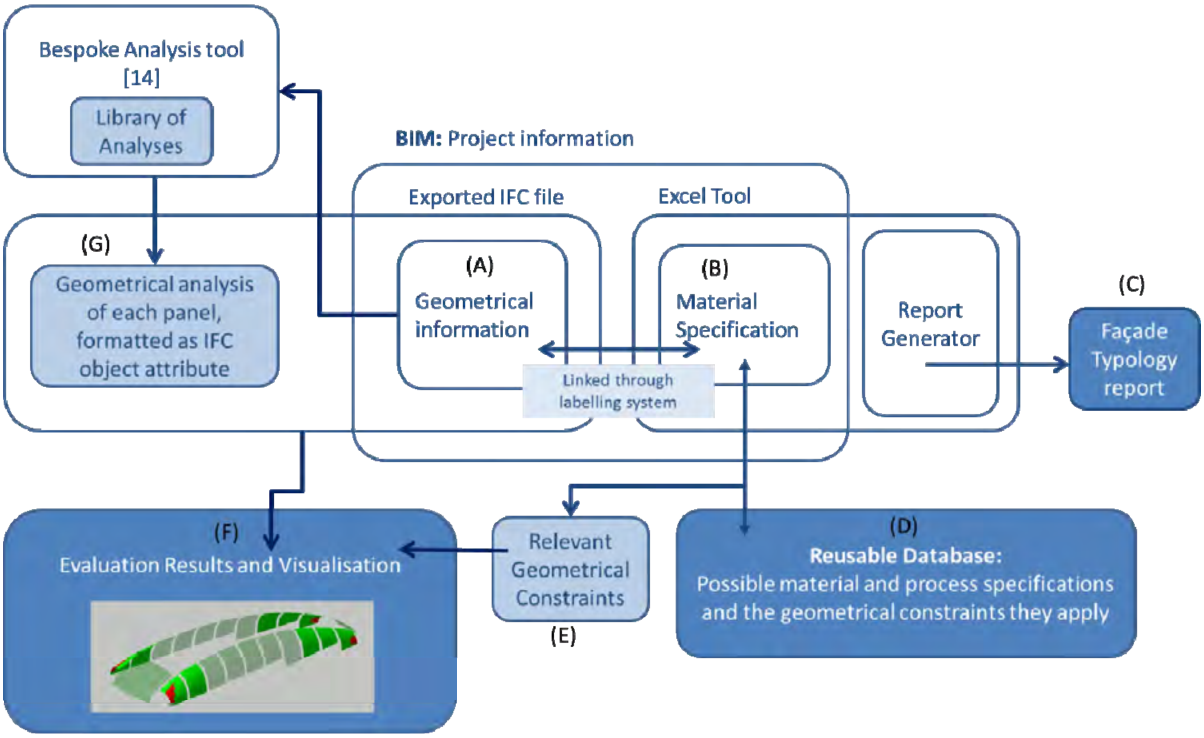

Figure 4: Diagram of the tool

When the user uses the tool to select the materials and processes to be used to make the panel, the tool also identifies the correct set of geometrical constraints. Several different checks may be required for each panel. For example, dimension, curvature and aspect ratio checks may all be performed. To aid this, the re-useable database (element (D) on Figure 4) stores a set of constraints for each possible material or process. As the user selects each material or process for a panel, the tool also identifies a set of constraints. The tool selects the correct constraint (maximum, minimum or range depending on the constraint type) for each check to form a final set of constraints (one for each check type) for each façade panel (element (E) on Figure 4). The constraints stored in the prototype tool have been gathered from interviews with industry members.

In addition to the identification of constraints, the tool provides the user with a storage facility that can be updated or expanded in parallel with a project. This encourages and enables live knowledge capture by facilitating the use of the knowledge on the current project; capture of knowledge as it is identified; and involvement of the supply chain.

The design is evaluated by comparing the constraints to the results of the corresponding geometrical analysis performed on the design data extracted from the BIM database (element (G) on Figure 4). The results of the evaluation can be provided visually, so as to ease communication of the design issue to the rest of the design team (element (F) on Figure 4).

## 5 Case Studies

The following two case studies aim to identify whether the proposed tool can help the façade consultant to identifying panels in proposed panelisation schemes that are shaped or sized in such a way that they either cannot be manufactured, or cannot be manufactured at a reasonable cost.

### Oxford Brookes, University Building

The proposed Oxford Brookes University Building has over ten different façade types, each type having many sub-types and each sub-type consisting of several different materials. The materials include among others: glass, with various coatings; fiber-reinforced concrete; and aluminium. The size and shape of these panels vary over the façade area, but to simplify modelling for the case study, a small representative area was selected.

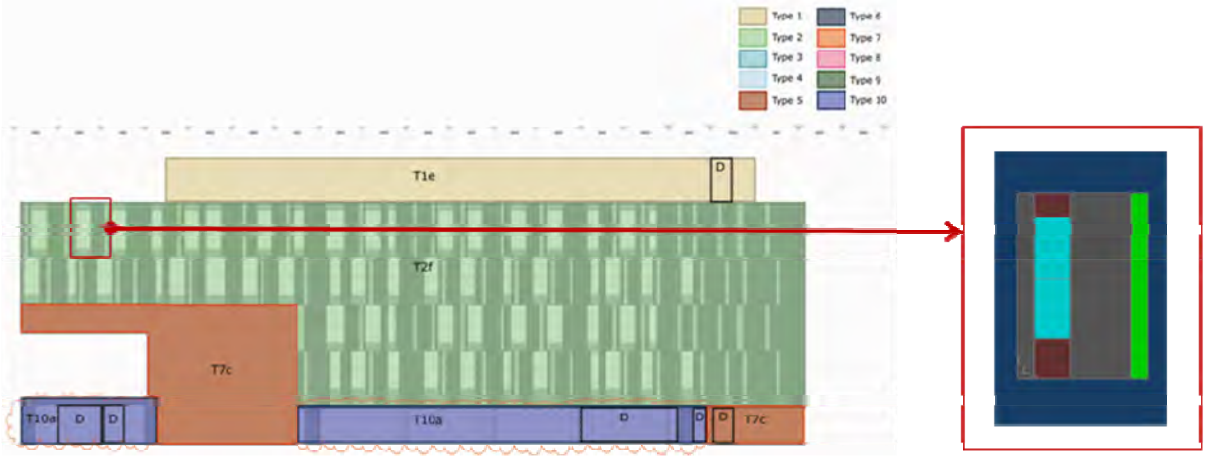

Figure 5: An elevation of Oxford Brookes. The section of the façade used in the test is highlighted with a red rectangle. (Image on left generated by Ramboll Façade Team)

The chosen section of façade was modeled using information from RIBA (Royal Institute of British Architects) Stage C architect's drawings. The RIBA Stage C façade typology report was used as the information source for the materials specification. The tool checked the panel geometry against three criteria: the maximum allowable longer dimension; the maximum allowable shorter dimension; and the aspect ratio (a correct aspect ratio prevents distortion of glass panels during heat treatments). These are constraints imposed by the manufacturing process of the panels.

The tool successfully identified problems with three panels. Both fibre reinforced panels had a maximum dimension that was too long, and, the coloured glass panel was too slender. Subsequent architect's drawings show that these panels were indeed modified, based on the consultant's comments

**Park House, Oxford Street**

Park House is a large, high-specification combined commercial and residential development in the center of London. The roof panels are glazed using a variety of high-specification treatments and glass coatings.

A key design issue for this project was manufacturing the curved panels. The cold bending technique of forcing the glass into shape without heating is considerably cheaper than hot bending, which requires heating the glass to allow it to sag under its own weight. Therefore it was important to understand the extent of hot bending required, and the zones in which it would be necessary. This information could be used to focus the design development, and to evaluate design iterations.

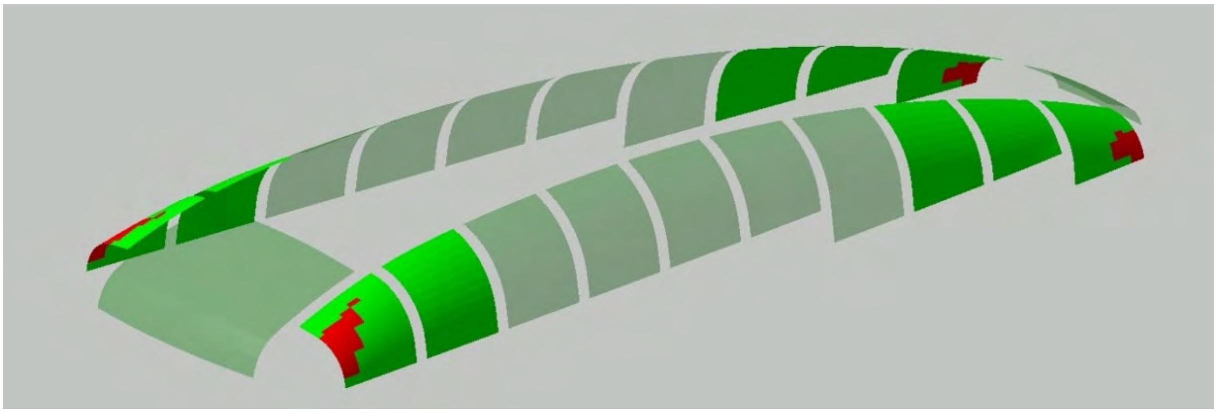

Figure 6: Park House roof; Visualisation of manufacturability analysis results

For the case study, the relevant geometrical information was extracted from the architect’s digital model and converted into the required IFC format. The study was performed using preliminary design stage information and so the panels were specified by the façade consultant only as Double-Glazed-Units; no further detail was available at this stage. The tool identified the panels that would require the hot bending manufacturing process. In Figure 6 these panels are highlighted in red.

A comparison of the result from the proposed tool and the sub-contractor’s design information shows a close match. The tool underestimated the extent of the panels requiring hot bending by 30% but accurately identified the area of the roof that would require further design development if hot bending was to be avoided. It is possible that the design heuristic should be adjusted if such limited design information is available.

## 6 Conclusion

A combination of two mapping methods identified *capture and application of manufacturing* constraints as an aspect of the façade design process that could benefit from knowledge-based support.

This paper proposes a rule based, semi-automated manufacturability assessment of façade panelisation schemes. The rule based knowledge management technique is found to be appropriate to manufacturability assessments. Interviews with industry members identified heuristic rules (or ‘rules of thumb’) that are used by consultants and contractors to highlight manufacturing issues for façades. This makes it possible to capture, in the form of a rule, the required knowledge for the manufacturability assessments.

The proposed modular tool has been tested on real world projects and was able to identify panels with possible manufacturability challenges. The results from the tool matched those generated by industry members. A key capability of the tool is to enable the live capture and use of expert knowledge. The tool automates the identification of manufacturability constraints using the material specification process undertaken by the façade consultant. In addition the tool stores and supplies these constraints in a computer interpretable form to semi-automate evaluation of the proposed panelisation scheme.

## 7 Further Work

An important area for further work is to expand the knowledge base to include geometrical constraints on façade panels that relate to maintenance or replacement of façade panels. For example, panels on the upper floors of buildings in tight urban environments may be restricted in size due to the size of the lift shafts in the building that will be used to transport a replacement panel.

The knowledge tool sits within a larger system that performs the required analysis of the geometry as well as comparing this analysis to the constraints selected by the knowledge module presented in this paper. This integration of the models is an on-going project and a key area for further development. In addition, testing of the overall system is planned on a selection of real-world case studies. The tests will aim to build an improved understanding of the system's performance compared to the current industry processes.

## 8 Acknowledgements

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# Individual Glass Solutions for Modern Building Skins

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## Summary

Today glass often plays a central part in the design of building skins. Therefore demands on such glazing become progressively complex and manifold. Depending on the respective environment, the occupancy and other relevant parameters individual solutions have to be developed. To optimize energy consumption of the façade, the insulating capacity, the sun protection and the solar energy transmittance have to be adjusted carefully according to particular boundary conditions. Translucent insulating materials (TIM), various systems for sun and energy control and individual design inserts allow a wide range of innovative possibilities for green buildings of the future.

**Keywords:** Insulating Glass, Sun Control, Energy Consideration, Individual Design

## 1 Introduction

Rising energy standards and peoples growing ecological awareness in terms of energy consumption and $CO_2$ emissions require new developments in the field of the building´s services facilities as well as the building´s façade. Nevertheless, today the technical limits in the field of the Thermal Insulation are very limited. Improvements may be achieved by exotic materials like translucent Silica-Aerogels [1]. Such nanoporous granulates prevent convection and conduction within the gas phase. Thus, an Insulation Glass Unit filled with such a material achieves a thermal transmittance of $U < 0.3$ W/(m²K). Evacuated glass units may once achieve even lower values. But a durable vacuum insulating unit with such U-values is not available at the moment due to various technical problems of keeping the vacuum durable.

Hence, a key development in the field of thermal insulation is very limited. Therefore, it is more effective to taken the thermal and solar parameters into account to optimize the building´s overall energy consumption. Even with an excellent thermal insulation glass buildings tend to overheat during the summer. Considering the fact, that cooling a room by air-conditioning requires approximately double the energy than rising the temperature about the same value, it is often more effective to design a suitable shading system than to reduce the thermal insulation to some percentages. The physical properties, especially the Insulating Capacity, the Visual Light Transmittance and the Total Solar Energy Transmittance have to be fitted carefully, depending on the individual boundary conditions to achieve an optimal performance.

Beside solar-control coatings, integrated blinds or metal meshes with optical properties can be used to obtain the required shading coefficient. In addition, such solutions create an individual design of the buildings envelope. As the technical parameters of the Insulating Glass Units often do not differ much, such design issues become more and more important.

# 2 Physical and Solar Properties

## 2.1 Insulating Capacity

Insulating Glass Units (IGU) consist of minimum two glass panes, separated by a spacer as illustrated in Figure 1. The spacer is filled with desiccant to absorb rests of moisture, captured inside of the cavity during production. The cavity can be filled by air or by a special gas like Argon or Krypton to improve the thermal insulation capacity. A primary seal of permanent plastic Butyl has the function of a vapour barrier. The secondary seal of Silicone or Polysulfide has a structural purpose to bond the glass-glass sandwich together statically. The insulating capacity achieved by the IGU is described by a physical parameter called thermal transmittance, respectively U-value.

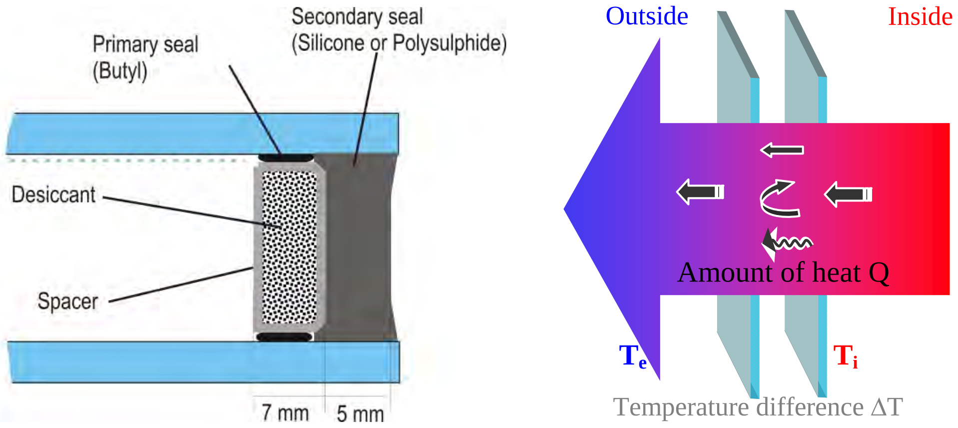

Figure 1: Make-up of a typical Insulating Glass Units (left) and the heat transfer from warm inside to cold outside through a double-pane IGU (right).

The U-value can be defined by the amount of heat Q which is transmitted through an area A within the time period t along a temperature gradient ΔT (1). The U-value can be calculated according to the standard DIN EN 673 [2]:

$$U \cong \frac{Q}{A \cdot \Delta T \cdot t} \quad , [U] = \frac{W}{m^2 \cdot K} \tag{1}$$

The insulating capacity is influenced by the internal heat transfer $h_i$, the heat transfer in the cavity $h_t$, which can be divided into ~17% heat conduction, ~17% convection and ~66% radiation and the external heat transfer $h_e$ (2).

$$\frac{1}{U} = \frac{1}{h_i} + \frac{1}{h_t} + \frac{1}{h_e} \tag{2}$$

It becomes obvious that the radiation in the cavity plays a dominant role which determines the total heat transfer. Therefore, the development of the coating technology was a main step. By reducing the long-wave Infrared emissivity of the glass surface from $\varepsilon_{glass} = 89\%$ to $\varepsilon_{coating} = 2\%$ the U-value could be reduced significant by blocking the heat radiation.

Before 1960 monolithic glass with a U-values of ~6.0 W/(m²K) has been standard. By introducing double glazing IGUs the U-value could cut in half. Today a U-value of ~1.0 W/(m²K) can be achieved with low-e coatings and gas fillings. Triple glazing achieve an U-value of ~0.5 W/(m²K), depending on the type of gas used, the glass thickness, the cavity and the inclination installed.

Generally, the dependence of the U-value on the inclination angle is not taken into consideration in daily praxis. The U-value is defined and measured in vertical position according to the appropriate standard DIN EN 674 [3]. Furthermore the DIN EN 1279 [4] refers to the U-value of DIN EN 674 and does not consider the actual behaviour. Therefore, the actual insulation capacity of standard IGUs can be much less than that expected of the preliminary design when used as a roof glazing. The reason for this behaviour is explained in Figure 2.

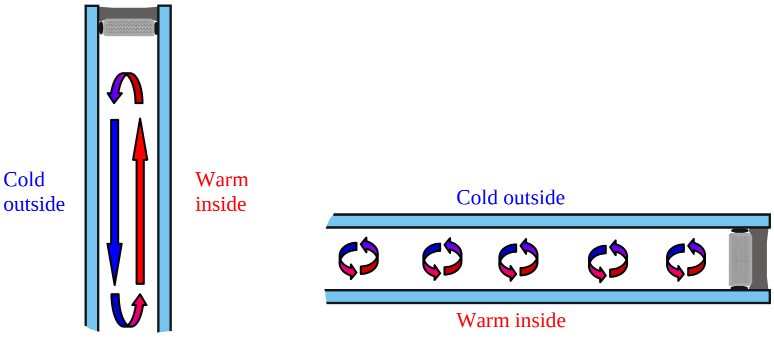

Figure 2: Convection inside an IGU in the case of façade application (left), convection inside an IGU in the case of roof application (right).

Inside a vertical glazing the thermal convection forms a long, slow loop as warm air rises along the interior side. The convection is not significantly high. In the case of a horizontal glazing, the warm air meets the colder outer side more quickly when rising. The result is the formation of many small rapid circuits and an accelerated airflow. Thus the thermal energy is transferred faster through the cavity and the insulating capacity degrades while the U-value rises. Therefore, the performance of a gas-filled standard IGU drops significantly, when used in a roof application. The real U-value can be more than 50% higher than the U-value measured or calculated according to the appropriate code. If this is not considered carefully the energy consumption of the whole building may unexpectedly rise due to the increased heat loss.

## 2.2 Radiation Properties

Beside the insulating capacity the radiation properties like the Visual Light Transmission and the Total Solar Energy Transmission characterise the functionality of an IGU. The Visual Light Transmittance $\tau_v$ is defined as the amount of visible light ($\lambda$ = 380nm – 780nm) passing through the IGU, less the reflected and absorbed fraction as illustrated in Figure 4. The ultraviolet part (UV) and the infrared part (IR) is not been considered. The Visual Light Transmittance usually is given in % of the original value and can be determined according to the standard DIN EN 410 [5]. $\tau_v$ specifies how much light comes into the building, in other words it indicates how bright or dark the glazing appears.

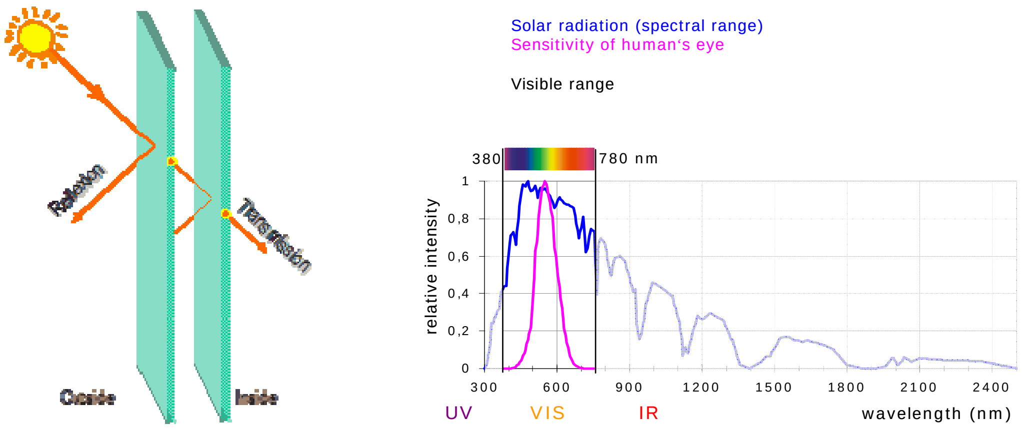

Figure 3: Visual Light Transmission, visible range from 380nm to 780nm.

The Total Solar Energy Transmittance (TSET) is also known as „g value“ or Solar Heat Gain Coefficient (SHGC). This value considers the whole solar range from 250nm up to 2500nm, including the ultraviolet (UV), visual (VIS) and infrared part (IR) of the solar spectrum [5]. Beside the direct transmission the secondary heat is included. The secondary heat is generated by the absorbed radiation, which is shifted into the IR range and emitted in any direction (Figure 4). The g-value is not independent from the Visual Light Transmittance $\tau_v$. Both values are connected by the equation $\tau_v/g < 2$.

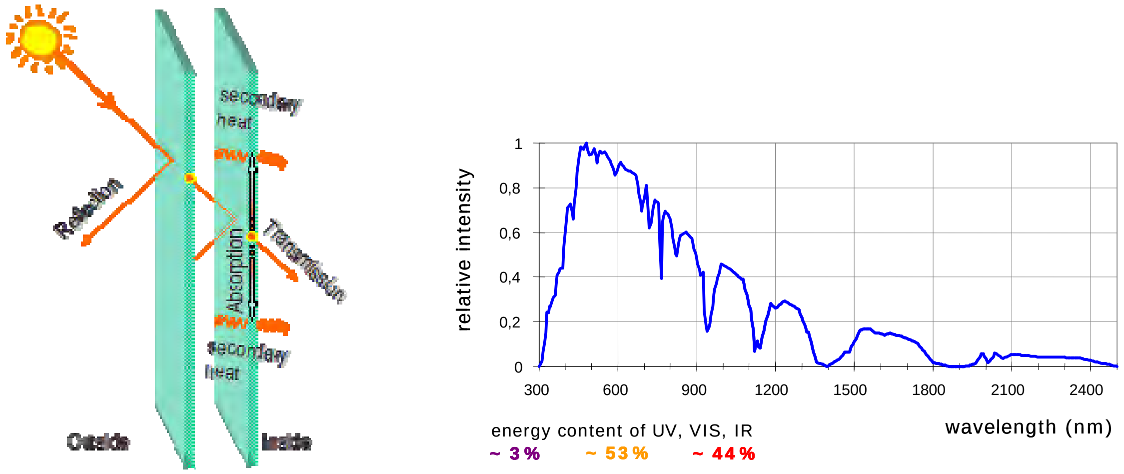

Figure 4: „g value", Total Solar Energy Transmittance (TSET) in the solar range 250nm to 2500nm.

The area beneath the graph in Figure 3 and 4 is equal to the appropriate energy content. The visual part of the solar spectrum contains already 53% of the total solar energy. Even the most effective sun control coating may only cut off the UV and IR part with together 47% energy content. Such an ideal coating with 100% visual light transmission and a Colour Rendering Index of 100% results in a ratio of $\tau v$ = 100% divided by g = 53%. Hence the result is 1.89 (not considered the secondary heat), thus the ratio is < 2. This physical fact is called the Spectral Selectivity.

One way to increase this ratio is to cut away the tips of high energy content in the visual range. In this case the colour rendering index will be less than 100% as some belts were missing in the spectrum. In other words, the glass will not be neutral and the entering light will have a certain colour. Another way, influencing the Spectral Selectivity is the use of different inserts. To control the different aspects and fulfill the whole range of demands, the cavity of the IGU can be used [6]. Not only gas fillings and coatings but also integral louver systems, capillary honeycomb slabs or even high insulating Silica-Aerogels allow controlling the physical properties over a wide range.

## 3 Translucent Insulation Materials

### 3.1 Function

Light diffusing insulating material, usually called Transparent or Translucent Insulation, is often used to achieve a low U-value and a certain solar energy gain for the building. The working principle of such materials is based on the polar bear coat. The material collects and conducts the light, respectively the solar energy. At the same time a good thermal insulation is achieved.

### 3.2 Capillary Structures

Such materials can also be used inside an IGU to expand the features of the façade. When embedded inside the cavity, inserts like capillary honeycomb slabs improve the thermal performance by preventing convection. On the other hand the heat flow in the material increases at the same time. By using a 16mm thick light diffusing capillary insert (Figure 5), the U-value could be reduced from ~3.0 W/(m²K) for an air filled cavity to ~2.0 W/(m²K) without any additional coating or gas filling. Adequate triple glazing units with an additional gas filled cavity and a low-e coating even reach a U-Value of ~0.6 W/(m²K). This benefit of an IGU with a Translucent Insulation insert even increases when used as a roof application. Despite a conventional gas filled unit the U-value of an element with an adequate insert stays constant, if it is inclined to the vertical (Figure 7). Aside the low U-value of such materials, their light diffusing characteristic brings the light very deep into the room while the colour rendering index remains by ~100%. For that reason the translucent insert fulfills multifunctional demands and offers additional advantages like sound insulation, the use of glare free natural daylight and a unique façade design.

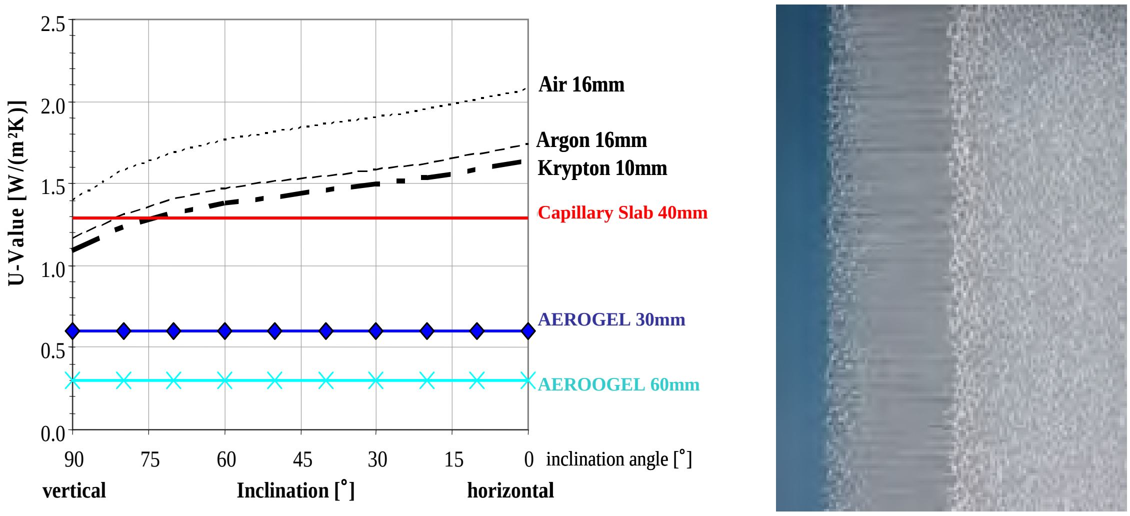

Figure 5: Dependence of the U-Value on the inclination, capillary structure of PMMA.

The natural daylight is used efficiently and without any disturbing glare. As a result, comfortable lighting and heating conditions can be achieved, and direct solar radiation avoided. For that reason the user’s comfort increased and the energy consumption for heating, cooling and artificial lighting is reduced. Consequently such materials are often used wherever good light conditions, low U-values and a variable Light end Energy Transmission is necessary. Typical applications are museums, production- and sport facilities. Figure 6 shows a gym in Herzebrock. The capillaries inside the cavity of the IGU distribute the light and illuminate the whole area homogeneous without glare.

Figure 6: Typical daylighting application at a gym in Herzebrock.

Another application which became more and more popular in the previous years is the use of such translucent honeycomb slabs inside of U-profiled channel glass (Figure 7). As such a double-shelled U-profiled glass wall cannot be installed as a hermetical sealed system a gas filling is not possible in this case. Hence an alternative solution has to be found to achieve the appropriate U-value. By using a

40 mm thick capillary slab in combination with an low-e coating an U-value of ~1.4 W/(m²K) is possible.

A nice example of such an application is the new extension to the Nelson Atkins museum in Kansas City from Steven Holl Architects.

Figure 7: Capillary Slab light diffusing insulating panels in double-shelled U-profiled glass.

The translucent shell of the glass cubes is mostly made from U-profiled panels. The capillary inlays softly diffuse the daylight into the exhibition rooms and show very high light transmission values and protect the works of art from damaging UV radiation. During the day, the translucent glazing of the cubes allows the natural daylight to illuminate the exhibition areas below. The diffuse daylight produces a bright and pleasant atmosphere in the rooms below ground.

## 3.3 Silica-Aerogels

The use of translucent Aerogels as a highly efficient insulating material inside the IGU´s cavity represents the best possible thermal insulation at the moment. Again the U-value does not rise when used as a roof glazing (compare to Figure 5). This extremely lightweight material is produced using a Sol-Gel process. The products nanoporous particles with a diameter of 0.7mm to 3.5mm basically consist of $SiO_2$, the basic material of sand and glass (Figure 8). However the Aerogel has an air content of about 97 % and only weighs 75g per liter. This makes Silica-Aerogel the lightest and best insulating solid in the world at the moment.

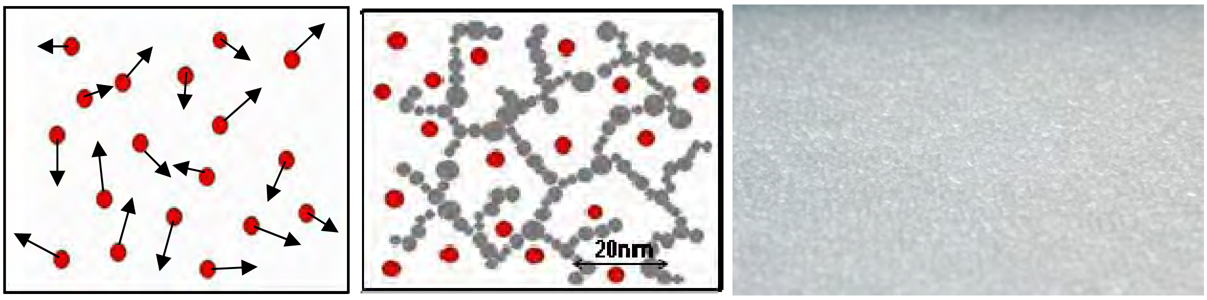

Figure 8: Schematicall illustration of movement of gas molecules in air (left) and the gas molecules trapped in the nano-porous Silica-Aerogel structure (middle). Silica-Aerogel granulate (right).

Due to the low solids content of the granulate the heat conductivity is minimal. The three dimensional lattice of the material forms a structure with a mean pore size of approximately 20nm. Gas molecules are enclosed in these pores, reducing their possibility to vibrate and to transfer heat by colliding with each other. Hence, not only the convection but also the thermal conduction in the gas phase is efficiently hindered. As a result the insulating capacity is improved and the speed of sound drastically reduced. Therefore the material offers excellent sound and thermal insulation uniquely combined with a high light transmittance and light diffusion. These advantages offer new design solutions for those who want to achieve a maximum of daylight as well as an optimum of energy efficiency [1].

Figure 9: British Antarctic Survey Research Station Halley VI.

One project, realized with a 60mm Aerogel filling inside glass, is the new complex of the British Antarctic Survey Research Station Halley VI, located on the Brunt Ice Shelf, a floating area of ice that is moving westward by approximately 700m per year. Since 1956 the first Halley bases were used to conduct research into meteorology, glaciology, seismology, radio astronomy and geospace science. The new station will allow long-running research on global change to continue at the site where the ozone hole was discovered. The new modular station is to be made up of eight individual modules, which are connected together by short, flexible corridors. The modules are kept above the snow surface using hydraulic legs mounted on skis. As well as keeping the buildings above the rising snow level the new design will allow the station to be periodically relocated across distances of many kilometers. The central, red colored module illustrated in Figure 8 accommodates the majority of the stations social areas and therefore consists of double height with a large east-facing window made of OKAGEL. The translucent façade has an U-value of $U < 0.3 W/(m^2K)$. Because of the extreme temperatures of -60°C and less, a standard insulation glass would not perform properly. The primary seal of Butyl would be too hard and too brittle to keep the cavity permanently proof. Hence the gas would get lost quickly and humidity may penetrate into the cavity

## 4 Directionally Selective Inserts

### 4.1 Sun Control Blinds

Buildings with large glass surfaces often need an effective sun and glare control to prevent them from overheating. Therefore additional sun control louvers can be used. These do not necessarily need to be mounted on the façade or on the interior of the building. An alternative possibility is an IGU with integral louvers systems in the cavity. Depending on the type of insert the function is equivalent to that of a system mounted on the exterior (Figure 10).

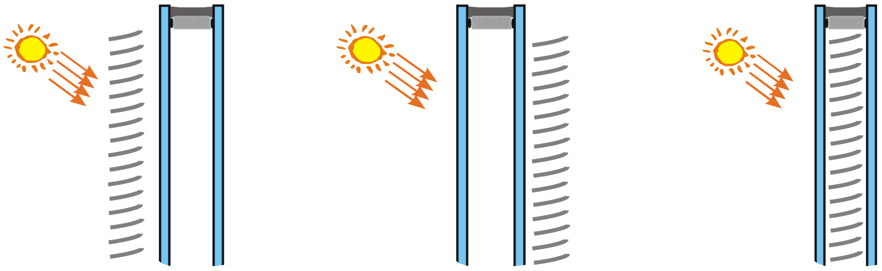

Figure 10: External blinds (left), Interior blinds (middle) and Blinds inside the cavity (right).

External blinds achieve the best performance concerning sun control and protection against overheating. Disadvantages are the cost of maintenance and the appearance of the facade. Interior blinds offer sun protection only, without avoiding overheating, as the heat is already inside the building. Blinds inside the cavity offer a good compromise of functionality, maintenance and design. An integral louver system has more to offer than merely an aesthetic advantage. Because they are located inside the cavity, the blinds are protected from weather influences and do not get dirty which means they are totally maintenance free. More important, the functional glass fulfills all of the requirements of thermal insulation while allowing a differentiated daylighting to the interior. Integrated systems exhibit a slightly higher amount of total solar energy transmission than systems mounted on the exterior. Blinds mounted on the interior have the worst functionality in this comparison. Practice proves them to be extremely prone to becoming dirty as well as needing intensive maintenance. They are also hardly able to keep the summer heat out of the interior rooms. They only afford a certain amount of glare control.

Integrated sun control systems are therefore a good compromise for a variety of different requirements. These systems can be either fixed or movable. Even fixed louver systems, without any moving components, allow for effective sun control and a self-regulatory function. Compared to conventional glass with a homogeneous sun control coating the amount of incoming sunlight and with it the total solar energy depends strongly on the position of the sun (Figure 11).

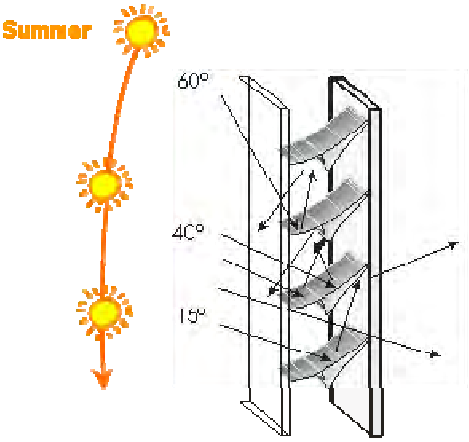

Figure 11: The selective light and solar energy transmittance of fixed integral louver systems depend on the sun angle.

The cross-section and surface of the slat as well as the spacing and the orientation of the single slats are decisive for perfect functioning of a sun control system. But the function also depends on the current radiation and weather conditions. The system should be designed in such a way as to largely suppress direct sunlight in summer allowing only diffused daylight to enter the room.

Figure 12: Integral sun control system at the façade of the Landesdenkmalamt Baden-Württemberg, Esslingen.

Due to its selective properties, the amount of total solar energy and light transmission entering through such a sun control system depends on the season and on the position of the sun. In order to optimally adapt the sun control to the buildings boundary conditions, information concerning the geographical location of the building (coordinate and orientation) and the inclination of the facade is needed. The result of optimal function is sunny rooms which are evenly illuminated by natural light without becoming overheated in the summer. The sun from the south is blended out while at the same time allowing the daylight to enter the room. Systems like this are not only suited for sun control on façades but also for horizontal roof glazing [7]. Figure 12 gives a good impression how an integrated sun control system may work under optimal conditions.

## 4.2 Individual Design Solutions

Individual and customized Design Solutions became very important for sophisticated architectural applications. Architects and owners are looking for new ideas and possibilities to make their building distinguish to all the other buildings. Often, the building owner is less interested in getting a unique (and maybe more expensive) façade design, but has to make a good case for potential investors. Today one of the best arguments for lessees and vendees is a good design. An alternative to glass coatings or sun control blinds is an insulating glass with a metal inserts (Figure 13). Herewith a similar functionality is possible while lending the glass façade a visual structure, colour and textured shine. Many different designs of wire mesh, expanded metal or perforated metal sheet can be integrated as a design element. The material and the manufacturing process of the insert determine not only the aesthetics but also the function. A directionally selective sun protection is also possible as a partial through-vision from inside and very good heat insulation.

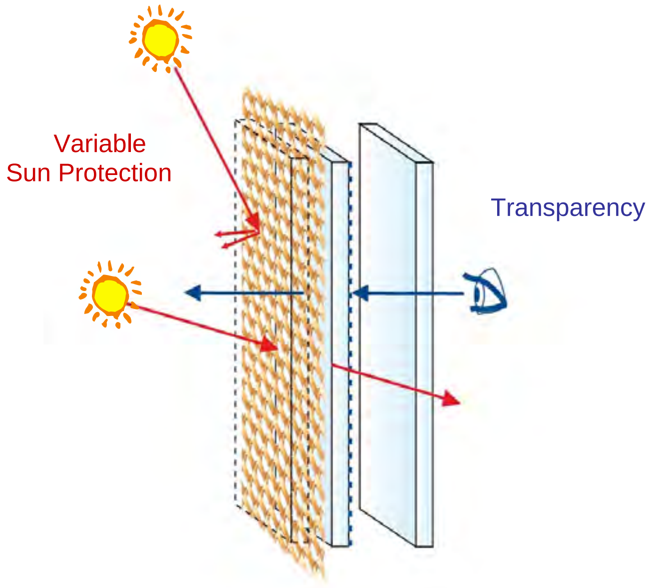

Figure 13: Integral sun control system at the façade of the Landesdenkmalamt Baden-Württemberg, Esslingen.

Figure 14 shows an IGU with an expanded Copper mesh developed for David Chipperfield's Central Library in Des Moines, Iowa USA.

The expanded copper inlay produces soft light in the interior of the building and provides effective protection against sunlight and glare. The glazing is semi-transparent. The fine mesh perforation pattern offers a privacy function, as people inside can look out, but people outside can't look in.
But the inlay copper is not only a design attractive design element; it also performs the function of a directionally selective sun protection system. The asymmetrically arranged metal perforations act as miniature shading elements. When the sun is high, the inlay screens it out the sunlight completely, when the sun is low, the total solar energy transmission reaches a value of ~0.13.

Figure 14: IGU with Expanded Copper Mesh at the Public Library Des Moines. The left picture shows the vision through the glass units from the inside. The picture on the right the appearance from the outside.

## 5 Acknowledgements

The Insulating Glass Unit, once developed to guaranty proper thermal insulation for window glazing, has to assume multiple functions nowadays. Even contradictional demands have to be fulfilled. Highly efficient insulating systems will become more and more important, even though the technical limits will be reached soon. IGUs with special inserts can improve the functionality, combining excellent thermal insulation with an efficient use of natural daylight and sun control. Even energy generating systems will be integrated into the buildings skin. Such concepts will play a major role in the future to fulfill the rising energy saving requirements. This development does not only offer new potential for the planer, it is also a challenge to the glass manufacturer's flexibility and technical know-how. However, the buildings envelop will become more distinctive, architects and designers will get a new range of possibilities to realize their ideas and finally users will benefit not only from an increased comfort but also from reduced costs for energy and maintenance.

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# Integration of Solar Thermal Components in Sandwich Panels

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## Summary

The paper at hand deals with the integration of pipes into sandwich panels for using the panel as a solar collector. The optimal location, shape, length and hydraulic diameter of the pipes are analyzed using numerical calculations. Also the influence of various materials on the estimated performance of the panel is investigated. The results of the performed parametric study are presented for further use. The proper functioning of the numerical model is proved by simple test objects.

**Keywords:** industrial buildings, sandwich panels, solar

## 1 Introduction

### 1.1 Initial Situation

Generally industrial buildings provide large areas of building envelope with a comparatively small amount of window area. Resulting from the requirements on industrial buildings, the buildings are rather compact. That results in a huge building volume surrounded by a comparatively small area of building envelope. The claddings of industrial buildings are mostly assembled from industrially produced thin-walled metallic building components. Examples are:

- Trapezoidal or corrugated sheeting in the inner and/or outer shell
- Liner trays in the inner shell
- Sandwich panels with steel faces as inner and outer shell

Low costs, high load-bearing capacity, modularity and variability were of primary interest. At that time, further requirements especially those related to building physics (reaction to fire, fire resistance, heat and noise protection, air tightness) were of minor importance.

### 1.2 Potentials

The current discussion on sustainability and energy saving confirms the global need for action concerning $CO_2$-reduction. Industrial buildings with their large areas of building envelope offer great opportunities for production of energy via photovoltaic cells or solar thermal collectors. The conventional method to mount a load-bearing framework or rack on the roof can be discarded due to esthetic criteria. This method will only be applied in those cases were no visual demands exist. And apparently, this method cannot be applied in walls. The solution for these problems is to integrate the cells or collectors into the components of the building envelope. Up to now only a small percentage of these wall and roof areas are activated for production of energy. Therefore the integration of a simple, unglazed solar collector into the cladding and roofing is worthwhile.

Within the framework of a German FOSTA-sponsored research project [1 Nasta-homepage], the integration of solar thermal collectors and photovoltaic cells into industrially produced building components for exploitation of heat and electricity is investigated. The focus is laid on sandwich panels. The investigations cover the optimization of the integrated systems with regard to energy production, but also the use of the collected energy and the interface with the existing building equipment and appliances. At best the feed-in of energy directly into the running production processes is possible. Further attention is paid to the impacts of the integrated solar system on the load-bearing behavior of the building components itself. This includes on the one hand changes of the load-bearing capacity and on the other hand additional stresses resulting from temperature loads.. Finally, attention is drawn to the fully automated production process of sandwich panels. For economic reasons, the machinery already installed for the production of sandwich panels has to be compatible for the new sandwich panels with only a few adjustments necessary.

The results of the project will be a base for individual product development. The paper at hand deals with the integration of pipes of a solar collector into sandwich panels. The location, shape, length and hydraulic diameter of the pipes are analyzed with regard to the optimization of the energy production. Analysis is done with numerical models, using Finite-Element-Models. The numerical calculations are proved by recalculation of temperatures measured with simple test set-ups. A sandwich panel with integrated pipe system is shown in figure 1.

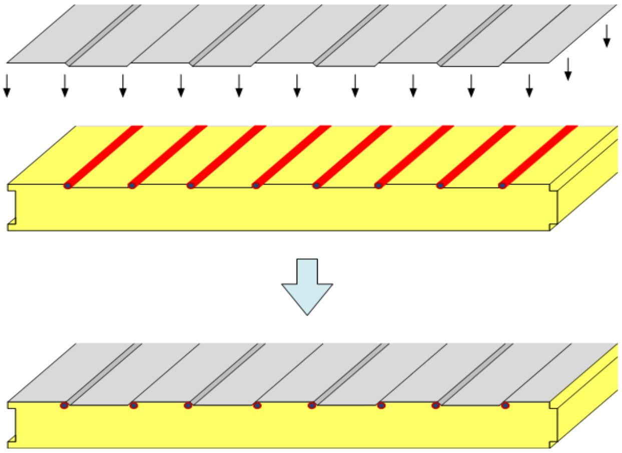

Figure 1: Sandwich panel with integrated pipe system for thermal activation

## 2 Implementation

### 2.1 Sandwich Panels – Passive Potential

Compared to double -shell-systems assembled from steel trapezoidal or corrugated sheeting for the outer shell and steel liner trays for the inner shell, sandwich panels provide several advantages:

- Sandwich panels' core material provides a thermal separation between the inner and outer shell. The core material itself is acting as a thermal barrier.
- Composite systems, such as sandwich panels, provide high load-bearing capacities. The force-fit connection between the faces and the core material stabilizes the thin walled faces. By increasing the thickness of the insulation, the internal lever arm increases, providing even higher load-bearing capacity.

- Compared to walls with an outer shell made out of trapezoidal or corrugated sheeting, the flat-plane faces of sandwich panels provide a visually appealing appearance. The organic coating with the great variability in colors is also of great importance which allows emphasizing or backing-out the complete building or only parts of it.
- Production of the faces by roll-forming allows complex geometry for the longitudinal joints, achieving airtight joints.

All of these points refer to passive achievements of sandwich panels. Further potential exists.

### 2.2 Sandwich Panels – Active Potential and Integration of Solar Collectors

Up to now, sandwich panels were not used or activated for solar thermal applications or for the tempering of buildings. Similar to additive collector systems, thermally activated sandwich panels can be mounted on a substructure and, beside their passive task, perform also an active task. In addition to its function as a building envelope, the modified building component is part of a collector system in which the surface itself is a solar absorber. Solar heat is used for warming a fluid that transports the heat for further usage. The outer faces and the adjacent pipes provide a so-called unglazed collector. Compared to glazed collectors, unglazed collectors work without a translucent cover. This results in high thermal losses, because only a small difference of temperature between the absorber surface and the air temperature can be reached. The efficiency is comparatively to photovoltaic cells low. Therefore the application of unglazed collectors is in the low-temperature-field. In applications with large surface areas as provided by industrial buildings, the low efficiency of unglazed collectors can be compensated. Unglazed collectors are predominantly used for pre-heating in water-supply systems, assistance of heating system or heating of swimming pools. In summer times with small temperature differences, an efficiency of 0.60 or even 0.70 can be reached.

Core piece of an unglazed collector is the so-called absorber area. This area absorbs the direct and diffuse solar radiation as well as the thermal energy of the surrounding. The thermal energy is transported to the consumer via a fluid in an integrated pipe system. The efficiency strongly depends on the absorption and emissivity characteristics of the surface’s coating, the geometry of the absorber area and the connection between the absorber area and the pipes.

## 3 Numerical Simulation

### 3.1 Introduction

The performance of a thermally activated sandwich panel is, apart from the heat input at the surface, dependent on the concerted interactions of the joint components of the panel. Not only the chosen materials but also the positions of the single components in the panel mainly influence the efficiency of the whole system. To assess and optimize a planed panel according to its efficiency the knowledge of the thermal distribution inside the element are urgently necessary.

The numerical simulations aim at identifying the different effects of each parameter on the efficiency of the whole system. With the help of the developed solutions, a sandwich panel with integrated solar system can be analyzed regarding unused possibilities of improvement. In general the required research tasks can be divided into two sub steps:

First the numerical models of all components of the system are created and tested. This includes the pipe, the sandwich panel and the glue. These single components are coupled to create a thermally activated sandwich panel. The correct functioning of the whole system is proofed by a separate constructed prototype. Because of the complexity of the system it is required to abstract the model to achieve economic computing times. These abstractions are analyzed according to their influence on the results.

The second step is to carry out the parametrical study. The results and the most important discoveries are displayed to enable further usage.

### 3.2 Development of the Numerical Model

The most important task while developing the numerical model is to ensure its correct functioning. Some numerical details, for example the heat transfer from the pipe to the foam or the heat transfer from the foam to the surface, is numerical non-critical and thus in the scope of testing the single components not further investigated. The most challenging part of the numerical simulation is the heat transfer from the fluid to the inner wall of the pipe. This transfer is dependent on the properties of the fluid, the velocity and the geometry. Based on a circular pipe, there are two possible ways for a numerical simulation. The more accurate way is to simulate the fluid with all its changing properties depending on its position in the pipe. Such a simulation leads to more realistic total values, but the simulation itself becomes very complex. Thus the second way, the numerical simulation with the abstraction, that fluid is assumed to be uniform over the width of the pipe, is chosen. The results of the numerical simulation, using the simplified heat transfer from the fluid to the pipe, are proofed by using calculation methods given by '[2]'. After combining the models of all components to create a sandwich panel with an integrated solar system, the accuracy of the whole model is verified by the use of a constructed prototype.

The prototype is a 0.5 mm thick steel sheet with a pipe system underneath. The pipe is made of copper and has an inner diameter of 6 mm and an outer diameter of 8 mm. It is glued directly to the steel sheet. The total length of the pipe is 10.61 m. The total size of the prototypes surface is 1 m x 1 m.

To avoid changing influences of the sun and wind, the prototype is operated inside the building. In fact, the prototype is not used as a collector but as a heater instead. Constantly heated water circles with a defined velocity. The temperatures are measured at the inlet, the outlet and the air. The schematic set-up of the prototype is shown in figure 2.

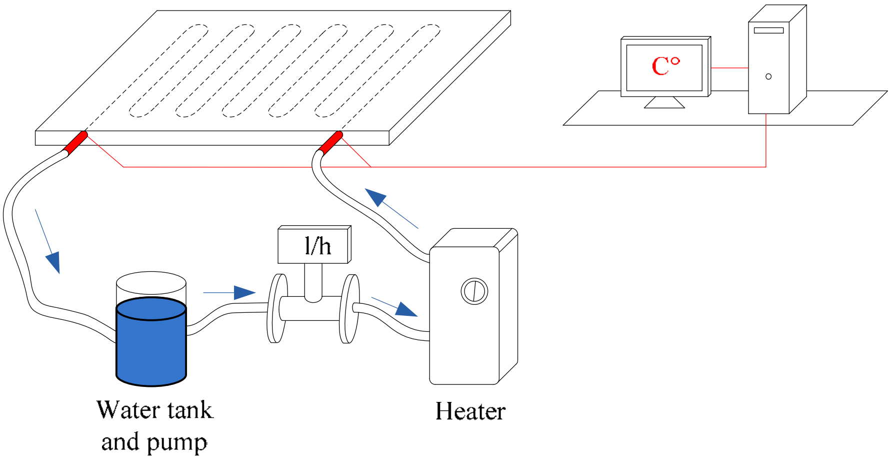

Figure 2: Schematic set-up of the prototype

For the numerical simulation of the prototype the surrounding air is assumed to be stationary. Also heat losses from radiation are neglected. Because of the fact, that it is not possible to glue the pipe always directly to the steel sheet with direct contact between both metals, a constant, filled with glue, gap of 0.1 mm is assumed. Table 1 shows the results of the comparison between the measured and calculated outlet temperatures. In addition to the measured outlet temperatures, a thermal image of the prototype during test number 4 and the associated solution of the numerical calculation are shown in figure 3. The comparison of the results of the numerical simulation with the measurements of the prototype confirms the correct functioning of the developed model.

Table 1: Comparison between prototype and numerical simulation

| Test number | Inlet temperature [°C] | Fluid velocity [l/h] | Air temperature [C°] | Measured outlet temperature at the prototype [°C] | Calculated outlet temperature by numerical simulation [°C] |
|---|---|---|---|---|---|
| 1 | 22,8 | 0,9 | 16,6 | 16,8 | 17,3 |
| 2 | 29,5 | 11,4 | 16,7 | 26,7 | 26,8 |
| 3 | 35,8 | 11,3 | 17,5 | 31,5 | 31,7 |
| 4 | 36,0 | 8,0 | 16,9 | 28,6 | 29,3 |
| 5 | 37,4 | 3,4 | 16,9 | 24,7 | 25,6 |

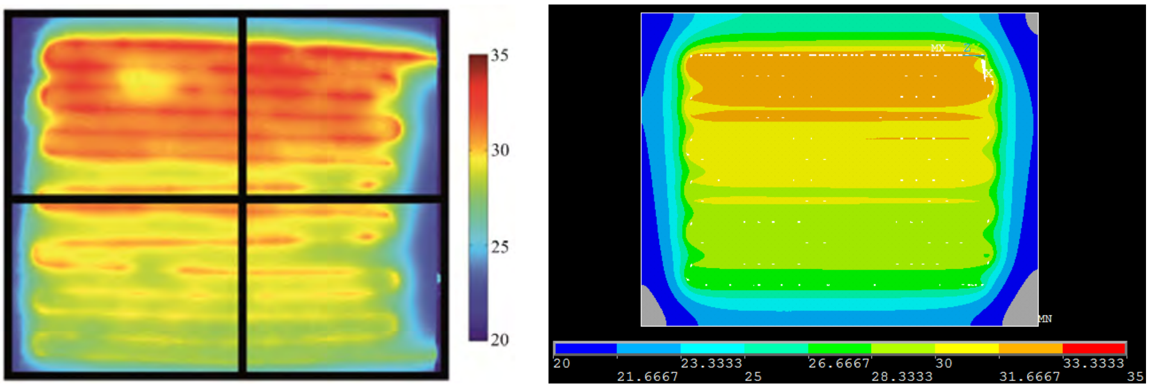

Figure 3: Distribution of heat during test number 4

In the next step the excessive computing times of the model get reduced by straightening the pipe. For the realistic application possible curves of the pipes are negligible compared to length of the straight sections. But nevertheless the influence of the curves toward straight pipes is investigated by using different boundary conditions. Figure 3 shows the results of the comparison. There are no remarkable descrepacnies.

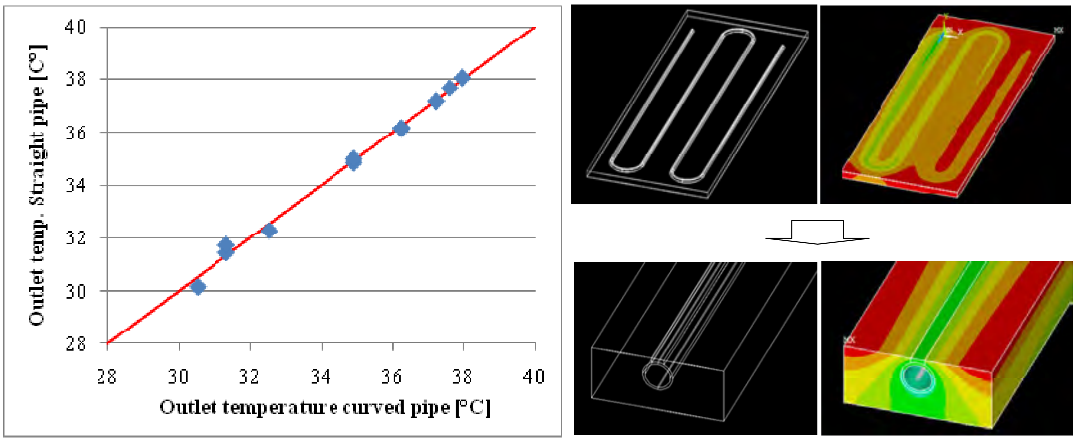

Figure 4: Comparison of the numerical solutions between curved and straight pipes

For transferring heat from the fluid to the inner wall of the pipe, the heat transfer coefficient is the most important parameter. It is dependent on the temperature and velocity of the fluid and the diameter of the pipe. In this case of a sandwich panel with an integrated solar system, heat transfer coefficients from 200 to 2000 W/(m$^2$K) are theoretically possible. But to achieve an economic performance the fluid flow is assumed to be laminar. This results from the investigations documented in section 3.3. Thus heat transfer coefficients from 200 to 600 W/($m^2$K) are used. Performed numerical calculations show, that the used range of coefficients has just a small influence on the results.

## 3.3 Parametric Study

By using the developed numerical model, a parameter study to assess the influence of the involved components is performed. Beside the geometric parameters shown in figure 5, also the material properties of the transitional layer (red) or the pipe (grey) and velocity of the flow are varied. By choosing a good thermal conductivity of the transitional layer, an increased contact area between pipe and surface layer can be approximated. That simulates for example a pre-formed surface layer.

The heat transfer coefficient from the surface layer to the air is assumed to be constant 15 W/($m^2$K). Most numerical simulations are performed with a maximum heat input of 920 W/$m^2$ at the surface layer and a heat loss of 50 W/($m^2$K). The results represent the steady state condition, according to the chosen configuration of parameters.

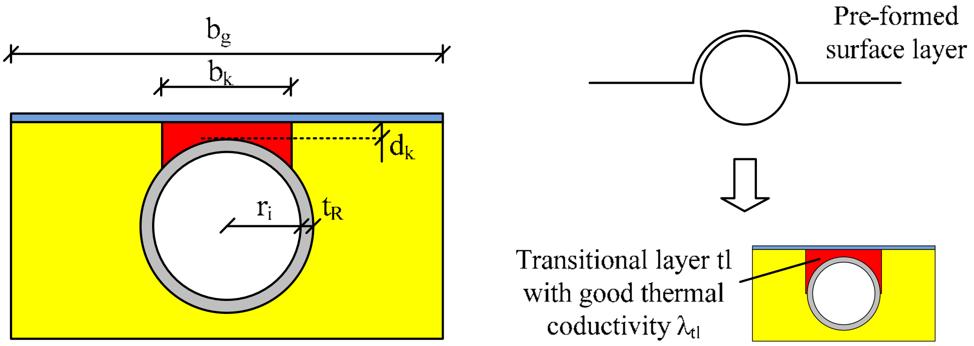

Figure 5: Geometric parameters

Because of the various interactions of the parameters, a final solution for an optimal configuration for a sandwich panel with integrated solar system cannot be presented. The following figures show the influence of changing parameters, while keeping the other ones constant. In all diagrams, the function fluid temperature vs. length of the pipe is shown. For any inlet temperature of the fluid, the outlet temperature dependent on the length of the pipe can be read out.

In figure 6 the influence of the distance between pipe and surface layer is displayed. The pipe and the surface layer are made of steel ($\lambda$ = 40 W/(mK). A transitional layer of just 1 mm made of polyurethane foam (PU) leads to a reduction in efficiency of more than 70%. An increase of efficiency by increasing the contact area between pipe and surface layer cannot be achieved. Also increasing the width of the transitional layer ($\lambda$ = 40 W/(mK) $b_k$ cannot improve the heating of the liquid (not shown in diagram).

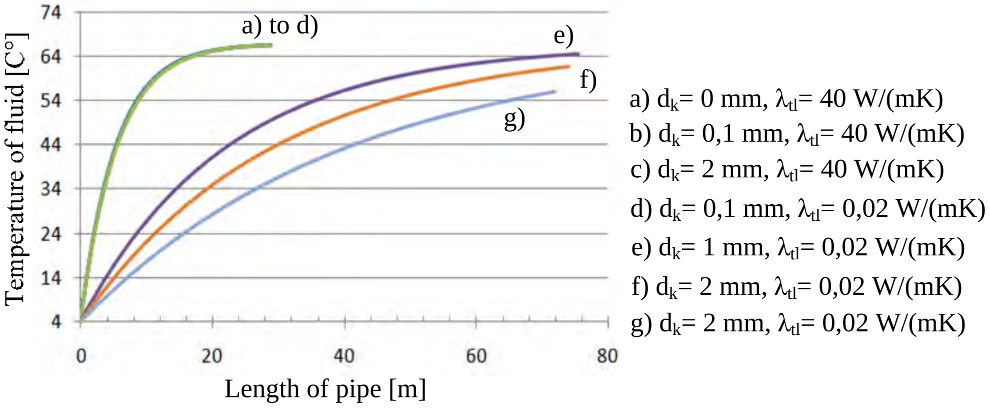

Figure 6: Influence of the distance between pipe (steel) and surface layer

The next series of calculations investigates the influence of the distance between pipe and surface layer if a pipe of plastic ($\lambda = 0.23$ W/(mK)) is used. The results are displayed in figure 7. In this case, the width of the transitional layer $b_k$ ($\lambda = 40$ W/(mK) also influences the efficiency. Thus, for example, a preformed surface layer can improve the efficiency of the system.

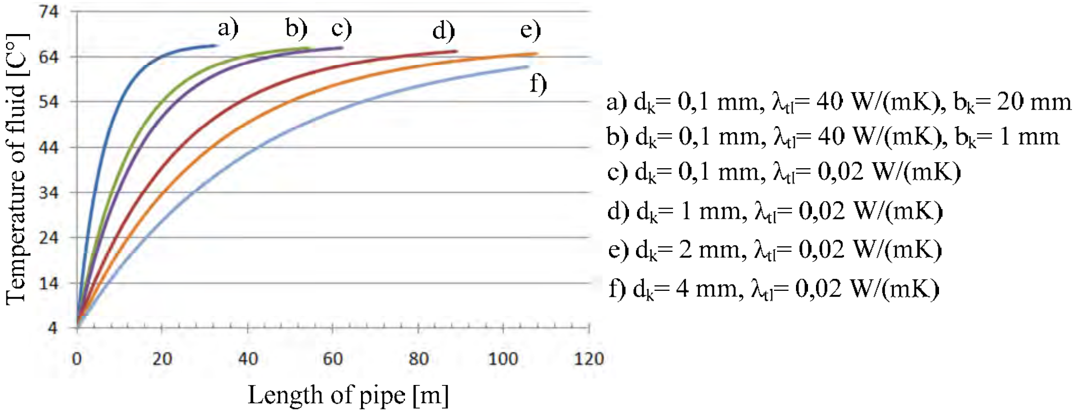

Figure 7: Influence of the distance between pipe (plastic) and surface layer

The third series of calculations, shown in figure 8, represent the influence of parallel fixed pipes. The pipes are made of steel and fixed directly to the surface sheet. A distance between the pipes of more than 100 mm leads to no further increase of efficiency.

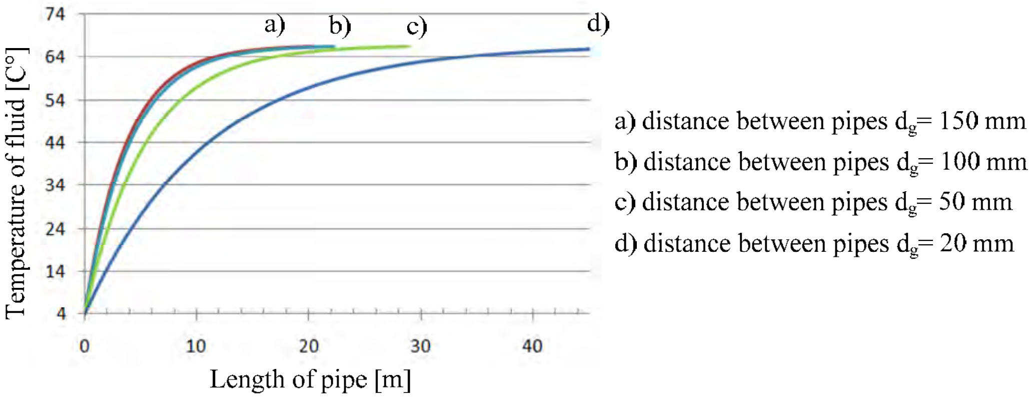

Figure 8: Influence of the distance between parallel fixed pipes

The presented results are just a choice of the performed investigations. Of course, there are a lot of more interactions between used materials and geometry. The entirety of numerical simulations are the basis for following test set ups with fully installed sandwich panels with integrated pipe systems. The construction of these thermal activated sandwich panels will connect the theoretical and numerical analyses with new procedures for producing and installing these products. The first installed panel is planned for summer 2012.

## 4 Conclusion

The most important results of the numerical simulations are information about useful dimensions of the pipes and the influence of gaps between the pipes and the layer sheet. An additional important result is that with the use of plastic pipes also a good efficiency can be achieved.

On the basis of the new findings three specific sandwich panels are planned for construction. The first one will be a panel with nearly even surface layer with pipes with an inner diameter of 6 mm underneath. The distance of the plastic pipes will be 100 mm. For the second and third panel a structured surface layer, normally used for roofing, is chosen. The inner diameter of the plastic pipes will be 6 mm and 10 mm.

Beside the practical tests further analytical investigations will be performed. This includes an energetically conclusion of all involved components to draw up the overall efficiency. This is important, because there are several dependencies of the surrounding components on the expected profit. For example the diameter of the pipes has great influence on the energy consumption of the pump.

By combining the measured results of the installed sandwich panels and the results of the numerical and analytical simulations, an overall forecast of the efficiency of thermal activated sandwich panels will be possible.

## 5 Acknowledgements

This research has received financial support from the Forschungsvereinigung Stahlanwendung e.V. (FOSTA). We express our sincere gratitude for this support.

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# New Limits for Building Design?

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## Summary

The European Parliament Directive 2010/31/EU, Article 9.1, requires that all new buildings will have to be “nearly net zero energy” by 2020 (2018 for public buildings). A constant solar heat gain coefficient or g value - as defined in the relevant standards - is inadequate for optimizing the energy consumption of a building. It is necessary to take the angular dependence of g values into account. Photovoltaics mounted on buildings can generate enough electricity in principle on an annual basis to enable a building to compensate for energy that is consumed for its operation, but there is a large mismatch between when the electricity is demanded and when the electricity is supplied.

**Keywords:** EP Directive, net zero energy, total solar energy transmittance, BIPV

## 1 Introduction

According to the European Parliament Directive 2010/31/EU, Article 9.1, all new buildings will have to be “nearly net zero energy” by 2020 (2018 for public buildings). Thus, any energy required for the operation of the building will have to be compensated over the course of one year by the equivalent amount of energy supplied by the building. In order to be creditable, the energy supplied by the building has to be obtained from renewable sources, since otherwise again primary energy from conventional sources would be used. This directive immediately has three implications for the future usage of energy within buildings:

- Consumption of energy from primary sources has to be reduced significantly.
- Energy usage within buildings has to be as efficient as possible.
- Usage of renewable energy sources is imperative to compensate for any energy acquired from sources external to the building.

Due to the fact that the provision and the usage of energy from some renewable resources – such as hydroelectricity, wind energy or biomass – within any building is very limited, it is much more likely that the energy used for compensation will have to be converted from solar energy. Solar energy not only possesses the advantage of being comparatively evenly available to everybody but it is also easily accessible and harvestable in systems with dimensions ranging from very small – such as those used in individual households - to very large - for office or industrial buildings. Solar-thermal and photovoltaic products that ensure reliable and sustainable kWh generation have been developed and are available worldwide at reasonable prices.

The energy consumption of buildings is typically in the form of heat or electricity. Thermal energy is required to either heat or cool the building to a desired operation temperature. Thus the energy required is related primarily to the type of building usage and the thermal losses or gains through the building envelope. This correlation is mainly described by the U value and g value of the product or the combination of products.

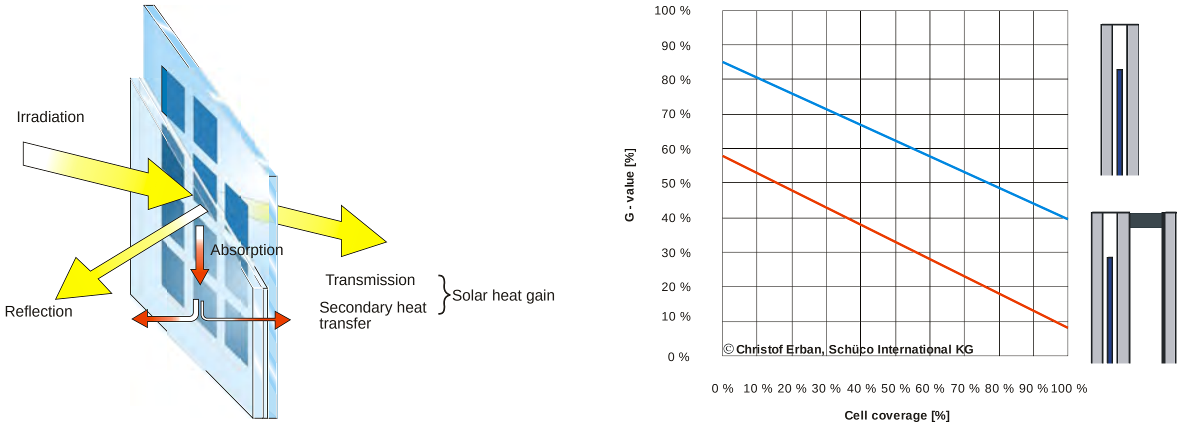


Figure 1: (a) Interaction of solar radiation and PV modules. (b) Total solar energy transmittance (g value) of semi-transparent PV elements vs. cell coverage for monolithic panels and insulating glazing

Unfortunately, constant boundary conditions are assumed when the U or g value is determined experimentally or calculated as described in the relevant standards. Especially the g value – describing the total solar gain through a component – is strongly affected by the reflectance, absorbance and transmittance of the component. As can be seen in Figures 2 and 3, these characteristics are for glass not constant for varying incident angles.

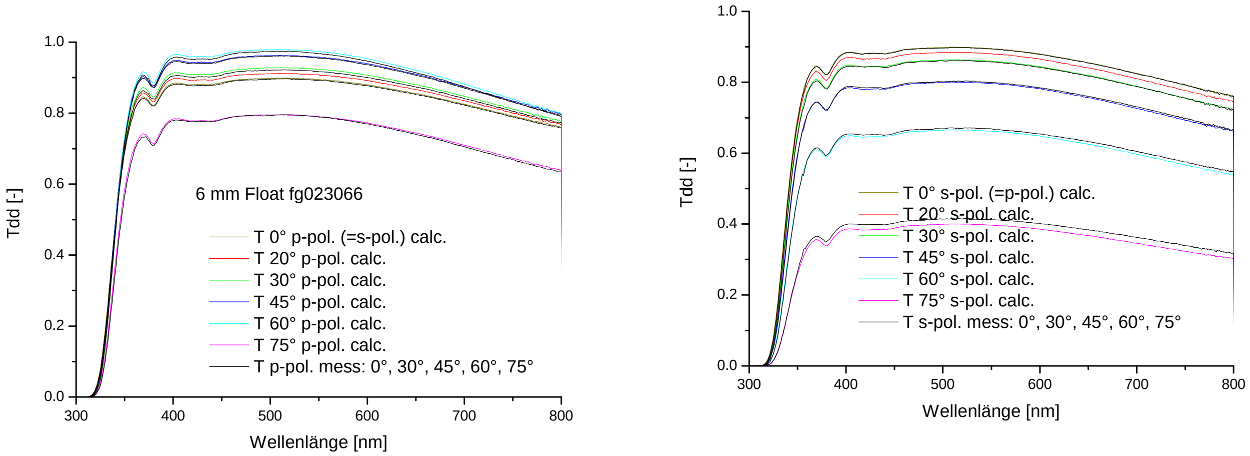


Figure 2: Transmittance spectra of 6 mm float glass for p and s-polarized light and different angles of incidence [1]

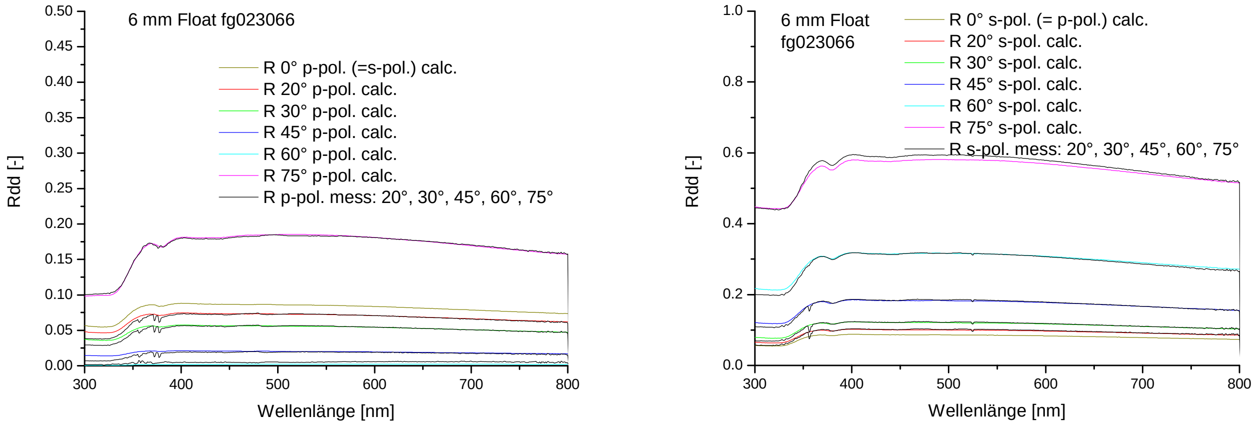


Figure 3: Reflectance spectra of 6 mm float glass for p and s-polarized light and different angle of incidence [1]

As both the reflectance and transmittance values depend significantly on the glazing configuration, including the number of panes, glass chemical composition, coatings, and surface structures, different glazing specimens not only have different U values and g values for normal incidence, but also show differently varying behavior when the incident angle is changed. Figure 4 shows that coated glass, in particular, shows large deviations from the g value determined at an incidence angle of 0°.

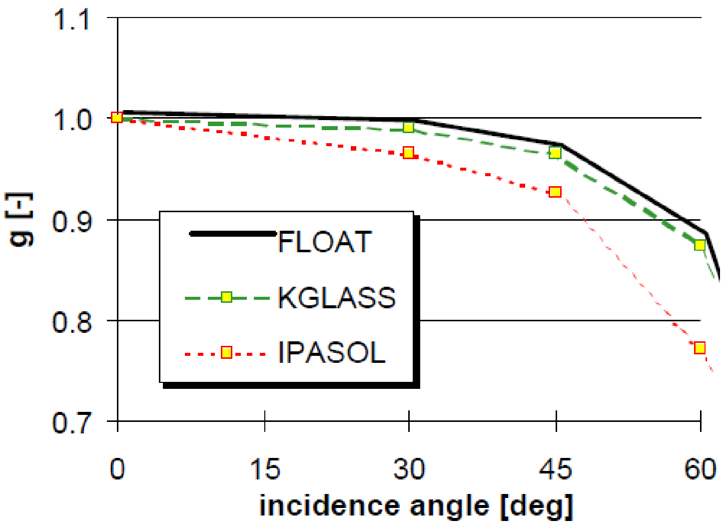
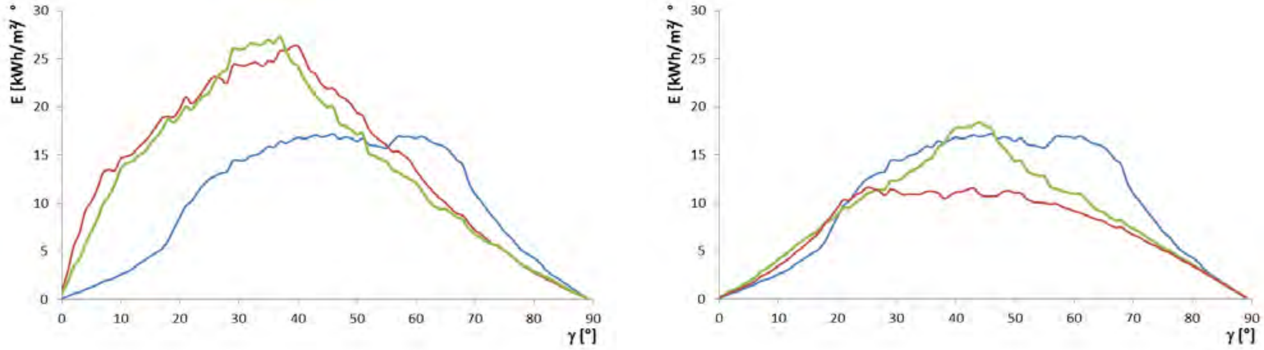


Figure 4: Calculated angular functions of total solar transmittance g for three DGU [2]

Inadequate consideration of the incident angle dependence would not be of interest for calculating the thermal impact on buildings if the total irradiation at non-zero angles did not contribute significantly, since the solar gain is the product of the g value and the incident solar energy. However, as figure 5 shows, the opposite is the case. The incidence angle of 0°, for which the solar heat gain coefficient is determined conventionally, contributes insignificantly to the annual total, whereas significant thermal impact results for solar irradiation at incidence angles deviating from 0°.

Note: Variations in orientation have a less significant effect on the angular distribution than variations of the tilt angle for constant orientation.



south, vertical (blue),
south, tilted 30 ° (red),
south, tilted 60 ° (green)

south, vertical (blue),
west, vertical (red),
west-south-west, vertical (green) [3]

Figure 5: Dependence of annual irradiation totals on angle of incidence for differently oriented and tilted surfaces in Freiburg (latitude 48 °N)

The incidence angle of solar irradiation on a glass surface depends on the position of the sun, the orientation and the tilt angle of the surface itself, and the location of the building. Consequently, surfaces that are oriented differently will have very different thermal impacts on a building. Likewise, surfaces that are oriented identically but are situated at different locations will have very different thermal impacts on a building.

**Conclusion:**

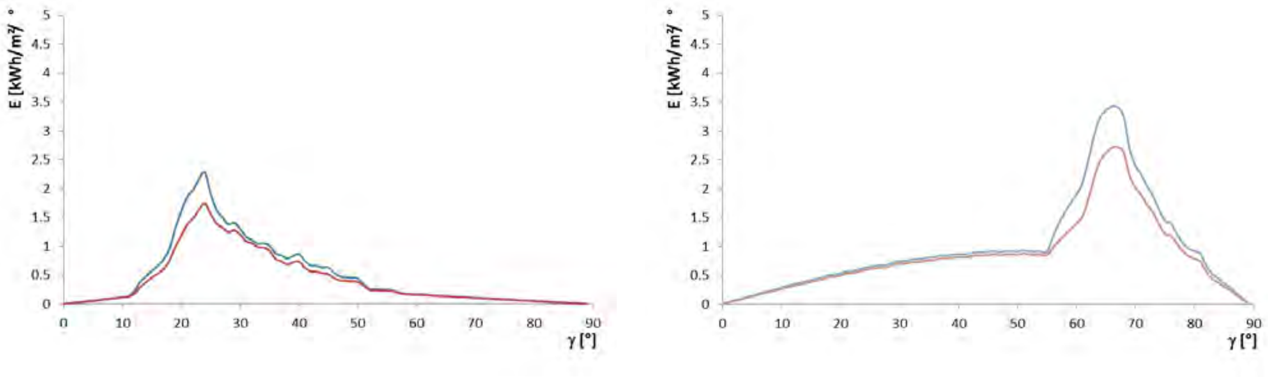
The constant solar heat gain coefficient or g value - as defined in the relevant standards - provides a simple means to compare one product with another, but it is practically useless on its own when the energy consumption of a building is to be optimized. If the dependence on incidence angle is not considered, even simulations that account for the orientation of the surface as well as the solar position, are not exact enough to really optimize the thermal behavior of a building. Simulations and calculations like this might be state of the art for commercial or public buildings. For residential buildings there seems to be a lack of an adequate consideration of the angular dependence of the total solar transmittance. The same glass type is most likely being used on all sides of these buildings.

A low value for a solar heat gain coefficient is not desirable per se. It does not necessarily lead to the optimum when the annual energy performance of buildings is investigated. In winter, a rather high but controlled solar heat coefficient is desired for passive heating whereas in summer a rather low solar heat gain coefficient is desired to reduce the risk of overheating or eliminate the need for active cooling.

Figure 6 shows the angle-dependent distribution of total monthly irradiation incident on a south-oriented, vertical surface in Freiburg for selected months. (Monthly data have been taken from 22nd of the previous month to the 21st of the current month to adjust for annual symmetry in respect to summer solstice. Data have been normalized to 30 days per month.)
Both images clearly show that:

- The maximum value for incident solar irradiation in winter occurs at much smaller incident angles than in summer.
- The weather has a significant effect on the absolute value of the irradiation total per angle, as indicated by the difference between January and December (left) or June and July (right) (Meteonorm test reference year data have been used) The angle-dependent distribution of the monthly irradiation totals is affected very little by the weather.

- The maximum value for incident solar irradiation in winter is smaller than in summer for south oriented vertical surfaces, but when taking into consideration that the total solar transmittance is much greater for incident angles of 20° than for 70° (see. Figure 4), the seasonal effect of the thermal impact on the building is only relatively weak.



January; 22nd Dec – 21st Jan (blue),

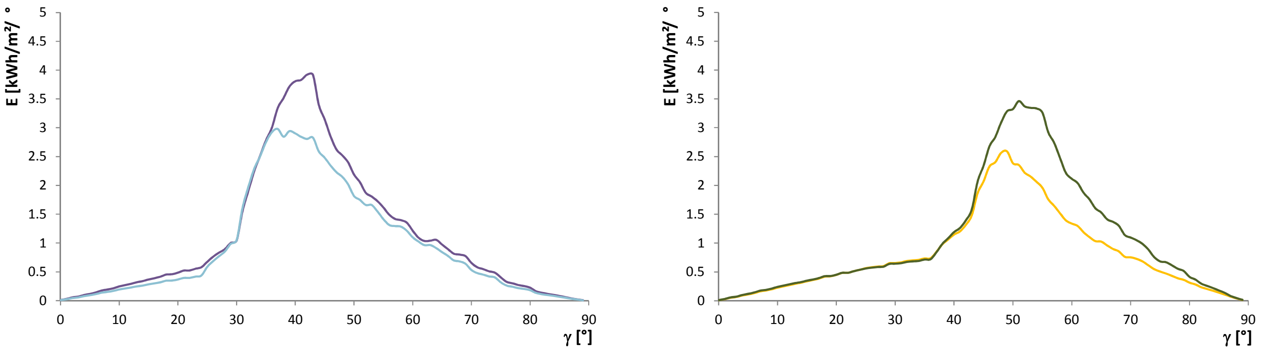
December; 22nd Nov – 21st Dec (red)

June (blue); 22nd May – 21st Jun,

July (red); 22nd Jun – 21st Jul, [3]

Figure 6: Angle-dependent distribution of total monthly irradiation incident on a south-oriented, vertical surface in Freiburg for selected months

Even in months (Figure 7) that have their maximum of incident solar irradiation at an incident angle for which the g-value is less than 5% inaccurate (see figure 4) more than 30% of the annual energy impact occurs at incident angles for which the g- value is more than 15% inaccurate.



March; 22nd Feb – 21st Mar (purple),

October; 22nd Sept. – 21st Oct (light blue)

September (green); 22nd Jul – 21st Sep,

April (yellow); 22nd Mar – 21st Apr, [3]

Figure 7: Angle-dependent distribution of total monthly irradiation incident on a south-oriented, vertical surface in Freiburg for selected months

## 2 Considerations Concerning the Compensation of Energy

The European Parliament Directive 2010/31/EU, Article 9.1 requires all new buildings to be “nearly net zero energy” by 2020. As stated above, solar energy will most likely provide the means to compensate the use of energy in order to achieve an annual net-zero energy balance.

In order to fulfill this requirement, one needs - in addition to knowledge concerning the solar irradiation incident on the building - to know :

- how much electricity a photovoltaic system is able to generate per m² of photovoltaic modules at the location the building is located
- how much electricity a photovoltaic system is able to generate per m² of ground floor area considering the orientation of the building and the tilt angle of its roof
- how much electricity a photovoltaic system is able to generate per m² of ground floor considering the topology of its roof.

Figure 8 shows the global horizontal irradiation (GHI) map as published by PV-GIS [4].
It shows that the annual irradiation total in the region covered by the scope of European Parliament Directive 2010/31/EU varies roughly by the factor of two - from approximately 800 kWh/m²/a in Northern Europe to approximately 1600 kWh/m²/a in Southern Europe.

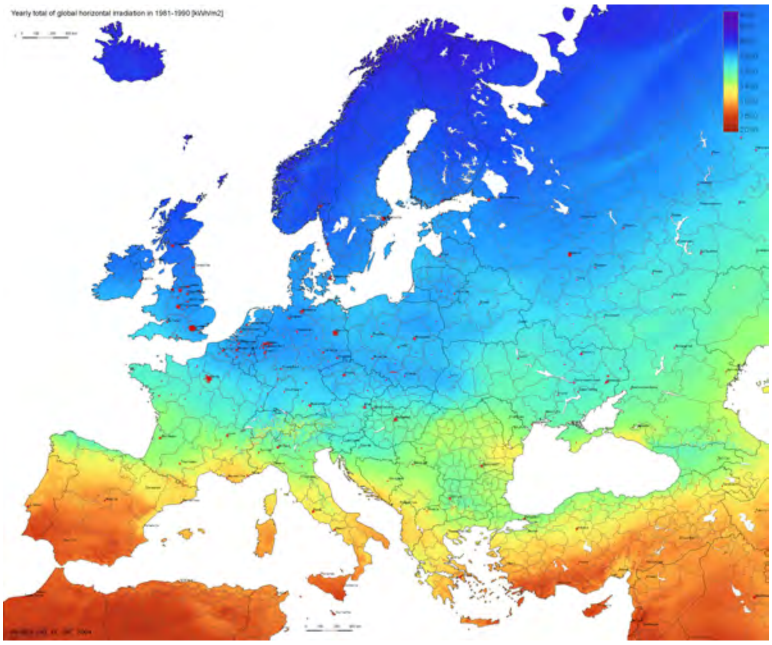


Figure 8: Annual total global horizontal irradiation [4]

Thus on a ground area of 100 m² the annual GHI total ranges from 80,000 kWh in Scandinavia to 160,000 kWh in southern Spain. Considering an average system efficiency of 13% for crystalline pv-cells (which account for 81.1% of the PV market in Europe [5]), one can estimate 10,400 kWh of electricity in Scandinavia and 20,800 kWh in southern Spain for a horizontally mounted photovoltaic system. Since most roofs are not horizontal but are tilted, one requires the dependence of irradiation with respect to tilt angle and orientation of the roof area.

Figure 9 shows the global irradiation distribution from clear skies for differently oriented and tilted surfaces relative to the maximum achievable value at this location. The figure is calculated for Germany, but shows very minor variation for all of Central Europe.
Note: Figure 9 does not take account of local weather conditions.

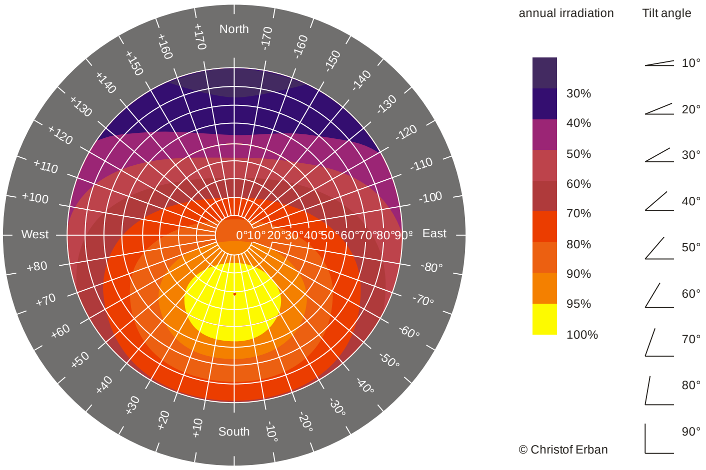


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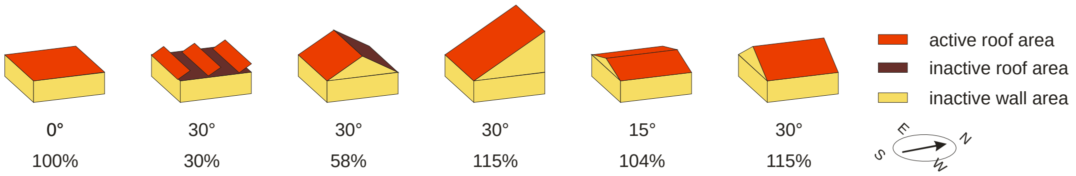
Figure 9: Annual total irradiation for different orientations and tilt angles in Central Europe relative to the maximum achievable value

Figure 10 introduces the topology and the orientation of the roof. It can be derived that the topology has a much larger influence on the energy yield per m² ground area than the orientation of the roof. When both parameters are combined, the deviation from the minimum to the maximum is 3.88.

Thus the range of electricity generation on a 100 m² building ranges from 3640 kWh (type 2 building in Scandinavia - appr. 4.3 kWp) to 28288 kWh (type 4 building in Southern Spain - appr. 15 kWp).



| | | | | | | |
|---|---|---|---|---|---|---|
| tilt angle | 0° | 30° | 30° | 30° | 15° | 30° |
| rel. area covered[1] | 100% | 30% | 58% | 115% | 104% | 115% |
| energy yield[2] | 100% | 118% | 118% | 118% | 100% | 92% |
| energy yield[3] | 100% | 35% | 68% | 136% | 104% | 106 |

Figure 10: Energy yield for different roof topology and roof orientation

[1]active roof area/ ground area, [2]in comparison to GHI as in Fig. 7, [3] eq. 1 * 2

In Europe, the installed power of photovoltaic arrays on residential roofs typically ranges from 3-5 kWp. They are oriented – more or less – due south and provide enough electricity over the whole year to compensate for all electricity demands in the building if the building is not heated or cooled by electricity. If the topology and orientation of the roof is chosen properly, this holds true even in Scandinavia. The surplus in summer is fed into the grid and sold.

On an annually averaged basis, photovoltaics in Central Europe can even contribute a significant share of electricity for heating using a heat pump. This requires building designs with a high electricity yield per m² ground ratio.

Buildings like this – incorporating photovoltaic systems as described before - thus would meet the demands of the European directive for an annual net zero energy balance, but as figure 11 shows, there is a mismatch between the time when photovoltaics supplies electricity – in summer – and the time when the electricity is required by the heat pump – in winter.

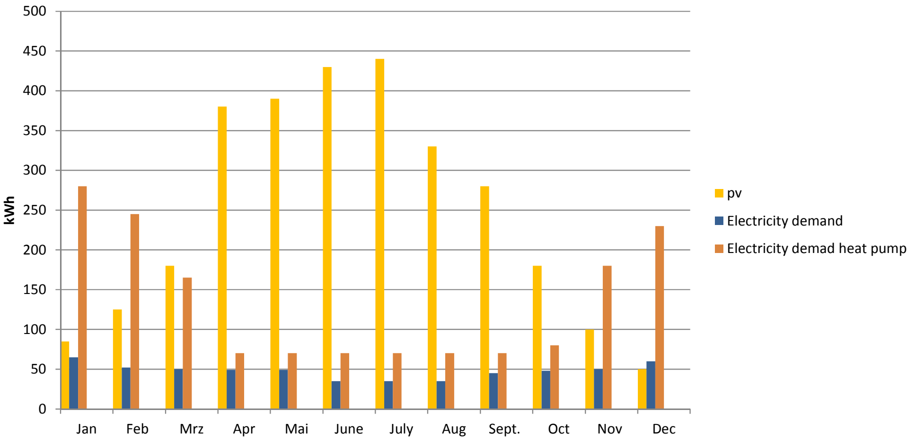


Figure 11: Monthly electricity balance for a house with a 3 kWp photovoltaic array vs. a house with a 3 kWp photovoltaic array and heat pump (passive house standard) [6]

Today there are not any financially viable means or products that could provide the required seasonal storage of electricity for single households. In addition there are limitations imposed by the capacity of the utility grid on transferring large amounts of solar electricity to e.g. centralized seasonal storage units. In countries with large numbers of installed photovoltaic systems– such as Germany – photovoltaics contributes significantly to the noon peak electricity supply (figure 12 - which shows data from June 2011 that were extrapolated by the amount of photovoltaic and wind power installed in 2011). On weekends, the public grid reaches its capacity limits and cannot accept more photovoltaically generated electricity, since the output of nuclear power plants and lignite-fuelled power plants cannot be changed within a few hours.

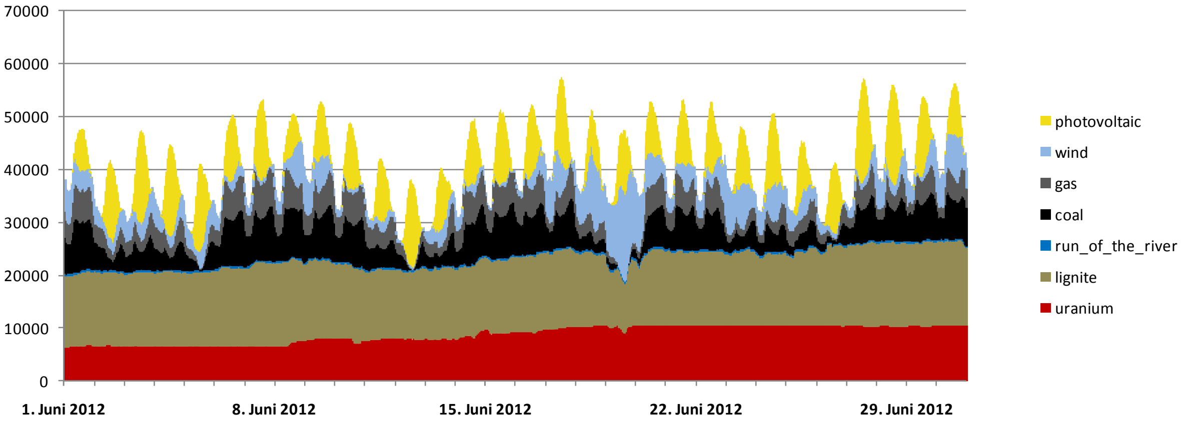


Figure 12: Simulated electricity generation for June 2012 in Germany [7]

To summarize: Depending on the location of the building and the building design, photovoltaic systems can generate enough electricity in principle to fulfill the EPD directive. However, with the rapidly increasing number of installed photovoltaic systems, critical problems concerning timing, storage and transfer will arise. The usage of photovoltaic modules that do not feature high efficiency or building designs that are not designed to optimize the generation of electricity or that are subject to excessive shading will not be able meet the EPD directive.

Just by being mounted at different orientations and tilt angles, photovoltaic systems can be used to shift both the daily generation peak away from noon and to generate electricity with a more even annual distribution than systems that are optimized solely for the highest annual total in kWh.

## 3 Summary

The European Parliament Directive 2010/31/EU, Article 9.1, requires that all new buildings will have to be “nearly net zero energy” by 2020 (2018 for public buildings). A constant solar heat gain coefficient or g value - as defined in the relevant standards - is inadequate for optimizing the energy consumption of a building. It is necessary to take the angular dependence of g values into account, if the thermal behavior of a building is to be effectively optimized as a step toward meeting the requirement of the Directive.

Photovoltaics mounted on buildings can generate enough electricity in principle on an annual basis to enable a building to compensate for energy that is consumed for its operation, but there is a large mismatch between when the electricity is demanded and when the electricity is supplied. In countries with a large number of photovoltaic systems, already the limited grid capacity today limits the amount of photovoltaically generated electricity which can be fed into the grid. A better match between photovoltaic supply and public demand can be achieved by adapting module orientation and tilt angles to shift the generated electricity peak away from noon.

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# Solar Thermally Activated Building Envelopes

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## Summary

Within the framework of a research project financed by BMU, and in collaboration with partners from industry and research, a solar collector for office building façades is being developed. This completely integrated collector not only functions as a power generator but as sun blind for the reduction of cooling loads during the simultaneous use of daylight. The energy gained with the aid of the façade collector can be used to heat drinking water and as a solar supplement to heating and cooling. The panel/collector that has been developed received the 2010 Intersolar Award.

**Keywords:** activation of the building envelopes, renewable energies, integration

# 1 Introduction

In recent years, solar thermal systems have established themselves on the market, mostly to augment domestic water heating. In 2006, about 1 million square meters of collection panels were established in the sector. On the whole, collectors are mounted on or integrated into rooftops. Given around 5 square meters of collector area, solar water heating systems cover between 5% to 12% of the total heating demand of a single family home. To increase the solar thermal percentage further, combination boilers are used. For this purpose, collection panels larger than 10 square meters are required, which, based on levels of sunshine and the required amount of heat in office buildings, are best integrated into the façade, since roof space is rarely available. The only systems on the market are façade mountable, adaptive systems.

Till now, only thermal insulation manufacturers have developed products, such as flat plate collectors, which can be integrated into their systems.

Non-residential building, particularly office and administration construction, is only now beginning to take an interest in solar thermal systems -- not least because of the associated positive image. Since in such buildings roof spaces are in short supply, solar thermal systems must be integrated into the facade. In the façade, the solar thermal system is visible from outside and in certain cases may also be visible from the inside and can be used to enhance image. The reticence of office and administration construction in using solar thermal energy for heating water, for in-house canteens or cafeteria, for solar cooling, or possibly also for heating assistance, is among other things largely due to the fact that there is no system on the market which integrates them into conventional façades. Photovoltaic systems have a similar developmental history. Originally either roof mounted or roof integrated, they have, unlike solar thermal energy, managed the leap into architectural realization. Meanwhile, there are a large number of award-winning buildings (mostly administrative buildings), where this technology is successfully used in the building envelope. Photovoltaics enjoy clearly signaled support at the political level, which encourages the active use of solar energy use in building envelopes. Thus the current draft of the EEG (Renewable Energy Sources Act) states that integrated systems will receive increased financial support and facade integrated systems, the maximum rate. The EEWG (Renewable Energies Heat Act) has already been adopted. As with the modules of a photovoltaic system, with solar thermal systems the collection panels are the eye-catching element. They occupy roughly the same areas of the building envelope, although a partial shading of the panels is less important than with photovoltaic modules. For flat panels, there are already systems that allow integration into the building envelope. Currently there is no integration of vacuum tubes. However, thanks to their aesthetic structure and geometric advantages, they offer great potential benefits for building facades.

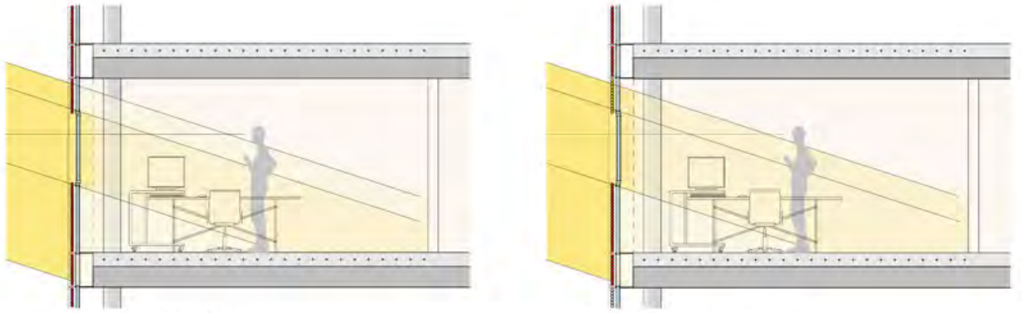
# 2 Research project

Integration of solar thermal systems in facades of office buildings. The promotion of renewable energy sources by the BMU seeks to lead long-term development towards economic alternatives to the primary energy supply in Germany. The aim of energy research programs, besides ensuring security and efficiency of supply, is environmental sustainability, which means meeting future energy demand in Germany in an environmentally friendly and cost-effective manner via exploitation of all technically and economically viable options, replacement of limited resources of coal, oil and gas and prevention of environmental and climate-related emissions, above all CO2.
The overarching goal of the project is reducing the use of finite energy sources for the supply of offices buildings with heat and hot water, thereby minimizing the emission of greenhouse gases, particularly CO2. For the development of a broadly applicable system, scientists, along with FGHK, TU Munich, IBK2 and Solites, Stuttgart, supported by the industrial firms Frener + Reifer Metalbau, Metalbau Früh and Hydro Building Systems will work on technical implementation in the facades area based on the general relevant details. Support with respect to issues concerning collectors has been taken over by Paradigma of Ritter-Solar. In the research project for the integration of vacuum tubes into facades of office buildings, two different facade panels with multiple functions, which differ in terms of their position to the thermal level, were developed. In addition to their ability for active solar

energy use, they function as transparent sun protection while also using daylight. For one thing, the mounting of vacuum tubes outside the facade (consent has already been granted by the Office of Building Technology) has had to be adopted for architectural and energy considerations, and the collector pipes installed behind protective glass panes, on the grounds of safety and cleaning issues.

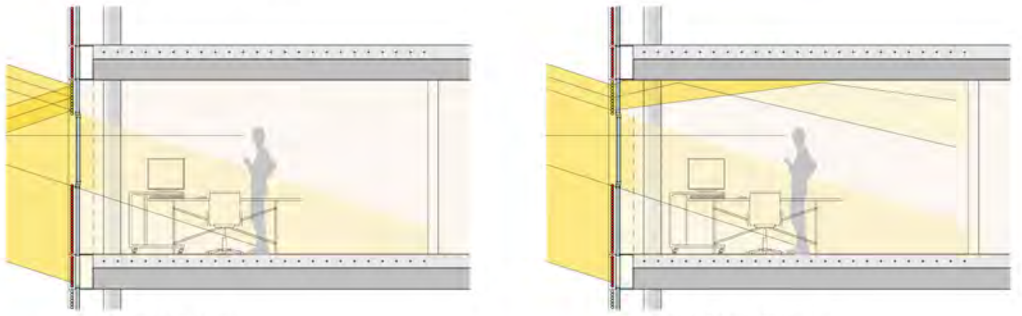
## 2.1 Multiple functions of the integrated system

- Energy
- A facade integrated solar collector provides absorbed heat and energy gain for the different uses such as domestic hot water for sinks and kitchen, solar cooling, and can be used to support space heating or the like.
- Sun protection by reflection and / or absorber plate and heat dissipation
  The trapped heat from the sun is dissipated by heat transfer. Through the vacuum insulation of the tube, the heat absorbed by the tube is not released again, since the surface of the vacuum tube is not warm.
- Daylighting
  With proper arrangement of the tubes or corresponding perforation of the absorber panel, daylight is streamed into the interior, despite the sun protection properties.
- Maintenance of transparency
  By keeping the necessary distance between the tubes, through the transparent construction and /or perforation of the absorber panel, the view out of the interior is maintained.



Energiegewinnung

Transparenz



Sonnenschutz

Tageslichtnutzung

Figure 1: multiple functions of the integrated system

## 2.2 Multiple positions of the system

In the current research projects, two of the four scenarios examined with regard to the installation position of the facade collector and thermal level have proved to be useful.
Installation position of the external facade collector before insulation glazing:
This achieves the highest energy returns, architecturally structuring the outer skin of an building. Their weak points are in the difficulty of cleaning due to the outlying tubes, and in the area of safety, where approval is still required in individual cases. For the actual installation in the planned pilot project SOLPOWER1 consent has already been granted. Installation position of the collector behind a facade glazing: This nets about 30% less energy than vacuum tubes installation position outside the front

facade. The effort required to clean the glass facade is not increased by the protective glazing does nor are there additional security requirements in case of damage. The two different installation scenarios meet different needs and requirements from the market and therefore could even work symbiotically. As part of the research project, the technical grade of the facade collector (vacuum tube outside and behind glass) was further developed and improved towards small series. Due to the departure of the Schott Glass Tube company, a new vacuum tube type, the Paradigm Sydney-tube, and the review of the program in terms of the new vacuum tube type is necessary. Important aspects in this regard were, in addition to energy, cleaning and security in the event of damage, the function of the collector as a facade for sun protection and daylighting in office buildings.

## 3 Thermal measurements and simulations

Both installation scenarios have been assessed based on functional prototypes. The baseline measurements for the thermal efficiency of the collector were carried out by the Institute for Thermodynamics and Thermal Engineering (ITW), University of Stuttgart.

Figure 2: Measures of the façade collector system at the ITW of the University of Stuttgart

The simulation calculations performed on the basis of these measurements by the Solites Research Institute for Solar and Sustainable Thermal Energy Systems at the Steinbeis Foundation produced encouraging results.

For the load case "office" at the Freiburg site, the proportion of demand met by solar energy was 40% for heating and 30% for cooling. In essence, the research project simulations showed that the support of the architectural development in particular is essential. This is due to the fact that the solar thermal yield of possible systems depends strongly on the geometrical arrangement of the vacuum tubes and the design details. Moreover, while generally speaking the yields achievable in a vertical facades through the use of vacuum tubes in comparison to flat plate collectors are high, this depends on system usage in the border area of an economically viable use of solar thermal energy.

The simulations were carried out on a solar thermal system for DHW heating, a solar thermal plant, and a combined system for solar cooling. The system size here was adapted to the planned pilot building SOLPOWER1. In addition, the solar thermal systems were simulated at three different sites in Europe. These comparisons showed that on the one hand, the use of vacuum tubes in the facade for solar thermal space heating is promising. On the other hand, the solar thermal yield from the use of vacuum tubes in the facade for solar thermal cooling is lower than expected. Which boundary conditions of solar thermal cooling with facade panels produce which economic advantages over a conventional vapor compression cooling machines driven by a photovoltaic field, need to be established.

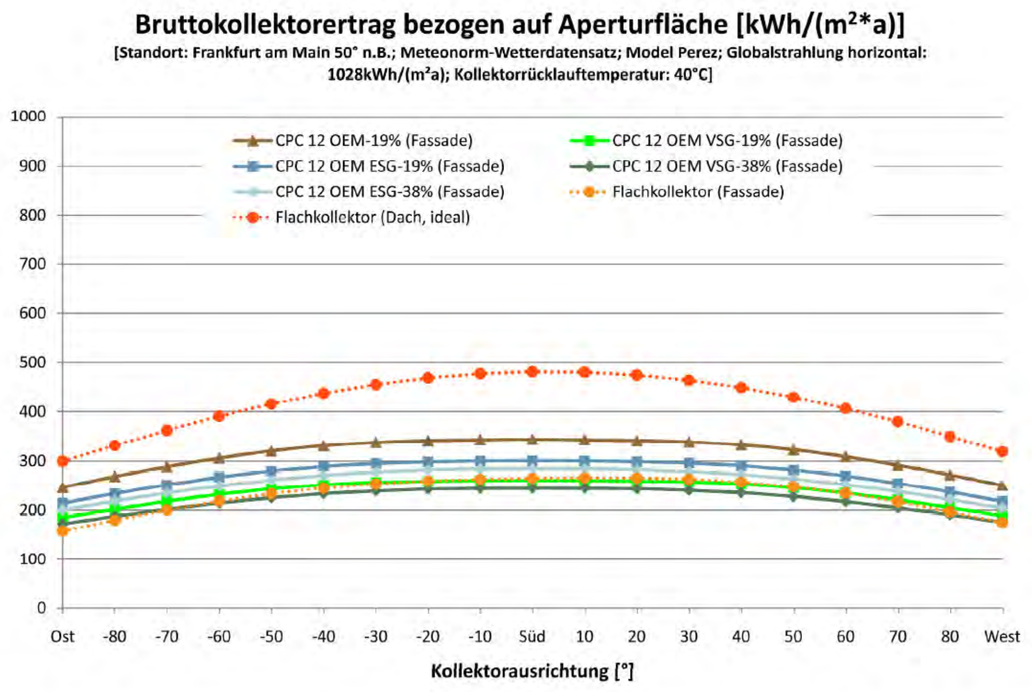


Figure 3: Façade yield in Frankfurt am Main, graphic: solites Stuttgart 2011

The installation in a flat collector box vacuum tube, which, due to the glass plate mounted in front of it, has a lower energy output, has advantages in terms of pollution and damage limitation. Technically, the most efficient and economically sensible integration of solar thermal systems were developed in the direction of small series installations.

### 3.1 Measurements under real-world conditions

Small collector area, Ritter small solar collector field, location at the premises of Ritter Solar To maximize the performance of the various aspects of energy, sun screening and daylighting, and to be able to test under real conditions, working prototypes for a pump station at the TU Munich and the another on the facade of a Ritter Solar company building have been installed. The solar collector field at Ritter Solar, with 8 façade panels connected in series, was run through into the existing building services to integrate solar support with the heating and cooling system. Using this equipment allowed small series thermal measurements to be taken. These results provide a good basis for the required connection technology, cable routing as well as integration with building services systems, with the aim of achieving an optimal cost/benefit ratio, taking into account all economic and overall energy considerations.

Figure 4: Test facade located in the area of Ritter Solar, Dettenhausen

## 4 Potential sunscreen / overhead measurements, location, solar station TU Munich

Against the background of an urgently required reduction in total energy consumption of buildings and in addition to the active use of solar energy in building envelopes, efficient sun protection to minimize the required cooling loads as well as the efficient use of daylight to reduce lighting energy demand is indispensible. To estimate the potential for sun protection and the use of daylight, the collector was installed on the facade of the solar station of the Department of Technology and Design of the TU Munich Chair of Building Envelopes and measured. The synthesis of solar energy by means of vacuum tubes and perforated mirror with simultaneous function as a sunscreen and the concomitant reduction in cooling demand is ideal. To ensure the quality and success of the facade collector, besides its functional capability, the energy-rich sunlight, along with the daylight in the interior behind it, is masked with the help of the integrated perforated reflector and integrated vacuum tubes. An adequate supply of glare-free daylight is vital to ensuring user uptake. Studies on the function of the collector facade for sun protection and use of daylight will be conducted to evaluate the integrated system but also to optimize it. Thus, for example, the perforated sections of the mirror will be altered and measured. The measurements will be carried out in a pilot series according to the issue under investigation and using different measurement technologies.

### 4.1 Sun protection potential

The measurements for sun protection potential were found in comparative measurements, ensuring the relation to conventional systems in a very direct way. For this test the container was divided into two equal-sized spaces and each was fitted with the identical transparent facade elements (h = 2550 m, b = 1600mm). In this way, a direct and tangible comparison can be made in addition to a precise measurement that allows for subjective experience along with scientific measurements and their analysis. One half of the test container, test chamber B, was fitted successively for the comparative measurements with different collector fields:

- OEM 21, Collector field with the Paradigm OEM 21vacuum tube collector. This is equipped with vacuum tubes without additional reflective mirrors.
- CPC 12 – 19%, Collector field with the Paradigm CPC 12 vacuum tube collector. This is equipped with 24 vacuum tubes and a specially curved mirror for enhanced reflection of solar radiation. To ensure visibility through the facade, the mirror is 19% perforated. The opaque portion of the tube's collector area has an effective light transmittance of 13%.
- CPC 12 – 38%, as above, for visibility's sake, the facade of the mirror is 38% perforated. With the opaque portion of the tube collector area has an effective light transmittance of 26%.

On radiation-intensive summer days, the two spaces (test chamber A without, test chamber B with facade collector) warmed differently. Test chamber A was equipped either with no shading or with conventional sun protection (aluminum blind). In this case, the blind was set so that the light transmittance of the slats, that is to say, the effective width of the openings corresponded to the respective slots in the facade collector. The test measurement protocols began with Phase 1 as a documentation of the temperature behavior of test chamber A and parallel addition of heat using a fan heater. The energy supplied was measured. Using the energy efficiency of the heater as a benchmark, it was possible to calculate the energy that can be designated as a sun protection effect. With respect to the sun protective potential average, collector type CPC12-19% came off best, in that the temperature curve remained far below that of test chamber A with the conventional blind.

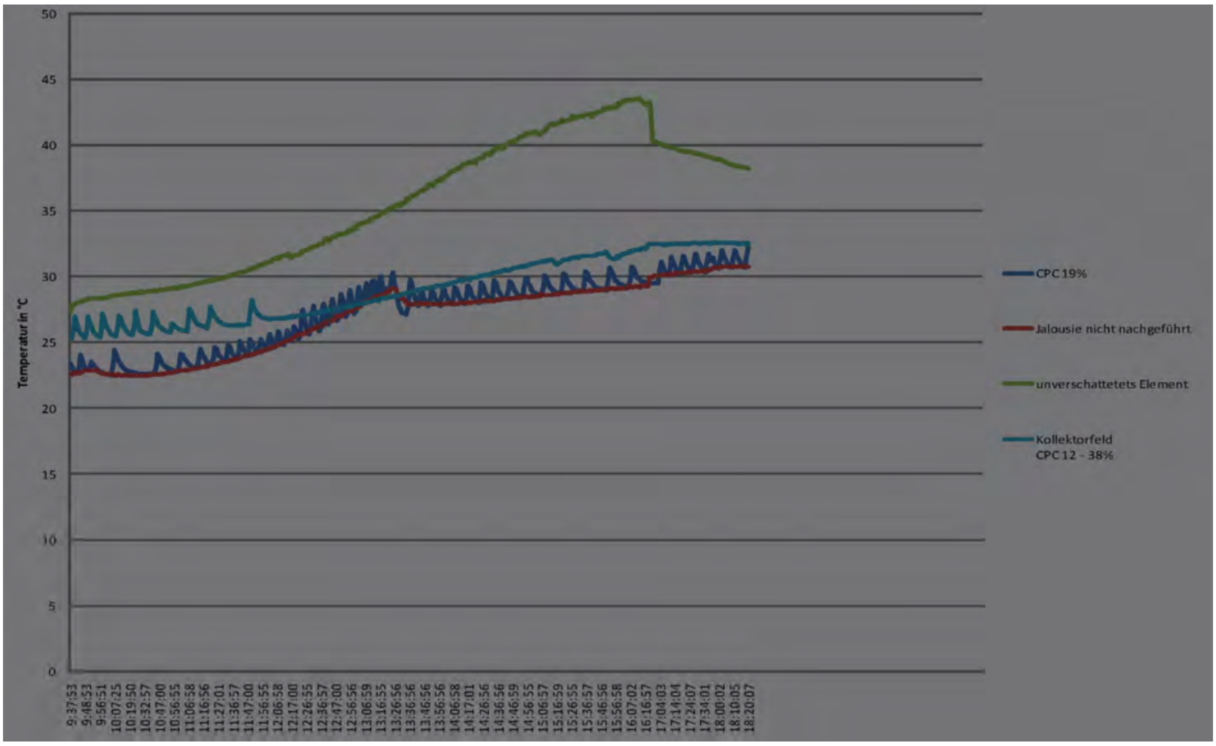


Figure 5: Comparison. Collector field CPC 12 19% - collectorfield 12 /38% - conventional blind –not shaded façade element

# 5 Photometric investigations

The photometric measurements were made up of three measurement procedures:

- Parallel photometric monitoring of the thermal measurements
- Quality of daylight in the interior
- Effects of shadows cast in drop shadows and shadow gradients

## 5.1 Parallel photometric monitoring of the thermal measurements

Alongside the measurements of the temperature behavior of the rooms, the lighting conditions of the test chambers are examined and documented. In three phases, the differences between the test chamber A and B are measured. Test chamber A is then measured successively with and without conventional sun protection. As sun protection, a venetian blind with slats of 80mm depth is used. In parallel, test chamber B is measured under identical conditions. This is then successively measured photometrically with collector panels CPC 12 - 38%, CPC 12 - 19% and OEM equipment.

## 5.2 Quality of daylight in the interior

Additional studies on the influence of the collector on the interior façade were later carried out independently of the measurements for sun protection potential. For this purpose, the dividing wall was removed in the measurement device. To determine the coefficients for daylight, sensors for illuminance and luminance distribution were placed around the chamber, and on a work table surface, the "field of view" set up. This enabled measurement of the level of internal illumination in relation to the external horizontal illuminance in unshaded position on an overcast day.

## 5.3 Effects of shadows cast in drop shadows and shadow gradients

The investigation of the facade from the interior focuses on the luminance differences in the immediate environment of a potential workplace, i.e. in the field of view and in the more distant environment, the inside of the facade and the surrounding walls.
The measurements were mainly taken on days with high global and direct radiation factors.
Of particular interest to the investigation was the luminance difference between the imaging patterns of stripes behind the facade.

Figure 6: Daylight factor CPC 19%: 1,13%

## 6 Results

In the studies on the potential for sun protection as well as the technical investigations in light, the facade collector type CPC 12-19% achieved the most favorable results. The measurements of daylight quotient were conducted using a work desk of 0.85m height at 1m distance from the facade. An exterior illuminance of 5440 lux produced an interior illuminance of 68 lux. The daylight factor was 1.25%. According to DIN5034 a TQ of between 0.75% - 1% is sufficient. In spite of the highly effective sun protection function, the measured daylight quotient in the interior exceeded the values required by workplace regulations. For the system to meet the ever-increasing demands on facade systems in administration buildings, further configuration options with regard to perforation of the mirror and additional adaptive layers for convection or glare protection will be investigated. The facade collector developed for active use of solar energy, which also takes on the sun protection function with simultaneous use of daylight, received the Intersolar Award at the Intersolar 2010 in Munich.

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# Closed-Cavity-Facade

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## Summary

Energetic sustainability, minimization of life-cycle-costs, a cost-efficient and future oriented façade type.

**Keywords:** Sustainability, Closed Cavity Façade, Building Skins

# First Part of the Lecture: A Closed-Cavity-Facade for the Tallest High-rise in Switzerland

The energetic sustainability of a building is significantly driven by the engineered interaction of façade and mechanical building services. With a completely new façade type, the Closed-Cavity-Façade, which solves all aspects of building physics, energy- and daylight aspects at a highly advanced level, one can achieve a sustainable and therefore future-oriented project goal. This new façade type does by no means make the current permanently ventilated double-skin-façades obsolete, but it enhances sustainability even further.

The building skin plays a key role, taking into account the numerous energy savings regulations in German speaking countries such as EnEV, MINERGIE, OIB-directive 6 and ÖNORM respectively, as well as the green building labels of DGNB, ÖGNI, LEED, BREEAM and so forth, which play a key role when marketing a building.

## 1 The Closed-Cavity-Facade (CCF)

The Closed-Cavity-Façade in its most original form is a completely sealed double-skin-façade construction with triple glazing internally and single glazing externally. Natural window ventilation is strictly speaking not intended anymore. This „purest“ form is in my opinion only suitable for self-occupied buildings. A project-developer, who frequently doesn’t now his future client or tenant yet during the planning phase, will not omit natural window ventilation for plain marketing reasons. A combination of CCF with operable window elements however is possible at any time. Drawings for such a layout are ready to be pulled out of the drawer.

### 1.1 Only a Sun Protection Protected from Pollution is Truly Energy Efficient

The sun protection, placed in the hermetically sealed façade cavity is therefore entirely weather proof. No contamination of any kind, which would heavily reduce the efficiency of the system, will take place at any time. The declaration of a highly efficient daylight system integrated into the sun shading is 100 % justified for the very first time. This is especially true for the daylight technical qualities of the upper 1/3 of the sun shading optimised for daylight redirection. Any external sun shading, such as often used in single layer façades, exposed to the elements and therefore prone to pollution will never allow for an efficient daylight redirection. Promising anything else would be only half of the truth. It is often ignored, that the constant pollution vastly reduced the efficiency. The regular cleaning in short intervals of small, light redirecting, usually highly reflective, multi-folded lamellae, to achieve the theoretical effectiveness achieved under laboratory conditions, is just pure, unrealistic theory, which could not be afforded anyhow with regard to life-cycle-costs.

### 1.2 Tallest High-rise in Switzerland with Closed-Cavity-Facade

The prospective tallest high-rise Switzerland 178 meters in height, in the city of Bale, has been designed by the architects Herzog & De Meuron for the pharmaceutical company F. Hoffmann-La Roche. The project is currently under construction. For the first time every energetical and building physical potential has been fully utilised in a product neutral design, in any way possible with regard to economic feasibility and justifiable financial expenditures.

The architects Herzog & de Meuron are designing jointly with Drees & Sommer as General Planer and the Roche-Project team an energetic „show piece“, which takes into account all aspects of sustainable building. According to the internal Roche User-Requirements, not to put any unnecessary Life-Cycle-costs as a burden to future generations, the building will not feature an entirely glazed façade, but one with a 32 % opaquely closed surface.

Figure 1: The prospective tallest high-rise in Switzerland with 178 meters in height, overview urban layout, High-rise F. Hoffmann-La Roche

## 1.3 A Closed Facade Area of 32 %

With regard to energetic sustainability the design does not propose a fully glazed surface, but features a closed façade area of 32 % to further enhance building physics values. Closed surface areas can be aligned either horizontally or vertically. The Architects Herzog & de Meuron chose a „horizontal layering“, to comply with the clients brief to architectonically integrate the large volume of the high-rise into the existing Roche buildings on the site. The aesthetic result is impressive, both in visualisations and even more so in the large, 1 : 1 scale visual-mock-up. The translucent glazed horizontal parapets with a white ceramic frit are designed with structural glazing details in a façade grid of 2.7 meters and feature a so called „shadow box“, a white aluminium flat panel placed in a 50 mm distance behind the glazing. This allows for impressive light reflections depending on different weather and daylight situations and creates at the same time an interesting visual depth to the panel.

## 1.4 Closed-Cavity-Facade with a $U_{cw}$-value just under 0,60 W/m²K

All in all the harvesting of all economically viable potentials in terms of insulation this façade allows by far for the best value ever reached, namely a $U_{cw}$-value of 0,59 W/m²K, which is a novelty compared to an earlier closed cavity façade, also erected in Switzerland, which featured a value of 0,84 W/m²K.

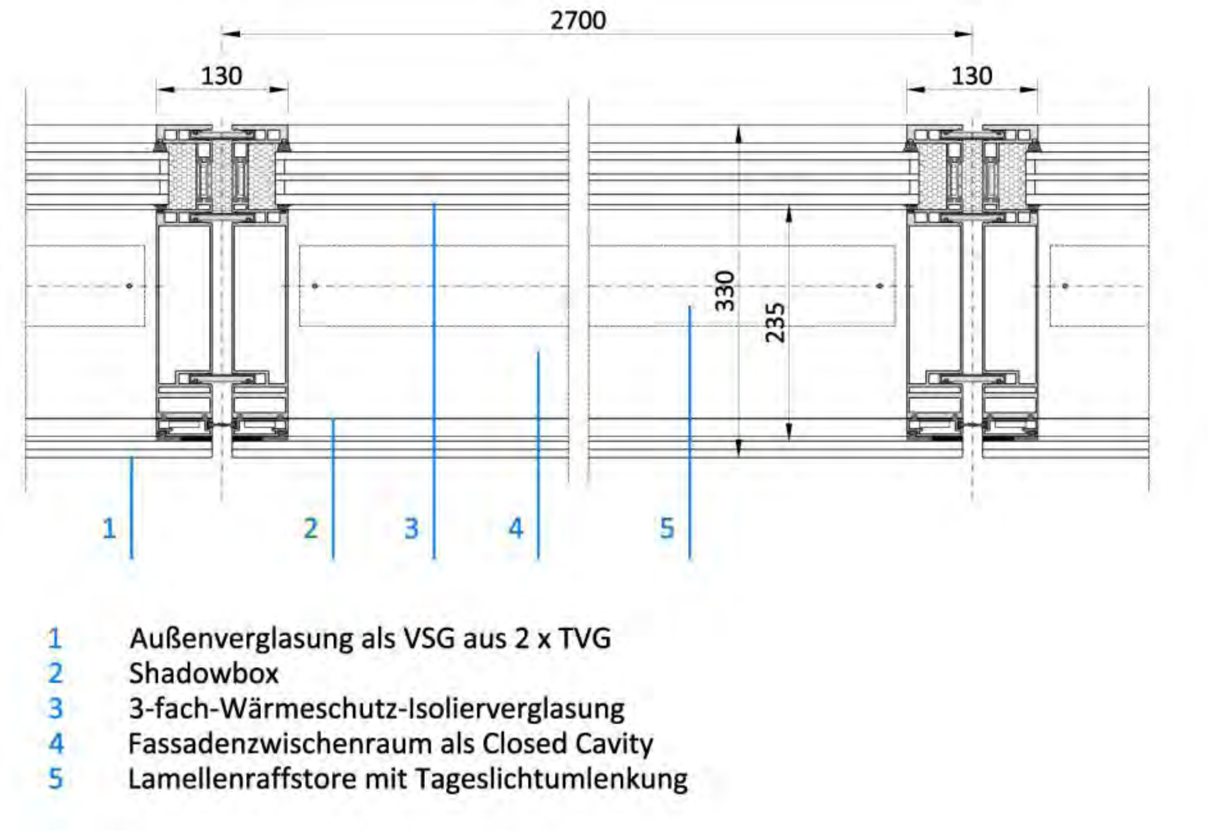
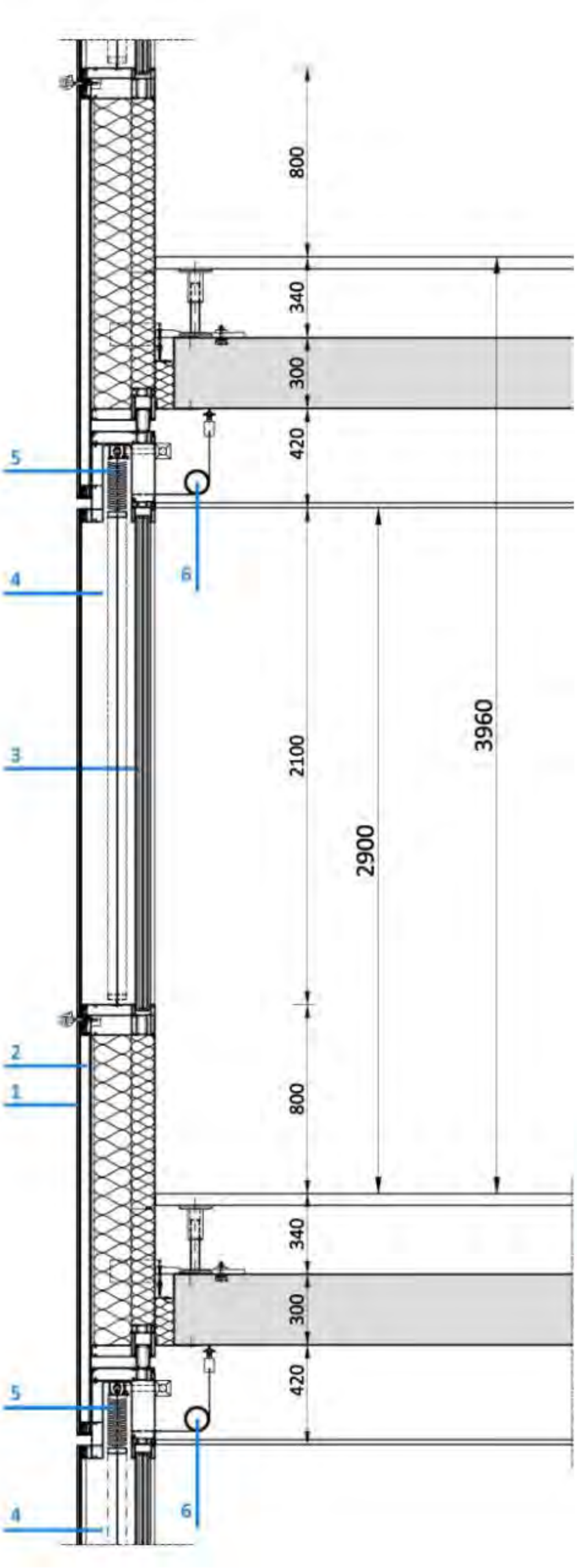


Figure 2: Horizontal section of the flush standard office façade facing north and south



1. External glazing laminated safety glass
2. Shadowbox
3. Triple glazed unit
4. Interstitial space as Closed Cavity
5. Sun protection louvers with daylight redirection
6. Dried air supply (circular duct)

Figure 3: Vertical section of the flush standard office façade facing north and south

## 1.5 Closed-Cavity-Engineering, Further Advantages

In addition to the named advantages of a Closed-Cavity-Façade there are further essential advantages compared to conventional single or double layer façades. But there are also technical challenges that need to be solved design wise jointly with the manufacturer and the façade planning team.

The second part of this lecture will deal with another project example, the Marina Tower, and will discuss how a ventilated cavity double layer façade can be optimised in terms of sustainability.

## 1.6 Delicate, Slender Facade Profiles

By omitting operable windows which require double profiles, the façade profiles themselves can be designed much more slender (by approx. 50 %!!), because they only need to hold fixed glazing elements. Visually they are connected almost flush to the glazing surface, which leads to an aesthetically much more pleasing design.

## 1.7 Facade Cleaning Costs Cut in Half

The decisive disadvantage of a regular double layer façade compared to a single layer façade is the fact, that a double layer façade also features double the surfaces of glass that need to be cleaned. Depending on the site of the building this needs to take place two or three times a year.

But not so in the case of a Closed-Cavity-Façade. Because the interstitial space of the façade cannot and doesn't need to be opened, the internal surfaces do not need cleaning … just as is the case in a regular single layer façade … but even better, the sun shading system, e.g. in the form of slender aluminium louvers in light colours, does not need any cleaning ever.
If one calculates these savings in cleaning costs over a 25-year life span of a large building, this accumulates, depending on the size of the project, to significant numbers in the area of 7 digit Euro sums.
A Closed-Cavity-Façade is of course predestined for countries or cities with strong air borne pollution, such as major cities in Asia and the booming regions of China, where façade cleaning twice or three times a year is not sufficient.

**Tasks to be solved in the Closed-Cavity-Approach**
**The lack of condensation needs to be ensured**
When designing a Closed-Cavity-Façade special care needs to be taken during the planning and production phase, to achieve a much tighter interstitial space or cavity than is usually necessary in a normal façade. Even with the utmost care this might not be possible ... a façade is not a Swiss watch.
To ensure the lack of any condensation a system of tiny stainless steel pressurized air ducts is installed, supplying the cavity by means of a capillary system with constantly cleaned and dried air at a small surplus pressure. This way a permanently conditioned cavity zone is ensured with a very low and safe dew point during all seasons. Pressurizing elements is a viable and well proven approach, which ideally supplies the pressurized air from a central plant. Weather data and necessary dried air supply is controlled electronically, ensuring a low energy input. Vertical air distribution in shafts and horizontal supply routes in stainless steel are maintenance free.
Each façade element can be adjusted individually in its air supply, even retrospectively, by means of its corresponding capillary system.

## 1.8 Technical Mock-up's and Long Term Trials

To double check all technical solutions of the façade element in a scientific way and to eliminate any risks, the client of the F. Hoffmann-La Roche project commissioned two separate 1 to 1 scale mock-up's to two different façade contractors prior to awarding the contract, and the elements have been tested thoroughly. These tests have been carried out by the most renowned independent German testing centres. Amongst others, the lack of condensation in the façade has been tested in correlation with the supplied air volumes and in correlation with the air tightness of the façade
In addition long-term tests have been carried out successfully, e.g. a 20.000 fold lowering and raising of the sun shading system under cavity conditions. The optimised louver system is stable despite of

peak temperatures of 85 °C. Unacceptable abrasions can be controlled as well as all other sun shading components prone to deterioration.

## 1.9 Competition in the Facade Market

Any client or investor of a future oriented façade with such supreme building physical and technical selling propositions will ultimately pose the question … is there a true competition in the market? Or is the knowhow regarding the Closed-Cavity-Façade closely linked to one manufacturer?
This question can clearly be answered, especially after awarding the contract for the
F. Hoffmann-La Roche in Bale in December of 2011. There is already true competition in the market, vital to any investor or end-user. Times when this knowhow rested with one company are clearly gone. The Closed Cavity Façade is by no means a high-tech or even high-end product utilising unknown products or materials, therefore within a short to medium-term time-span well established medium sized façade manufacturers will be able to build this façade type in the necessary quality and with a system guarantee of 10 years.

## Final conclusion about the Closed-Cavity-Façade

By its state of the art design the energetic sustainability of the Closed-Cavity-Façade is successfully linked to an essential minimisation of life-cycle-costs … all this at investment costs which make this new façade type predestined for future oriented investor projects.
Furthermore in the near future the Closed-Cavity-Façade will be predestined for the Chinese façade market as well, with the prevailing strong drive towards sustainability.

Figure 4: Design Herzog and de Meuron Architects, Basel

# Second Part of the Lecture: The Integration of Timber in the Facade of the First Eco-friendly High-rise in Vienna, Called the Marina Tower

The winners of the competition, Architects Hoffmann-Janz ZT, GmbH designed a 130 m high Tower as the main volume, beautifully located directly next to the Danube.
The Marina Tower is the very centre and at the same time the starting point of the Marian City, Vienna's answer to the Docklands of London or the Hafencity of Hamburg.

In between the Marina Tower high-rise and a low-rise complex spans a covered atrium, consequently incorporating the main entrance. As a defining unique architectural feature the office floors at the very top of the tower are cantilevering by 13.50 meters. Furthermore the Marina Park, a covered and planted busy street, is integrated sensitively, but expressively into the overall project

The office buildings feature a double skin façade, optimised in every respect, with integrated operable windows made out of local timber. The building skin therefore mirrors the clients project goal oft he utmost sustainability in every way. With the integration of timber as a renewable resource in the façade a threefold certification was achieved: DGNB/ÖGNI–Gold, LEED-Gold and BREEAM–Excellent.

Highly insulated aluminium profiles with a $U_f$-value of 1,6 W/m²K and tripple glazed units of 1,0 W/m²K allow for a supreme energetical overall value of $U_{cw}$ = 0,6 W/m²K.

A supreme value for the overall façade is highly transparent and with exception of a small 320 mm parapet fully glazed. This proves that high or even maximum transparency does not necessarily conflict with sustainability goals. Neither is transparency a contradiction even to the highest certification demands of any label.

An energetically highly efficient lamellae sun shading system, which is superordinated, but can be manipulated individually, reduces in a sound way the external heat loads to a minimum and the need for cooling and the cooling bill respectively. The double skin façade is fully unitised. 100 % prefabrication in the façade manufacturer's workshop ensures a top-quality in the building envelope.

All parties involved can be proud of the excellent result for the city of Vienna, achieved through outstanding team work in between investor, architect and technical planners.

Very important for any courageous, future oriented investor, fully committed to sustainability, is a compliance with the budget goal. The award of contract negotiations currently under way clearly show that all stringent budget goals, contractually dictated to DS-Plan, are not only kept but even undercut.

Figure 5: Marina Tower Vienna

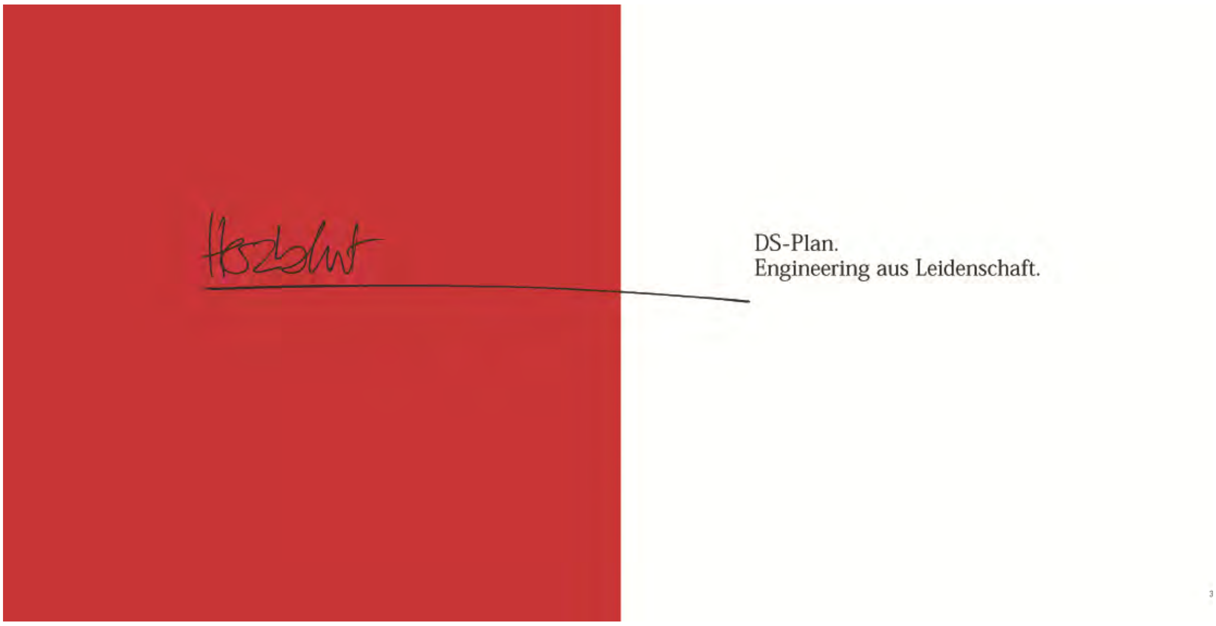


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*Figure 2, 3, 6 ©DS-Plan GmbH Stuttgart*
*Figure 5 Marina Tower Vienna, ©MARINA TOWER Entwicklungs GMBH Vienna*

# A New Concept for Energy-Plus-Houses and their Facades

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## Summary

Energy-Plus-houses generate more energy than their residents need from external sources. But the building should not be understood as a simple technical power station or an aggregation of adaptive energy technologies, but its integral design should also focus on living space quality and on resource efficiency.

Our concept divides the building into two zones interacting with each other both functionally and energetically. Next to a classical living space, the “energy garden” is an active and multifunctional space. Beyond the classical weather protection, it includes other functions like collecting, storing and distributing of energy, plants like in a garden and it can be used to park and re-charge a “clean” and small electrical car.

Classical overhead and vertical semi-transparent solar panels integrated in a glass façade are used to ensure a new high-quality living space between the classical “inside” and “outside”. Solar radiation also heats the air in the energy garden which is absorbed by a heat absorber and distributed through a ventilation system by using natural convection. The passive part of the building, the classical living space, is protected by a highly-insulating, opaque façade structure, which is a purely inorganic sandwich construction and combines an Ultra-High-Performance-Concrete-shell with an insulating cement based mineralized foam.

This article shall give a detailed insight into the architectural and energetical concept of the house and its façades.

**Keywords:** façade, Energy, energy garden, Ultra-High-Performance-Concrete, mineralized foam

# 1 Introduction

The energy transformation through the building envelope is a key topic in the planning of Energy-Plus-houses. Therefore the façade can be understood both as an energy barrier as well as an energy collector and converter. Besides the classic functions of the building skin, such as the protection against weather conditions a major challenge lies in the energy management. In addition to the energy efficiency, the essential function of the building as a living space has to be treated on an equal footing in the design concept.

To meet these very ambitious and fascinating challenges an intensive interdisciplinary dialogue is essential among all participants in the planning process. Architects and specialist planners for structural design, building physics, building service technology and energy supply work together on a coherent overall concept, which fulfills the basic idea of the positive-energy building with regard to room conditioning, hot water supply, lighting and operation of electrical appliances as well as the requirements of the comfort of the living space.

Due to the recent development of electric mobility the synergistic interface between mobility and property is a challenge in the future. Thus there is a need to coordinate the field of construction and automotive sector to generate a holistic energy concept. In the following proposed draft, which is the result of an interdisciplinary team project at the Technische Universität Darmstadt, this interaction between different disciplines and the resulting interfaces is shown by the example of the building skin. The team developed a concept for the building envelope, that represents an equal consideration of the competing goals of energy, resource efficiency and living space. For the integration of electric mobility a possible interface to the building service is shown. Finally, general approaches are discussed, how to consider multifunctional facade systems in an economic evaluation.

# 2 Architectural Concept - the Introduction of an In-between Space

Could it be that the widespread use of electricity driven cars will change our attitudes towards automobiles? Will it bring about a change in the status we attribute to cars and what consequences will result for their positioning and functioning inside buildings?
Maybe the car of our future will be one among many other means of transportation such as scooters, electric bikes and bobby cars. Quite contrary to conventional automobiles electric cars are relatively clean vehicles that are more comparable to a trolley or a bike. So we were questioning ourselves if it still aquires a space monopolized by it.

Figure 1: Visualization of the architectural concept

This assumption formed the basis for our design of a single family house with integrated electricity-driven mobility and our search for new efficient spacial solutions. Our suggestion proposes to transform the monofunctional areas which surround conventional family dwellings into a multifunctional space that serves multiple technical purposes and supplements the actual living rooms. A simple climatic protective skin guarantees usability also during the seasons between summer and winter. Electric cars may be stationed here among bikes and other mobility devices – but it is also a space where family gatherings and birthday parties can take place without any traces of those vehicles left.

Half of the building is completely built from elements of concrete which are fully recyclable and it is complemented by a volume which is defined by a transparent skin covered by solar panelling. We thus get a well isolated passive house supplemented by its climatically active counterpart.

The In-between space which connects inside and outside can be understood as integral part of the building skin as it actively regulates its climatic balance. It represents more or less an extension of the interface we have in windows with double glass plates into a more spacious and functionally well-equipped interval between the core of the house and its skin.

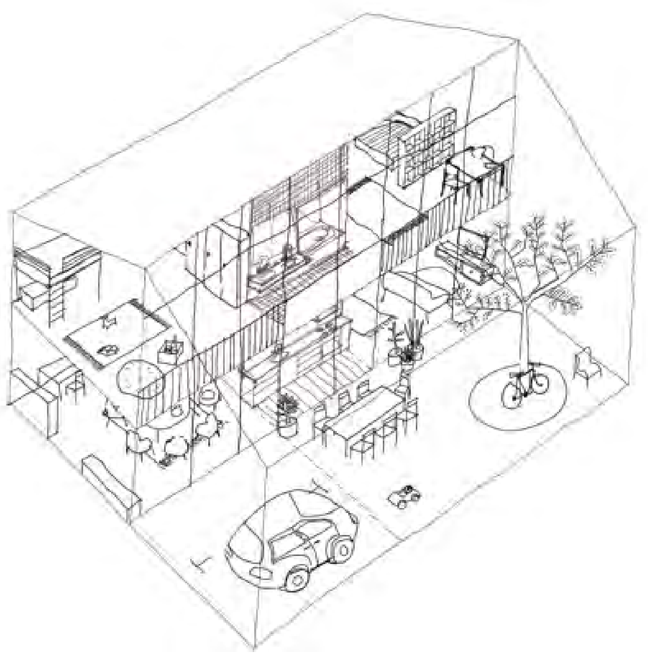

Figure 2: The energy garden as an extended living space

Such an In-between space is not a new invention. The flower-windows popular of the 20ties up to the 50ties, orangeries and the classical winter garden are the forerunners of this type of space incorporated into buildings. However in our judgement the integration of such intelligently used systems of space into a holistic view of residential buildings forms an essential part in developing long term sustainable concepts for buildings.

For those inhabiting the house this climatic interspace offers by the very fact that it has no predefined purpose free space for a variety of activities. Life inside the house can be extended into this space and withdrawn again if weather conditions change. Weather conditions thus have a direct say in the configuration of life inside. It makes the inhabitants perceptible to the linkage of inside and outside.

## 3 Energy Concept

In the basic considerations a building concept was sought, which creates an attractive living environment that integrates the systems of energy supply without compromising comfort and aesthetics. Only solar radiation should be used to provide the required amounts of electricity and thermal energy. Three architectural designs were compared with each other. Selected was the presented design concept, which is characterized in its outer contour of a familiar building geometry. But on closer examination there are two completely different halves of the building, both in terms of its function and structure. The northern half of the building consists of the living area, while on the south side of the building a so called solar garden is located. Thus, the proposed building is divided clearly into a passive and an active part.

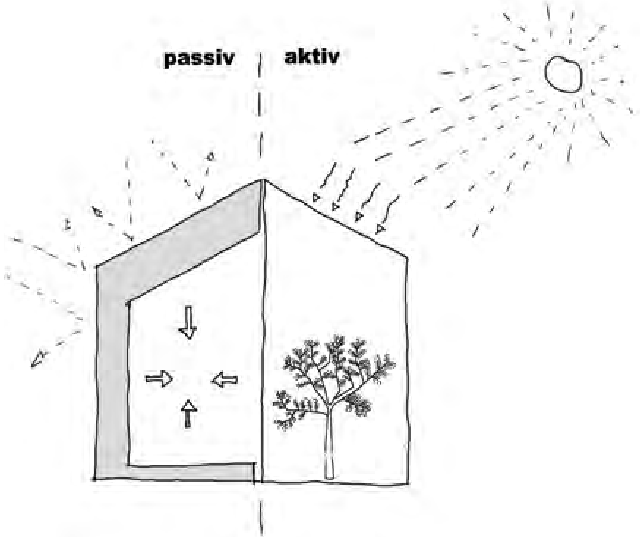

Figure 3: Idea of collecting and storing solar energy

The passive northern residential area is designed to minimize energy losses of the building. This is achieved by a highly insulating, airtight building envelope with a high effective thermal storage capacity of the components. To ensure a sufficient supply of daylight it is provided with daylight-optimized windows with triple glazing.

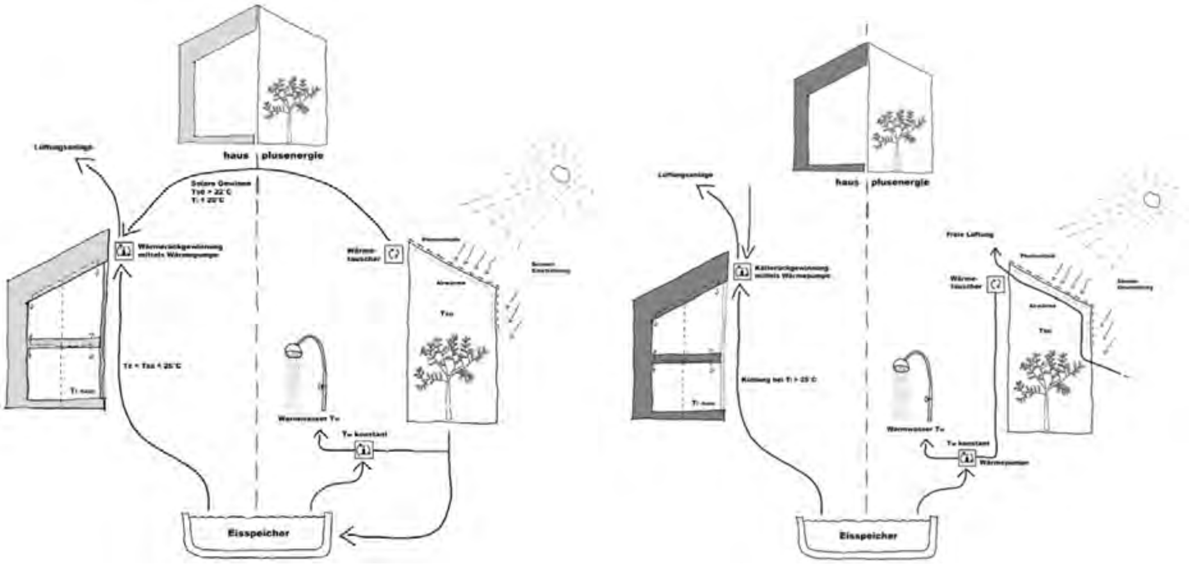

Figure 4: Energy concept under winter (left) and summer (right) conditions

The required air exchange rate of the building is ensured by a ventilation system with heat recovery. On the other hand receives the energy garden an active role in gaining energy to supply the building with thermal energy and electric power for the electrical consumers. For this purpose sections of the roof and the sides of the energy garden are covered with semi-transparent monocrystalline photovoltaic cells. The benefit of the glass-integrated photovoltaic cells is that the “waste” heat can be used in the solar garden as thermal energy and thus is not lost. On the other hand, the energy input into the fully glazed winter garden is reduced by the shading effect of the solar cells, what counteracts an overheating. By the photovoltaic generated electrical energy will be preferably used to ensure the electro mobility. The overhang can be used in the building or fed into the grid. Therefore will be used a flywheel energy storage as storage device. The thermal effect of the energy garden is that the losses of the south wall of the residential area are significantly reduced. In this connection at a suitable temperature level the generated heat can directly be used over the hypocaust floor slabs of the building.

Depending on the temperature level, the thermal energy can directly be fed into the bivalent hot water tank or the seasonal designed ice-storage. From here the required heat can be supplied by means of heat pump. The main advantages of brine-ice storage as latent heat storage, especially compared with the near-surface geothermal energy, for example, is the high heat storage capacity in the phase change of the storage medium. This amount of heat equivalent to that, which is required for heating of water by 80 K. Due to the low temperature level just below 0°C the storage works without losses even in wintry outside conditions. It is also possible to dimension it so, that the heat supply of the building considering seasonal requirements is also ensured in the long term. Furthermore the use of geothermal energy may provide additional environmental loads which are a risk for the safety of soil and groundwater. A disadvantage of the ice-storage is that the power supply only works with the help of a heat pump. But this can also be supplied with the generated solar power.

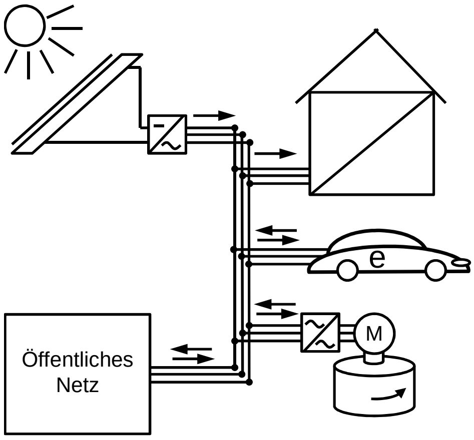

Figure 5: Interfaces to energy generators and consumers

Figure 5 shows the energy generators and consumers in the building. The photovoltaic system generates electrical energy, the building and the residents consume electrical energy. As a primary electrical energy storage is used a flywheel energy storage system. This system has the function to save energy in case of an energy surplus and to release energy in the case of an energy need. The electric vehicle consumes in the charging process energy, but also supports the flywheel energy storage system and release electrical energy at certain times of the day.

The overall goal of the electrical energy concept is to achieve the largest possible consumption of self-generated electricity and not to burden the public grid. Of particular interest is the interaction of individual components in the overall system. The components have to be sized and matched in a way that on the one hand, the energy losses are minimized and on the other hand a commercial use is possible.

## 4 Facade Construction for the Solar Energy Converter

The envelope construction of the energy garden is formed by single glazing system with integrated photovoltaic cells. Transparent all-glass folding walls offer generous opening opportunities into the garden and allow the access of cars. A specially modified interlayer in the glass that does not block solar radiation in the photosynthetic active range allows plant growth in the solar garden (Kleuderlein, Schneider, [1]). The glazing is supported by a slim post and beam construction. Motor-driven opening elements allow the controlled ventilation of the energy garden in combination with the large folding walls. The semi-transparent glass-glass photovoltaic modules have different degrees of transparency and combine electric power generation with a balanced degree of shading and a warming of the air layer next to the façade. The inner wall between the living area and the solar garden is built by a highly insulating triple glazing façade to experience the solar garden even in the opaque part of the building. Several opening elements on the ground floor and first floor allow an air change with the energy garden.

Figure 6: East and south view on the Plus-Energy-House

To use the described self-sufficient energy supply of the building by the energy garden, different simulations were done. On the one hand an adequate energy supply has to be ensured, on the other hand, the basic function of the solar garden had to be proven as a qualitative extension of living space, even in extreme winter and summer outdoor climates. For this purpose the behavior of the building was analyzed under the prevailing climatic conditions in Berlin. Interesting hereby were the daily and yearly temperature curves in the In-between space as well as the heat fluxes of the building envelope to determine the required heating and cooling loads. By thermal-dynamic building simulation with the software IDA Indoor Climate and Energy (IDA [2], CD adapco [3]) could be detected, that the temperature of the air even on very cold winter days is always 5 to 10 K above the ambient air temperature. In addition it arises a significant air warming, depending on the radiation supply in the course of the day, especially on sunny days (for comparable studies see Klein, Garrecht, [4]). The temperature conditions in winter also shows that a constant heat extraction by the heat exchanger is possible even on the cold and sunless winter days.

To analyze the temperature and air flow conditions in the energy garden for the cases of warm, sunny summer day and cold, sunless winter day, computational fluid dynamic simulations were done . Figure 7 shows the temperature and airflow distribution in the winter garden for the winter load case. Here can be seen that with the heat exchanger in the roof area, even at worst weather conditions, a constant heat extraction of more than 500 watts is possible, without compromising the use of the solar garden as a buffer space. For the summer case, it is shown by the CFD-simulation that by opening the longitudinally arranged doors, the garage entrance and the over windows in the roof area, there is no excessive thermal overload in the energy garden during very warm and sunny days, even without heat extraction.

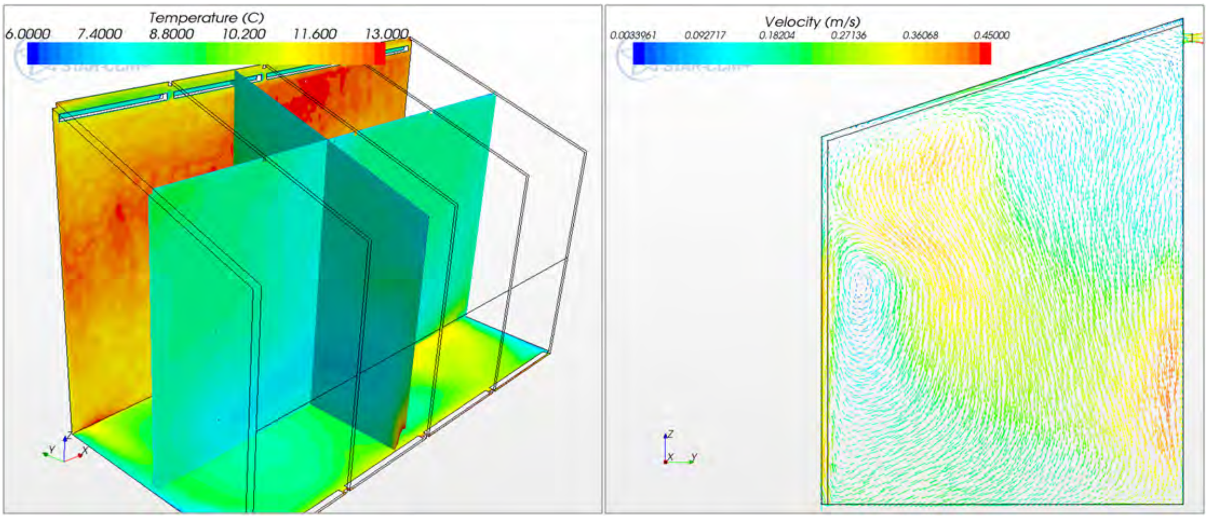

Figure 7: Temperature and airflow distribution in the energy garden (winter)

## 5 Highly-insulating Inorganic Sandwich Construction

The monolithic design is increasingly being replaced by composite structures in which various materials are used in different functional layers. Many clients, however, often wish to have an external wall of purely mineral construction. Also advantages of monolithic systems such as material compliance, ecologic compatibility of deconstruction, uniform hygric behavior and good bond of congeneric materials often are not considered anymore.

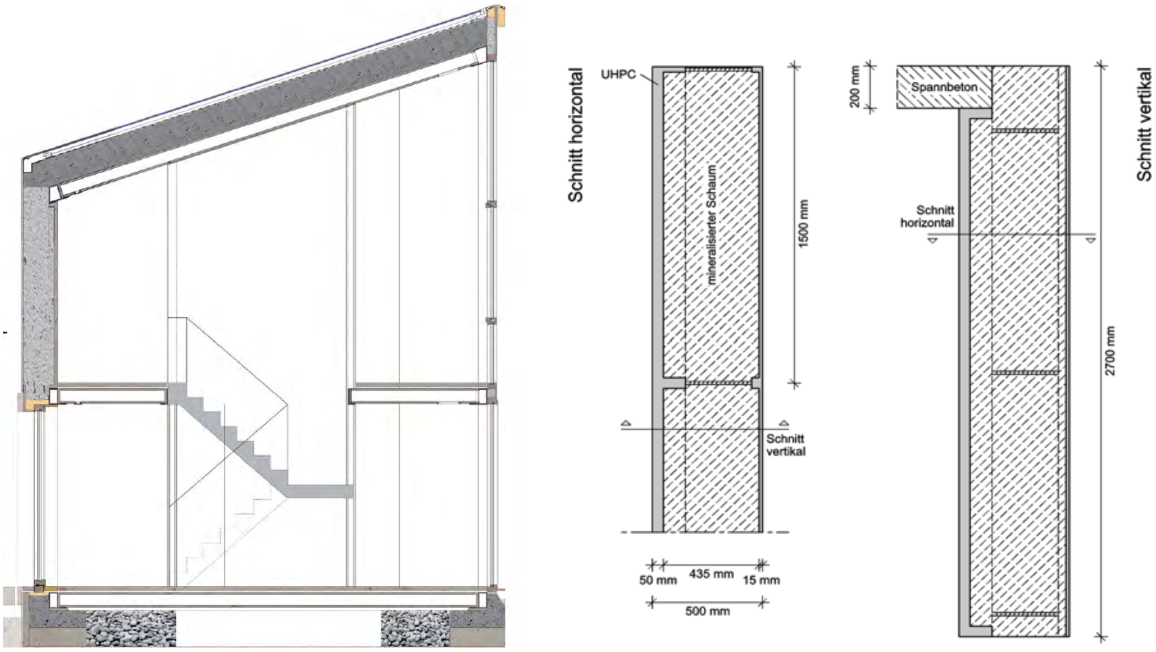

Figure 8: Vertical building section and vertical and horizontal section of the proposed wall system

The outer massive wall construction for the Energy-Plus-Houses is supposed to be a triple layer wall fabricated but using only concrete building materials. The inner U-shaped base course of the design consists of 4 cm thick ultra high performance concrete, which is also the support of the ceiling. The compressive strength of this UHPC is about 100 N/mm² (see Kuntsche [5]). The outer skin is ought to be 2 cm thick and made of UHPC too (Figure 8). In a horizontal production mineralized protein foam is to be inserted between the shells. With finely tuned mix between binder, protein foam and additive could realize heat transfer values under 0.06 W / (m · K) (Gilka-Bötzow, [6]). The foam mortar has a minimum compressive strength of 0.4 N/mm² and a density about 200 kg / m³. The proposed elements are characterized by a purely mineral structure and are capable modular precast concrete elements, which also ensure material compliance in terms of sustainability. The purely mineral composition furthermore ensures non-combustibility (Garrecht, Gilka-Bötzow [7]).

## 6 Cost-Oriented and Multidimensional Evaluation of Energy-Plus-Houses and Their Façades

The conceptual Design of an Energy-Plus-House and its façades on the one hand is a fascinating technological challenge. On the other hand, it requires a comprehensive cost-benefit-analysis which includes next to the (financial) costs also the ecological and social impacts of the project.

Concerning the financial costs, very often architects as well as building owners mainly regard the investment costs. These costs can partly be retrieved from construction cost databases. Those data bases consider material, labor and indirect costs for constructing customary buildings. However, concerning the more innovative parts of an Energy-Plus-House, like the sandwich construction of the opaque façade structure, the costs are much more difficult to calculate. As far as possible, they will be estimated relying on similar projects.

However, the investment costs build only a part of the whole life cycle costs. Additionally, the sum of present values of all future costs has to be identified. This includes on the one hand costs emerging during the utilization phase, for example energy and maintenance costs. On the other hand, costs emerging in the End-of-Life-Stage, such as disposal costs, have to be considered.

In order to evaluate the whole Energy-Plus-House, the main building elements are in a first step analyzed separately. Some first results concerning the life cycle costs of the kinetic energy store can be found in Ahsen et al. [8]. In a next step similar analyses on the life cycle costs of the different façades are needed. Finally, an overall picture of the project can be drawn. Thereby, also the impact of the expected lifetime of the building as well as the different components has to be considered. Most economic values are uncertain, some examples being the yearly real growth rate for constructing costs and for energy costs. Furthermore, the costs of the innovative elements can only be estimated. Thus, a sensitivity analysis is essential.

So far, only financial (internal) costs have been regarded. However, the design of Energy-Plus-Houses and their façades should consider multiple, and very often conflicting, objectives such as energy consumption optimization, financial costs reduction and decrease of environmental impacts. Concerning the environmental impacts, a major advantage of the opaque façade compared to conventional façades is the considerably improved possibility of deconstruction. Additionally, the transparent solar panels that are integrated in the glass façades are supposed to offer a very high quality of the living space, as described above. Thus, also social aspects should be regarded.

As a consequence, multi-objective optimization techniques can be applied (Diakaki et al. [9], Fesanghary et al. [10]). However, ideally, the environmental and social consequences of the Energy-Plus-House should be expressed in monetary values, referred to as externalities (Pearce et al. [11]). Externalities are generated when activities of one group of persons affect another group and the impact is not fully compensated for by the first group (European Commission [12]). Certainly, the estimation of external costs proves to be extremely difficult. One option here is to evaluate the preferences of individuals. The preferences can be measured by a willingness to pay (WTP) for a benefit and a willingness to accept compensation (WTA compensation) for a cost (Pearce et al. [11]). The usefulness of this approach has been shown for example in a project striving for an environmental and economic optimization of the floor on grade in residential buildings (Allacker [13]).

Based on this approach as well as multi-criteria-decision-tools we plan an in-depth evaluation of the façades of the Energy-Plus-House.

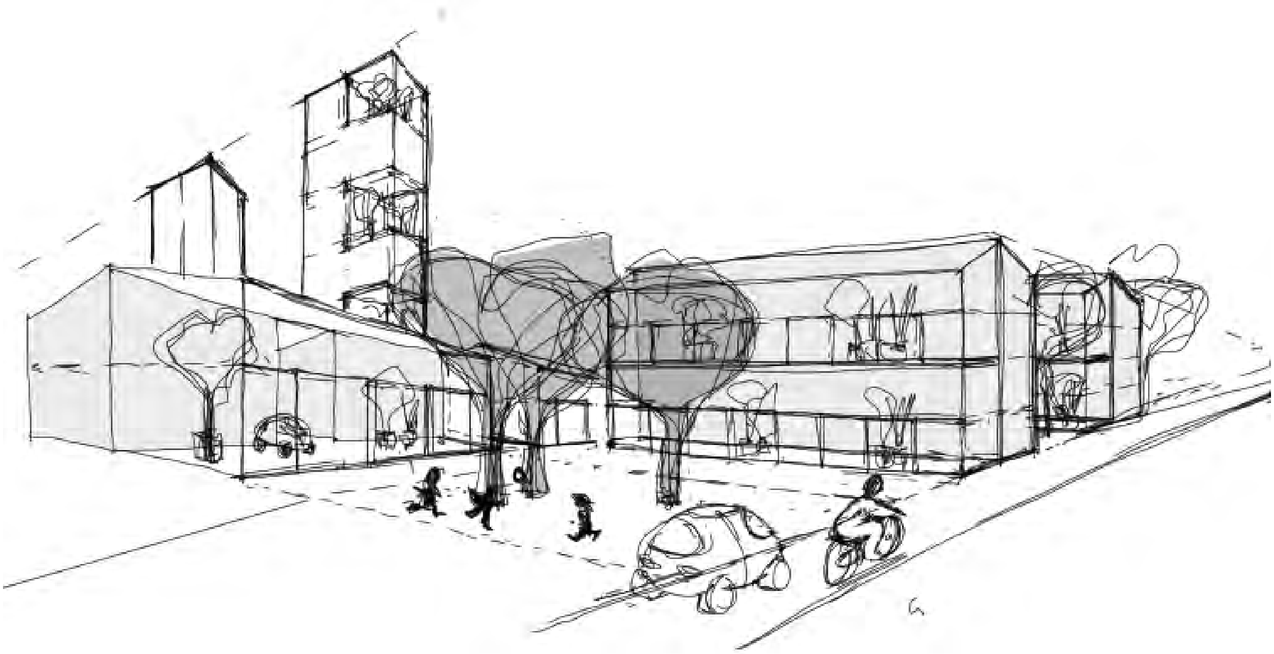

Figure 9: Integration of the Energy-Plus-House in an urban settlement by horizontal or vertical stacking

## 7 Summary and Outlook

Energy-Plus-houses generate more energy than their residents need from external sources. But the building should not be understood as a simple technical power station, but its integral design should also focus on living space quality and on resource efficiency.

Thus, the proposed building concept is divided clearly into an energetically passive and an active part. Half of the building, the passive part, is built from elements of concrete which are fully recyclable. The monolithic design consists of a triple layer wall fabricated which combines ultra high performance concrete with mineralized protein foam.

It is complemented by a volume which is defined by a transparent skin covered by solar panelling. All-glass folding walls offer generous opening opportunities and allow controlled ventilation. The concept assumes that solar radiation can be used to provide the required amounts of electricity and thermal energy. The so called solar garden transforms the monofunctional areas which surround conventional family dwellings into a multifunctional space that serves energy collecting purposes and supplements the actual living rooms.

In the evaluation of Energy-Plus-Houses and innovative constructions investment costs only consist of a part of the whole life cycle costs. Additionally, the sum of present values of all future costs has to be identified. This includes costs of the utilization phase, as well as costs emerging in the End-of-Life-Stage. Finally, the environmental and social consequences of the Energy-Plus-House should be expressed by monetary values in the holistic evaluation of Energy-Plus-Houses.

Especially when dealing with complex constructions like the introduced energy-positive facades, practical experience is essential. The interdisciplinary planning team of the Technische Universität Darmstadt is in the process of realizing the concept on a typical dwelling house. Only the use of the building will turn out whether innovative concepts that influence the usage habits of the residents are successful in practice.

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# Dynamic Facades

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## Summary

Kiefer Technic needed a showroom which clearly represented their innovative and high-quality product range. Alongside the aim to communicate the capability and spirit of the company, the flagship building would also have to be both energy efficient and flexible, in order to reduce costs and provide comfort for its employees.

Therefore, it was predestined that the Kiefer Technic showroom would have to be somewhat pioneering - and the solution is displayed in its dynamic façade.

**Keywords:** Technology, Energy Efficiency, Building Skins, Dynamic Façades, Kiefer Technic

## 1 Introduction

The façades of our structures have always been a vastly discussed part of architecture in general.
While in the past it were the subtle forms of expression through plaster and stone which communicated the esteem or position of the owner, recent times have shown a change in façades. Grid-like perforated façade systems showed industrial fabrication and were replaced by mesh, net or perforated constructions, which function as cladding while still negating the life behind the façade.

Figure 1: Kiefer Technic façade, completely opened. Photo *Paul Ott*

## 2 Every day is a new adventure
## Every day displays a new façade

In fairly recent times there were defined specifications for the number of axes that should be provided for a director or a simple employee, but through the introduction of ribbon glazing, these hierarchies were abandoned. Today it is possible to realise a completely transparent façade. This particular transparency expresses modernity and openness - attributes which are often desired in business philosophy, and thus also frequently expressed in office architecture. Simultaneously, the individual requirements for employees are met and should be brought to desired comfort in consistency.

The façade obtains a new impact; it becomes the interface between the public and the private realm, with the possibility to communicate. This is the reason why we engage in dynamic façades, which not only respond to physical restraints such as temperature and sun, but also can be regulated individually and thereby communicate an ever-changing façade image.

This new dynamic façade developed from the desire to reduce energy consumption and express sustainability, but is also an architectural response to the strong position of the individual in today's society, something that is expressed in almost every aspect of this building.

Figure 2: Kiefer Technic Dynamic panels. Photo *Paul Ott*

This new façade was first realised for the project “Kiefer technic showroom”. The Kiefer technic company is known for its premium high-tech products, predominantly in the hospital domain. For this reason it was predestined that their showroom should display this façade and thereby effectively express the competence of the company.
We can assume that the buildings in the near future will communicate among themselves, akin to the programmes that were developed by the vehicle industry to improve road safety.
Thereby, our urban room will receive a new dynamic component which not only demonstrates the 4th dimension, but also fills it with excitement and constitutes it permanently.

For the opening we created a choreography for this façade, which can be viewed on YOUTUBE (http://de.youtube.com/watch?v=rAn4ldWjw2w).

Figure 3: Kiefer Technic façade at night. Photo *Paul Ott*

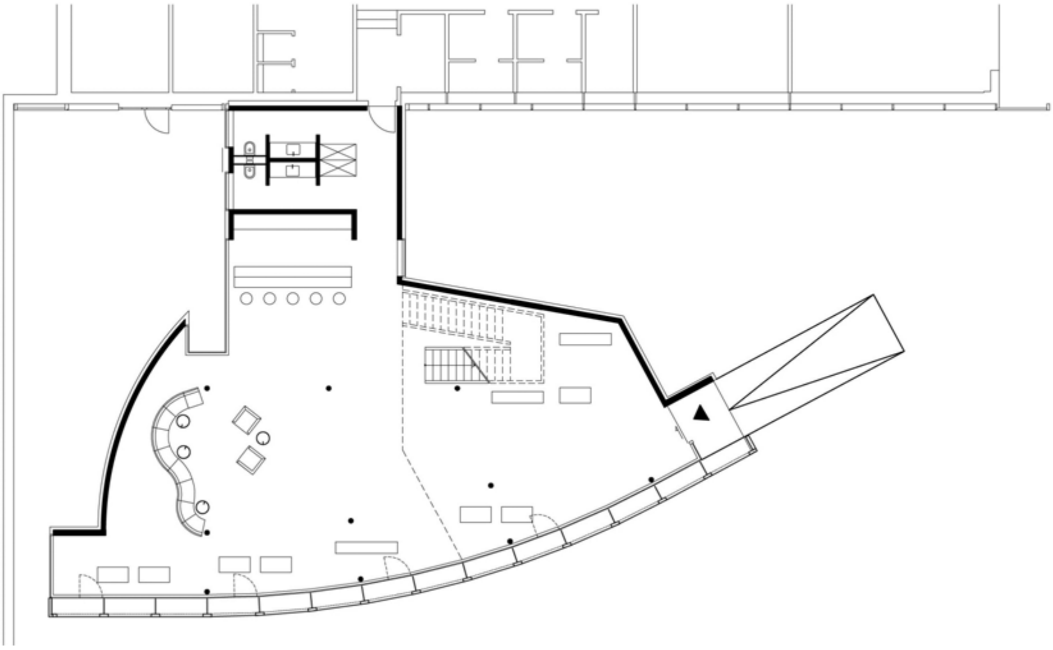

Figure 4: Kiefer Technic, Ground floor plan

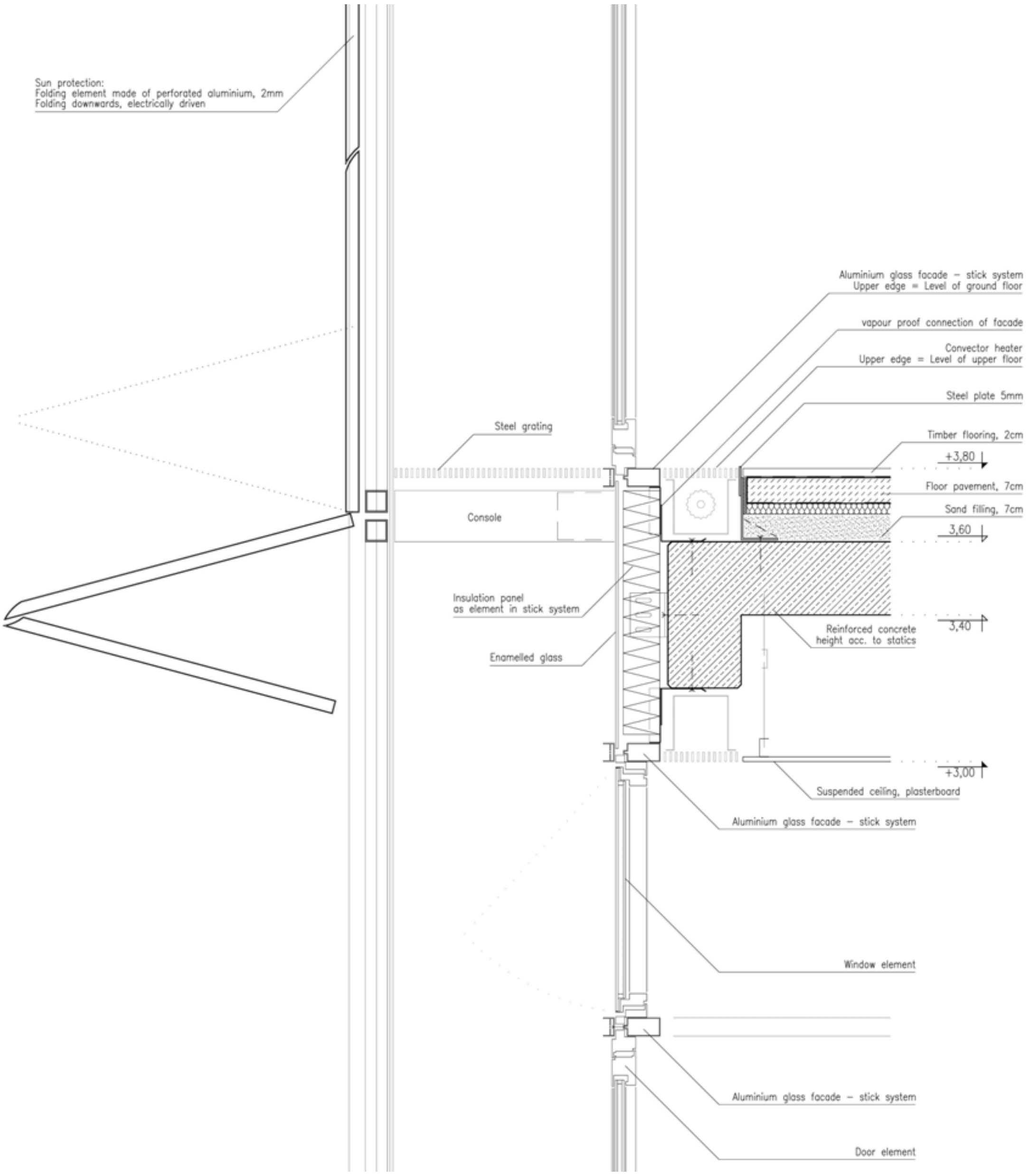

Figure 5: Kiefer Technic, Detailed section

## 3 Further Dynamic Facades

The office building at Hartenaugasse in Graz is a new building in an environment of classical architecture, manor houses and villas, embedded in a rich garden area.
This new building demonstrates the landscape reflected in the curtain wall facade and the reflection becomes a design feature in itself, ever changing due to the openable panels and constantly displaying new images of nature.
This also serves to demonstrate the new significance of nature in urban space.

This building also represents dynamics. While the core of the building may appear rigorous and solid, this is efficiently contrasted by the curtain wall and the effect is enhanced. The transparent, openable panels cover the office building in a distinctive slight curve along the main façade, leaving a relatively generous space in between the two. The façade is through its flexible panels dynamic in itself but transcend this state through the absorption of nature, the light, the movement and the ever-changing appearance of the landscape which is reflected in its surface. Through that; the façade of the

Hartenaugasse office building states an example of profound dynamics in building skins with a strong effect on both appearance and use.

Figure 6: Hartenaugasse office building, façade. Photo *Gerald Liebminger*

For the headquarters of Energie Steiermark the main objective was to increase energy efficiency and this was most effectively done through sensitive design of the façade.

A zoning of the surface was created: glazed areas with folding shutters for shade, that work with specially shaped elements in the skylight area for adjusted daylight use. Through this, a light deflection occurs due to reflection, which allows the daylight deep into the rooms and thereby minimises the need for artificial lighting. Windows can be opened for natural ventilation and this automatically causes the heating/cooling system to shut down.

Figure 7: Energie Steiermark Headquarters, façade. Photo *Paul Ott*

Figure 8: Energie Steiermark Headquarters, façade at night. Photo *Paul Ott*

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# Design Methods and Structural Components of Blast Enhanced Facades

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## Summary

A “blast resistant” façade requires different numerical design methods and different structural components than a “normal” façade. The impulsive load requires a dynamic analysis with consideration of mass and inertia. To withstand an extreme blast load a façade should be flexible and able to absorb energy in properly designed and analyzed crash zones. These zones are the laminated glass and additional elasto-plastic connections along the load path to the sub structure.

**Keywords:** Blast, load, façade, design, element, connection, cable, curtain wall

## 1 Introduction

In the last decade the topic “civil safety” was becoming a key objective in our multicultural world. All efforts to decrease the risks of assassinations by higher control of passengers in the public transportation are limited to a certain extent and are counteracting our request for fast und unrestricted mobility. The protection of buildings and especially facades against bomb blast attacks became therefore a more relevant topic in all design stages of potential targets itself and the surrounding buildings.

The dynamic behavior of facades under shock waves with short time durations but high impulse loads requires different design strategies, specialized analysis tools, and specialized connections between the façade elements itself as well as the connections to the primary building structure. The design philosophy is primarily to save lives and prevent injuries, and secondarily to protect buildings, functions, and assets. The design criteria take a balanced approach to safety, considering cost effectiveness and acknowledging acceptance to some risks.

For cable net facades as lightweight and transparent structures particularly at the podium or entry levels of buildings the connections from the glass panels to their fittings, from the fittings to the cables, and the cable end connections must be well designed and in most cases, in order to minimize their size, are designed to the limits. For curtain walls facades the load path from the glazing to the mullions and transoms into the brackets has to be blast enhanced designed and calculated. For both façade types – cable facades and curtain walls – new energy dissipative connectors with residual strength capacity were recently developed as well as design rules and new appropriated software packages. The intensive research was initiated, financed, and operated by Gartner Steel and Glass and the Permasteelisa R&D Group.

# 2 Explosion Loads

## 2.1 Analytical Determination of Explosion Loads

As a result of the detonation of an explosive charge a pressure wave spreads initially spherical in all directions, until it is reflected by surfaces (building, floor). In the explosion, a very large amount of energy is released within a few nano seconds. The pressure increase is in a time range of nanoseconds and the length of the overpressure phase in the rage of mille seconds. The short period of overpressure is characterized by the peak overpressure $\hat{p}_{10}$ and by the time $t_d$. The integration of pressure over time results in the specific impulse I. The negative pressure phase is longer than the overpressure phase, and the magnitude of the negative pressure is usually much lower than the magnitude of the overpressure. The barometric pressure is under normal conditions 101,3 kPa (1,013 bar) at sea level.

The peak reflected overpressure $\hat{p}_{r0}$ is formed by the reflection of the incident plane shock wave which encounters a structural system in a certain angle. The ratio of the peak reflected overpressure and incident peak overpressure is called the reflection factor. The reflection factor depends on the incident peak overpressure, of the angle between the shock front and the surface and the density and the rigidity of the material of the reflection surface. In detail, the main effects and influencing factors for the determination of reflection coefficients are shown in [1]. With known reflection factor, the reflected pressure time history can be derived, which has a similar time history as the incoming pressure if interaction effects are neglected. Figure 1 shows a typical reflected pressure-time history of an explosion in air.

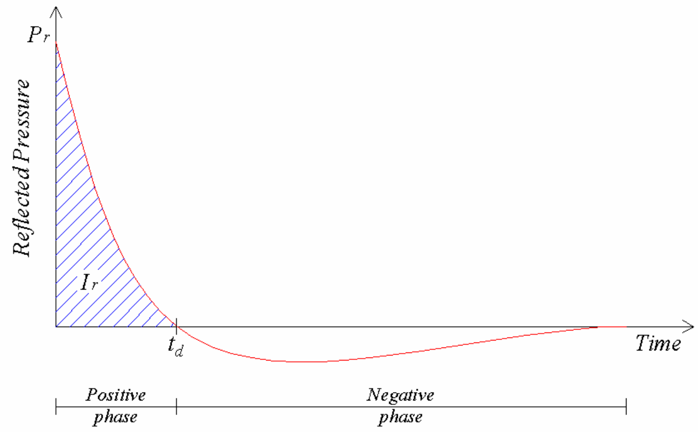


Figure 1: Schematic diagram of pressure time history of an explosion in air

The determination of the complete reflected pressure time history is essential for the structural analysis, because this affects the structure and its components. Using only the reflected peak pressure is insufficient. The specification of quasi static loads is not possible without the consideration of the system-dependent reaction. For explosion loads, a (usually nonlinear) dynamic calculation is thus necessary in any case. Above all the effective mass of explosive material, its height above the ground and the distance to the building affects the reflected pressure time history of an explosion. The mass of the explosive material is usually defined as the TNT equivalent mass (TNT= trinitrotoluene, commonly used military explosive). Other parameters are possible obstacles, such as protective walls or upstream buildings, as well as the type and geometry of the building itself. For light and flexible membrane structures and large-area cable net facades, the reflected pressure time history is affected additionally by the fluid-structure interaction and the aerodynamic damping [2].

### 2.2 Determination of Explosion Loads with Hydro Codes

The analytical approaches discussed in chapter 2.1 are applicable only for simple cases. Loads that differ significantly from the analytically determined pressure time curves can result through reflections on neighboring buildings. This is the case, for example, if explosions in adjacent streets or the influence of upstream buildings or walls are taken into account. In these cases, the pressure time history can be derived from either with the help of (possibly scaled) experiments or financially cheaper by numerical studies with so-called hydro codes. Hydro codes such as Ansys Autodyn or LS-Dyna, are based on the physical principles of mass, momentum, and energy conservation, and calculate the explosion and the subsequent propagation and reflection of the shock wave.

### 2.3 Normalized explosion Load Assumptions

Because it is very complex to determine the complete pressure time history due to a detonation and all reflection effects, standardized explosion load assumptions were set out first in the United States and then internationally (ISO) [3, 4, 5]. These explosion load assumptions provide a linear sloping triangular history for the reflected pressure. The reflected pressure is characterized by the reflected peak overpressure $\hat{p}_{r0}$ and by the positive pulse $i_r$. The duration of the overpressure phase in this linear approach is defined by:

$$t_{d,lin} = \frac{2i_r}{\hat{p}_{r0}}$$

The influence of the negative phase is neglected in these standardized approaches. This is justified in the dynamic calculation of rigid or heavy structures (e.g. reinforced concrete structures), because the negative phase hardly affects the structural response in these cases. On the other hand the negative phase can affect significantly the structural response of lighter and more flexible systems with lower natural frequencies [2, 6]. Despite this influence, which is present in cable net facades, only standardized explosion load scenarios in accordance with US or ISO standard are specified in most cases. It is assumed that the failure of the façade to the internal side is the critical design intent. Therefore the impact on people in the Interior of the building should be minimized. A failure of the system to the outside due to the negative phase is accepted.

In table 1 and 2 the essential design loads are grouped according to the US GSA/ISC standard and according to the international ISO standard. The specified quantities of explosives (TNT equivalent mass) and stand-off specify which explosives would create these loads in a ground detonation in front of a large façade. In an experimental attempt to detect the façade performance not the whole facade, but a mockup facade of 3.05 m x 3.05 m (GSA/ISC) and 3.15 m x 3.15 m (ISO) is usually tested. Due to clearing effects at relatively small mockups the mass of the explosive material and the stand-off must be adapted to create the same pressure and impulse values as for a large façade. The denotations of the ISO scenarios (e.g. EXV 45) consider this phenomenon. EXV xx means that the specified peak overpressure and impulse values are achieved with a typical test mockup of 3.15 m x 3.15 m with an explosion of 100 kg TNT at a distance of xx m (see table 2). This corresponds to an equivalent explosion scenario in front of a large facade (see table 2 and Annex C. 1 ISO 16933) [4]).

Table 1: Explosion scenarios of the US *General Services Administration* (GSA/ISC) [3]

| scenario | $\hat{p}_{r0}$ [kPa] | $i_r$ [kPa ms] | $t_{d,lin}$ [ms] | mass TNT [kg] | stand-off [m] |
|---|---|---|---|---|---|
| GSA C | 27,58 | 193,06 | 14,0 | 47,5 | 30 |
| GSA D | 68,95 | 675,71 | 19,6 | 340 | 34 |

Table 2: Explosion scenarios (vehicles bombs) of the ISO 16933, Annex C1 [4]

| Class | Peak reflected overpressure | Reflected Impulse | Length of overpressure phase (linear) | Stand-off 100 kg TNT in front of small mockup (3,15m x 3,15m) | Equivalent explosion scenario in front of large facade |
|---|---|---|---|---|---|
| | $\hat{p}_{r0}$ [kPa] | $i_r$ [Pa s] | $t_{d,lin}$ [ms] | Stand-off [m] | TNT [kg] |
| EXV 45 | 30 | 180 | 12 | 45 | 30 |
| EXV 33 | 50 | 250 | 10 | 33 | 30 |
| EXV 25 | 80 | 380 | 9,5 | 25 | 40 |
| EXV 19 | 140 | 600 | 8,6 | 19 | 64 |
| EXV 15 | 250 | 850 | 6,8 | 15 | 80 |
| EXV 12 | 450 | 1200 | 5,3 | 12 | 100 |
| EXV 10 | 800 | 1600 | 5,0 | 10 | 125 |

## 3 Safety Requirements for explosive Loads

Even slight pressure wave generated by small bombs or large bombs at a great distance (e.g. in a neighboring street), can lead to major damage if the facade is not properly constructed. To protect persons behind the facade from major injuries, an explosion-resistant function of the facade is frequently specified. Most specifications refer to a classification of the performance condition according to the US GSA standard [7]. The GSA method classifies facades into six protection and risk classes (protection and hazard levels, Figure 2). For the highest protection class 1 the glass must not break. In the other protection classes it is defined how far glass splinters are allowed to fly into a standardized test box. Most commonly the protection class 3B is specified in which the splitters may fly in maximum 10 ft. (3.05 m) into the test box.

The GSA protection classes are developed for window glazing spanning in maximum from floor to ceiling. The direct use of the GSA protection classes would therefore be inappropriate for multi-story high cable net facades. The key factors for the protection of individuals are: firstly, that the pressure wave is considerably damped to protect ears and lungs and, secondly, that glass splinters do not act as projectiles that cause heavy injuries. Therefore, a definition of the permitted flight distance of glass splinters in relation to the height of the glazing would be more logical and could be used for all types of facades. For numerical evidence, the speed of the glass splinters at the moment when the breaking strength of the glass is reached could be defined as a protection class. For this method it needs to be considered that the fracture stress significantly depends on the glass product and the load duration due to the effects of the surface pre stress and the crack growth of flaws in the glass surface. For very short impact loads, such as under explosions, much higher breakage strength is known compared to the breakage strength for wind loads.

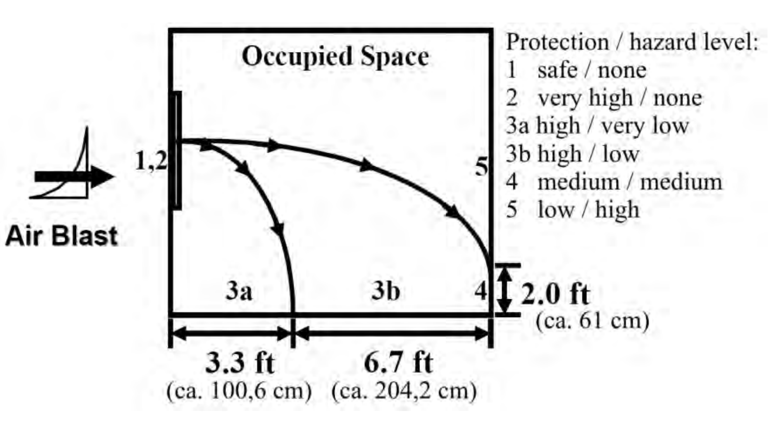


Figure 2: GSA/ISC performance conditions for window glazing according [7]

Table 3: GSA/ICE performance conditions for window system response

| Performance Condition | Protection Level | Hazard Level | Description of Window Glazing Response |
|---|---|---|---|
| 1 | Safe | None | Glazing does not break. No visible damage to glazing or frame. |
| 2 | Very High | None | Glazing cracks but is retained by the frame. Dusting or very small fragments near sill or on floor acceptable. |
| 3a | High | Very Low | Glazing cracks. Fragments enter space and land on floor no further than 3.3 ft. from the window. |
| 3b | High | Low | Glazing cracks. Fragments enter space and land on floor no further than 10 ft. from the window. |
| 4 | Medium | Medium | Glazing cracks. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no more than 10 ft. from the window at a height no greater than 2 ft. above the floor. |
| 5 | Low | High | Glazing cracks and window system fails catastrophically. Fragments enter space impacting a vertical witness panel at a distance of no more than 10 ft. from the window at a height greater than 2 ft. above the floor. |

## 4 Cable Net Facades without Blast Load Enhancement

### 4.1 Cable Net Façade Types

Cable nets façades can generally be divided into:

- Type 1: Systems with straight directions of the cables - as an example, see Figure 3.
- Type 2: Systems with polygonal directions of the cables - as an example, see Figure 4.

Figure 3: Cable net facade with straight cable direction (type 1): Hamad Medical City, Doha, Qatar (Gartner)

Figure 4: Cable net facade with polygonal cable direction (type 2): Sony Center, Berlin (Gartner)

For type 1 is to bear in mind that a straight cable needs to be deformed into a significant curvature before it can carry loads orthogonal to the cable line. The required curvature can be reduced by a pre stress in the cable. Additional cables (length $l_2$) with an angle to the primary cables (length $l_1$) could be used to stabilize the primary cables as well as to carry unevenly distributed loads. Unless the lengths in both directions do not significantly differ (approx.$l_2/l_1 < 1.5$), both directions can be considered for evenly distributed loads. However, the deformations of straight cables are significantly larger than deformations of elements with bending resistance.

The limit of the allowable deformation of a facade perpendicular to its surface depends on different factors:

- Obstacles in front of and behind the facade (e.g. building columns behind the facade, see Figure 3)
- Maximum permissible tension and compression of the glass joints
- Required glass support
- Permissible warping of the glazing in the transition areas to rigid connectors (edge of the facade, door frame). Forced twists may constitute a crucial boundary condition, in particular for insulating glass, which allow only a limited deformation of the spacer.

With suitably careful planning, deformations are possible up to 1/40 of the facade span.

For type 2 the positive and the negative wind loads are carried by two separated cables which are already shaped into a corresponding polygonal line. The pre stress in the cables can be much lower than in type 1 facades. To force a pre stressed cable into a polygonal line additional orthogonal forces, acting at the nodes of the polygon, are required. Compression struts between the two cables are usually used for this purpose, causing the typical fish-shaped cable networks.

### 4.2 Cable-End-Connectors

In addition to the allowable deformation of the facade, also the sustainability and the stiffness of the sub-structure can be a determining factor for the type of cable network. Often, the necessary high pre stressing forces for straight cables cannot be anchored. Balance springs at the cable end connections can be used to control the cable pre stress into a low range even under temperature changes and deformations of the sub-structure.

### 4.3 Glass Fitting

Spiders with drilled holes in the glazing (figure 4, 5) are the so far most frequently used form of glass fittings in cable facades. In the last years there was a clear trend to clamped connections (figure 3, 6, 8). Holes in the glazing are not required.

Figure 5: Spider connection, Court Square Project, Long Iceland, United States (Gartner)

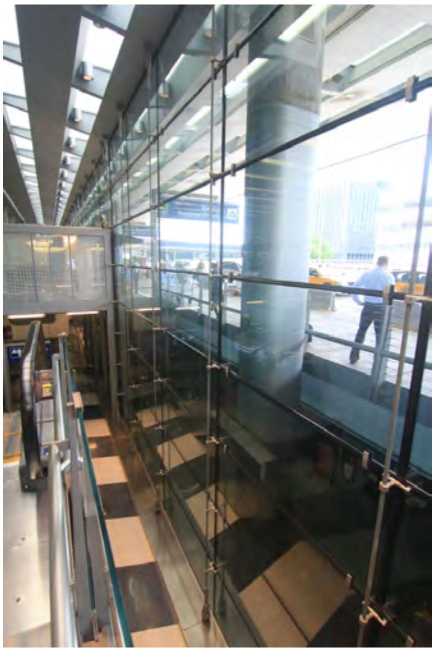


Figure 6: Clamped connection, Chicago Airport (Gartner)

# 5 Cable Net Facades with Blast Load Enhancement

## 5.1 Facades with Maximum Flexibility

Since the attacks on the World Trade Center Towers in New York 2001, more explosion-resistant cable net facades are built. In particular cable net facades with straight cable directions can be designed with blast enhancement. By the softness of this type of façade a pressure wave can be better absorbed and a higher aerodynamic damping is possible. For smaller explosion loads a sufficient protection can be achieved already, if the high deformations are considered in all details of the facade. Figure 7 shows an example of a facade that is designed in this type.

Figure 7: Explosion resistant cable net façade, Court square project, long Iceland, United States (Gartner)

## 5.2 Facades with Connectors for Blast Enhancement

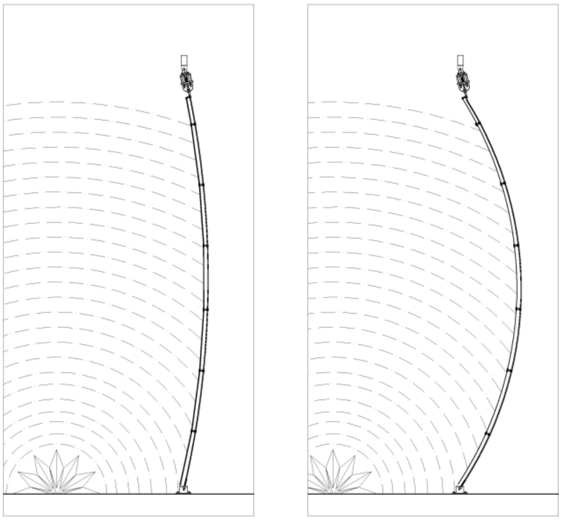
To reduce the stresses and forces in the components or to increase the residual strength of the system, special connectors are required [8]. Figure 8 shows an example of this type of facade.

Figure 8: Explosion resistant entrance facade of World Trade Center Tower 7, New York (Gartner)

While a pressure wave acts on a facade, two main phases can be defined, in which various connectors are acting with their function of blast enhancement. A definition of phases is shown in Figure 9 [9].

In phase 1, the pressure wave hits the glazing of the façade and the load is transferred by the glass clamp-cable connectors (see chapter 5.3). Already, through the use of plasticizers in these connectors, explosive energy can be absorbed at this stage. This results into lower surface tensile stresses in the glass and lower cable forces as with rigid couplings between the glass and the cables.

In phase 2, the stresses in the glass, as well as the cable forces rise. In case the glass breaks, the glass clamp connector described in chapter 5.4 provides residual strength and positioning. The cable end connectors described in chapter 5.5 can contribute to targeted energy dissipation at this stage and limit the maximum anchor forces at the main bearing structure.



**1 PHASE 1**

Activation of Glass Clamp –
Cable Connector

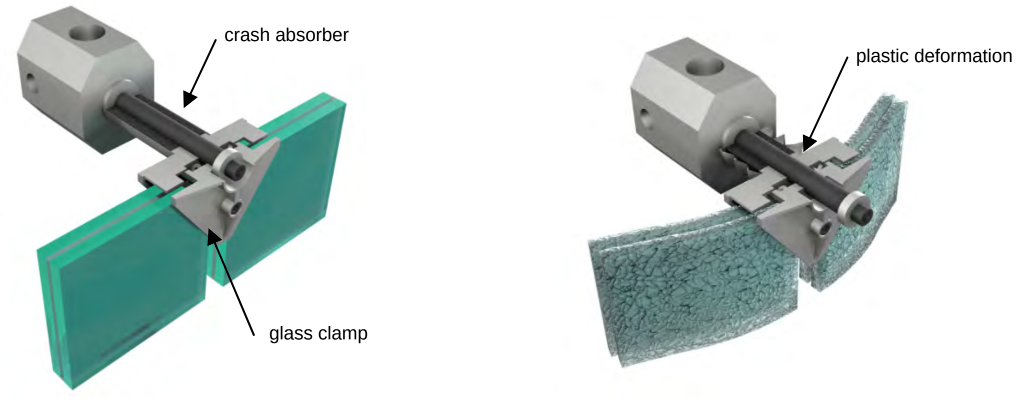
**2 PHASE 2**

Activation of Cable End Connector
and if necessary of Glass Clamp Connector

Figure 9: Load and response phases in explosion protected cable net facades. *Gartner* / *Permasteelisa*

### 5.3 Glass Clamp - Cable Connector

The connection between the glass clamp and the cable shown in Figure 10, allows a significant reduction of glass stress as well as the cable force by converting kinetic energy into deformation energy [9]. So it prevents already in the phase 1 either, that the glass break, or that in the case of glass breakage the splinters detach with to high speed from the laminated foil. A crash absorber, e.g. with aluminum foam, which is positioned between the glass clamp and the cable clamp will be deformed. To transfer the dead weight of the glass also after triggering the central bolt is decoupled from the crash absorber.



before triggering

after triggering

Figure 10: Patented glass clamp-cable connector before and after plastic deformation [10]

## 5.4 Glass Clamp Connector

The glass clamp connector shown in the Figure 11 allows a significant larger residual strength of broken laminated glass panes [9]. Much higher loads can be carried before whole laminated glass panes break out, however, so even higher loads affect the cables. In this connection a perforated plate of carbon is embedded into the layers of the laminated glass. The carbon plate is connected by Kevlar twines with a cone on the outside of the pane. The cone is free of any forces under regular loads and attaches the clamp only in the case of glass breakage and a larger deformation of the glass pane.

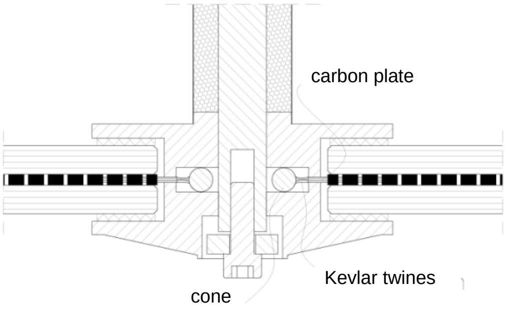


Figure 11: Patented glass clamp [11]

## 5.5 Cable End Connector

Cables with a straight direction require a high axial pre stress to limit the deformation under wind loads to an acceptable level. There is therefore the risk that the cables exceed their breakage strength and tear under explosion loads. A newly developed cable end connector is schematically represented in figure 12. This connector is very stiff until a defined activation force $F_A$ to ensure a minimal deformation of the cable under the regular load combinations with pre stress, self-weight, temperature, and wind. Under a blast load a triggering device allows a controlled elongation of the cable end connector with simultaneous energy dissipation. In the version shown in the figure 12 the activation force is determined by a breaking point in the primary load path. After triggering the axial tensile force is redirected to a secondary load path, in which one or more crash absorber, e.g. with aluminum foam, are integrated.

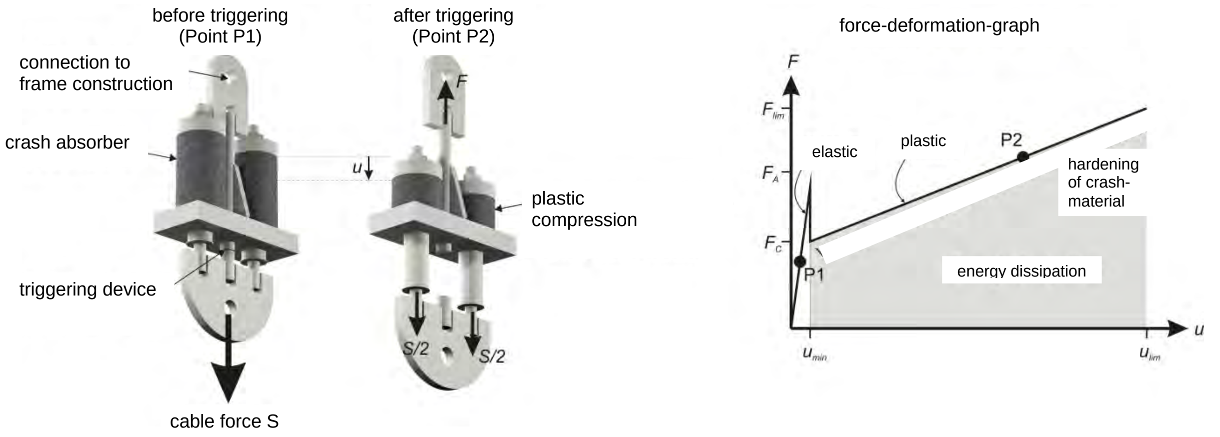


Figure 12: Patented cable-end-connector before and after fuse breakage [12]

In the crash absorber a yield force Fc ("crash force") is activated that is smaller than the activation force $F_A$. Crash materials show a hardening under increasing crash deformations. The challenge is to find the best force displacement function for the explicit facade and to realize this function with the belonging crash absorber (defined by the crash material, cross section and initial crash absorber length). A too slow hardening of the crash material requires a too long deformation length until the required amount of energy is dissipated (defined by the integral of the crash force over the crash

deformation). A too fast hardening limits the possible dissipation energy before the cable strength is reached.
Two significant effects are achieved by the new cable end connector:

- Significant energy dissipation due to high plastic deformations.
- Reduction and control of cable forces and thus reduction and control of the forces which are forwarded to the frame construction.

In the development of appropriate cable end connectors the following aspects were considered:

- a low increase of the trigger load under high strain rates as they occur under blast loads
- a small scattering of the activation force $F_A$,
- a small scattering of crash force Fc, and
- a choice of crash materials with different hardening behavior

The newly developed cable end connectors were tested quasi-static, as well as with realistic deformation speeds as they occur under explosion loads (1 m/s up to 5 m/s).

### 5.6 Development of an Assessment Tool

The structural behavior of explosion-resistant cable net facades is extremely complex. This is particularly true if the non-linear behavior of dissipative cable end connectors should be considered. In a joint project of the Department of structural analysis of the University of Armed Forces Munich and Gartner Steel and Glass GmbH in Würzburg, the dependencies of the different parameters were examined among themselves with a standardized load of explosion [13]. The results were implemented in a design tool, developed with Microsoft Excel, which is used for preliminary design and parametric studies [14].

As the load scenario the GSA-D level (table 1) was chosen. In the United States this is a common level for buildings with higher security requirements.The examined parameter combinations are summarized in table 3. Five idealized force displacement curves for the cable-end-connectors (SEV types) were defined (figure 13). The ratio of activation force to crash force is 60% for all cable-end-connectors (FA/ F(c) = 0.6). This ensures that under consideration of the scatter of both forces the activation force is always higher than the crash force.

The five SEV types differ in the plastic hardening area (Figure 13). For SEV 1 it is twice as large as for SEV 2 and SEV 3 has an ideal plastic plateau without hardening. SEV 1, 2a, and 3a are unlimited in their plastic deformation. For SEV 2b and 3b the plastic deformation is limited to 200 mm. After this deformation they harden again to a linear elastic behavior with high rigidity. This behavior considers that the length of the crash absorber and therefore the energy that could be absorbed by plastic deformation is limited. The variations of SEV 1, 2a and 3a are suitable to determine the required plastic deformation length and to design related crash absorbers. The assessment tool can be used to design cable-end-connectors with "tailor-made" capacity of energy absorption.

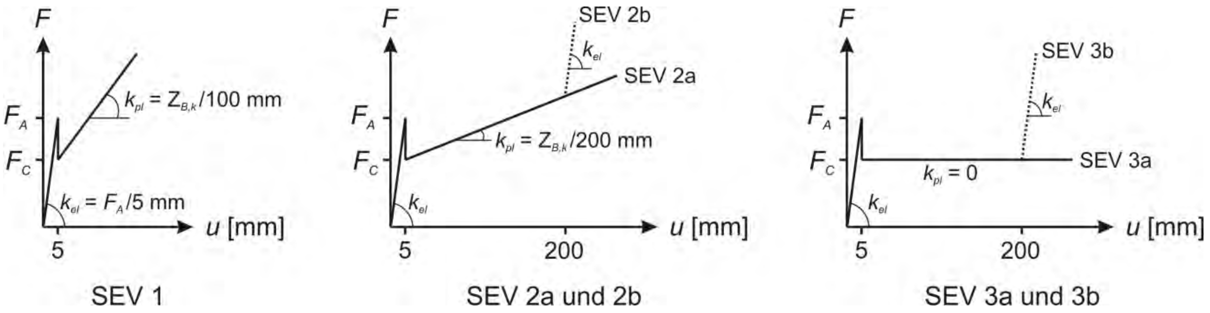
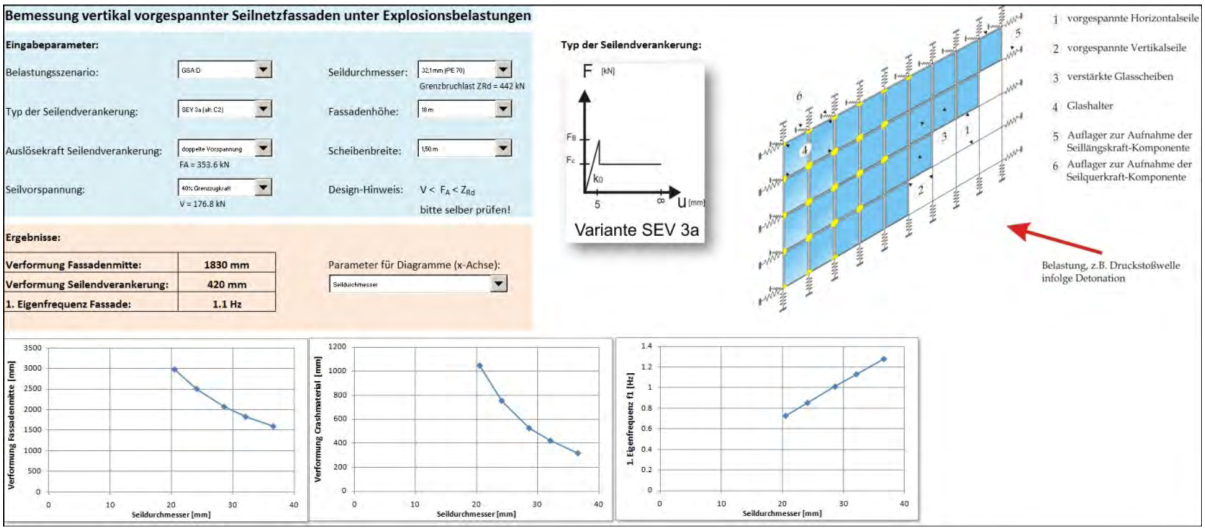


Figure 13: Idealized force-deflection curves of five cable end connectors (SEV) [13]



**Bemessung vertikal vorgespannter Seilnetzfassaden unter Explosionsbelastungen**

**Eingabeparameter:**

Belastungsszenario: GSA D

Typ der Seilendverankerung: SEV 3a (alt: C2)

Auslösekraft Seilendverankerung: doppelte Vorspannung
FA = 353.6 kN

Seilvorspannung: 40% Grenzzugkraft
V = 176.8 kN

Seildurchmesser: 32,1mm (PE 70)
Grenzbruchlast ZRd = 442 kN

Fassadenhöhe: 18 m

Scheibenbreite: 1,50 m

Design-Hinweis: $V < F_A < Z_{Rd}$
bitte selber prüfen!

**Ergebnisse:**

| | |
|---|---|
| **Verformung Fassadenmitte:** | **1830 mm** |
| **Verformung Seilendverankerung:** | **420 mm** |
| **1. Eigenfrequenz Fassade:** | **1.1 Hz** |

Parameter für Diagramme (x-Achse): Seildurchmesser

Figure 14: Screenshot of the developed design tool with Excel [14]

## 6 Curtain Walls with Blast Load Enhancement

In the last years Permasteelisa has developed its own software for the design of linear supported glazing under blast wave loads. This software simulates blast waves and the dynamic reaction of the façade [8].

The software makes it possible to perform two different types of analyses: single analysis and isodamage curve analysis. With the single analysis type, verification is performed on a façade panel governed by a blast law that simulates the wave derived from the explosion. Analysis of the isodamage curves, which can only be performed on façade panel with rigid supports, makes it possible to launch iterative (and automatic) single analyses. The final purpose of such analyses is to find pairs of points on the diagram (maximum pressure-impulse) that determine an equivalent condition — in terms of displacement and failure — over the dynamic behaviour of the panel.

Figure 15 shows the key steps involved in writing and solving a dynamic equilibrium equation for a system with a single degree of freedom. The concentrated parameters must be provided according to the characteristics of the system (in this case the façade panel) and, together with definition of the forces, they determine the unambiguity of the solution to the dynamic problem. This solution is evaluated through the choice of a specific stepped integration method for which the user can modify the parameters in order to counteract problems related to divergence of the solution. Once the outputs have been obtained, they are studied to ensure their conformity with the set objectives.

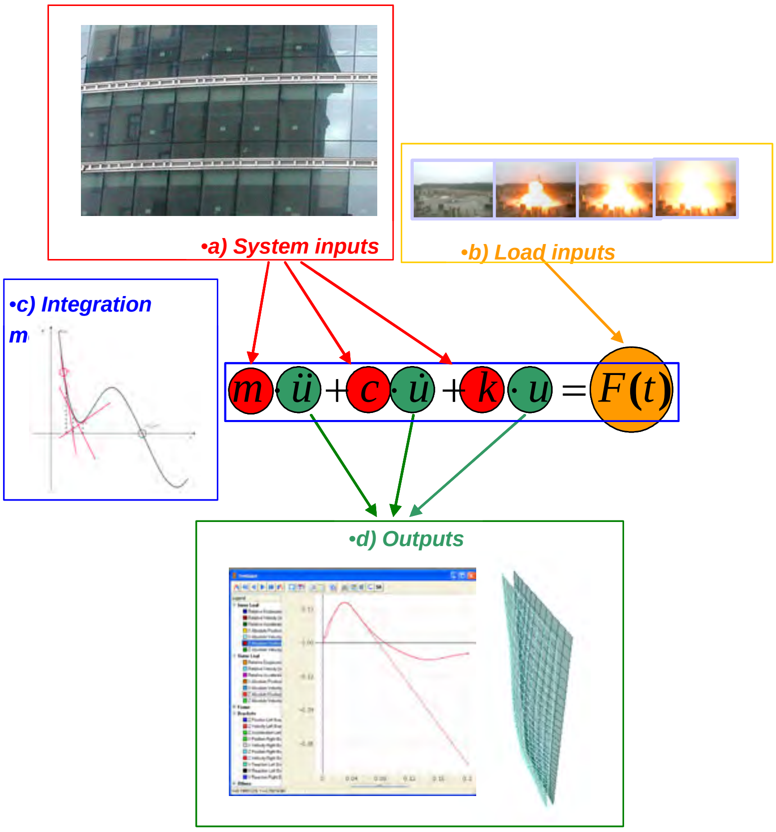


Figure 15: Structure of a dynamic equilibrium equation for a system with one dof [15]

One mayor aspect of the software is the realistic consideration of the resistant function of laminated glass, as shown in figure 16. Here four different components can be identified:

1) During the first phase, the resistance function shows a nearly linear trend, guided by the fragile performance of the glass
2) Then, with the failure of the first slab of glass, the resistance collapses suddenly and the second phase takes over in which the second slab of glass effectively determines the overall resistance
3-e) When the second slab of glass breaks, the "package" deformation of the layers of PVB ensues. First of all, the resistance offered acts within the elastic field with a nearly linear branch
3-p) Finally, once the yield strain has been reached, we enter the field of large-scale membrane deformation, i.e. the area where most of the blast wave energy must be dissipated.

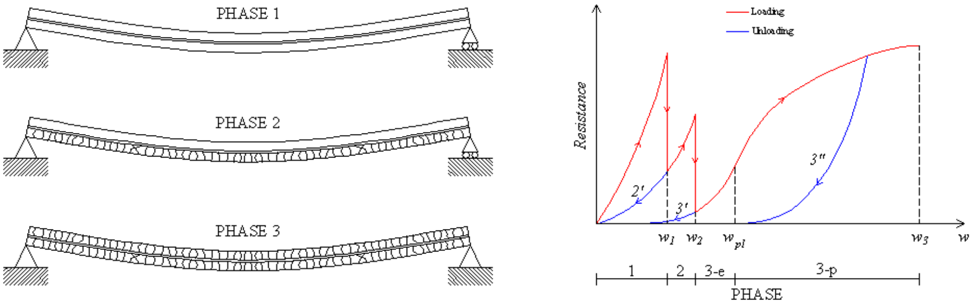


Figure 16: Progressive phases of the behaviour of laminated glass [15]

The further development of the software allows now the analysis of complex façade systems with double or triple glazing (including laminated glass), plastic hinges in mullions and transoms, and elasto-plastic deformations of the brackets. Figure 17 shows exemplary brackets that can be trigger to the appropriate force-deflection function for a specific blast load scenario.

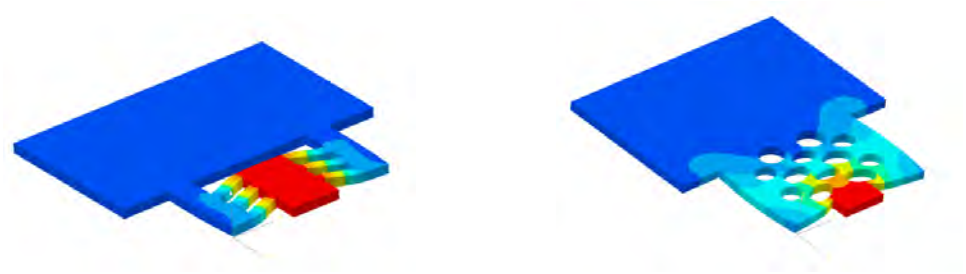


Figure 17: Patented elasto-plastic bracket plates for curtain wall systems [16]

## 7 Acknowledgments

This paper gives a short overview of design methods and structural components that were developed by Gartner Steel and Glass and the Permasteelisa R&D Group in the last years – special thanks Marc Zobec and Guido Lori. Financed by Gartner / Permasteelisa several tests and calculations were done at external institutes - special thanks to BAM in Berlin and the Universities of Applied Science and Armed Forces in Munich.

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# Modern Steel and Glass Constructions – A Review of Current Projects

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## Summary

For a number of years now, Thomas Lorenz ZT GmbH has been heavily involved in national and international projects in structural engineering for steel and glass constructions and façades. By taking the leading role through the drafting process with these projects, the author has gained large amounts of first-hand experience in this field. This paper will introduce the most recent projects, explain the details, and describe the design process covering the calculation of the geometry to the creation of the calculation models and the detailed planning of the glass, junctions and supporting points. Special particularities and creative solutions are described as well. The topics covered range from complete glass shells where the glass has the primary load-bearing function, to glass used as free-formed grid shells for steel and glass constructions, as well as modern façade constructions.

**Keywords:** building skins, steel-glass constructions, façades, glass shell

## 1 Introduction

As a transparent building material that can be used to define spatial boundaries, glass is becoming increasingly significant. It is being used more and more for self-supporting roof constructions on the one hand, and as panelised façades on high-ride buildings on the other. This brings new challenges, especially for structural support engineers who have been tasked with combining a functional supporting structure with the bold visual forms of modern architecture.

The realisation of demanding structures made of glass and steel can only work when there is close cooperation between architects, structural support engineers and the construction managers. It is often the case today that the basis of a construction tender is only a sketch of the structural support or central construction objects. In such cases, the complete detailed planning and development of the details, including any assisted prototyping occurs only after the awarding of the tender. While this way of doing things has established itself, it ultimately leads to difficulties in the calculations and eventually can impact the construction timelines of the structure.

In recent years Thomas Lorenz ZT GmbH has been engaged multiple times by leading companies as structural support planners and have been required to provide system and detailed development as well assisted prototyping within a short time frame. Thomas Lorenz GmbH were able to meet these challenges to the satisfaction of all involved and were able to gain a wide range of experience in doing so.

Example projects include:

- The covering of the Münzhof ("Coin Courtyard") for the Federal Department of Finance of the Republic of Austria in Vienna with a barrel formed, cable-tensioned pure glass roof (2009-2010)
- The new station buildings for the Funicular Railway in the inner city of Baku / Azerbaijan (2011-2012)
- The covering of the shopping mall in the central area of the Flame Towers in Baku / Azerbaijan (2011-2012)
- The façade construction of the multifunctional building complex built above the Vienna train station "Wien-Mitte/Central Vienna" (2010-2012)
- The façade construction for the currently being built DC-Tower in Vienna – with 220 meters, this will be the tallest building in Austria (2010-2012)

## 2 Projects

### 2.1 Roofing of the Münzhof („Coin Courtyard") / Federal Department of Finance Building

In the course of the general renovation of the Federal Department of Finance building in the inner city of Vienna, one of the courtyards, the so-called „Münzhof" ("Coin courtyard"), was to be covered. A glass shell construction was planned as the roof for the courtyard that covers 120 m². In the tender document, a sketch of a shell structure in the form of a barrel was provided that consisted primarily of load-bearing, rectangular single pieces of glass and a round steel frame as the roof edging.

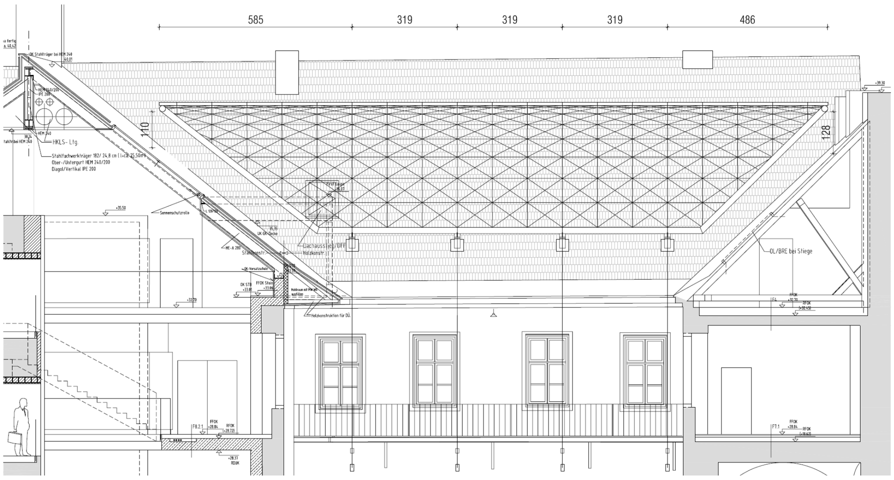

Figure 1: Longitudinal section view

A particular challenge for the structural support planners was the relatively short time period in which to perform the calculations and component prototyping. The greatest difficulty lay in the development of the details, the building of the model and the research into the behaviour of the structural support.
To report on the limits of the load-bearing capacity of the roof, load combination and failure cases were defined beforehand. The complete load-bearing capacity was then investigated using a 3D calculations model using around 2,000 struts. In order to calibrate the calculations and to verify these results, prototyping of a single glass panel as well as a 1:1 model were conducted in parallel. The central, key element was to develop a joining node that functioned to transfer the load from not only those glass panels in parallel but also those normal to the plane. Particular attention was placed on storing the glass sections in a tension free environment as well as the clean application of load to the glass. The joining nodes were in the form of steel shoes that were glued to the corners of the glass and then keyed to the central steel core. In order to stabilise the roof construction against wind suction and skewing, as well as to ensure that enough stability can be guaranteed in the event of damage to the individual glass panels, the barrel roof was supported with a network of steel cables that was fixed to each joining node.

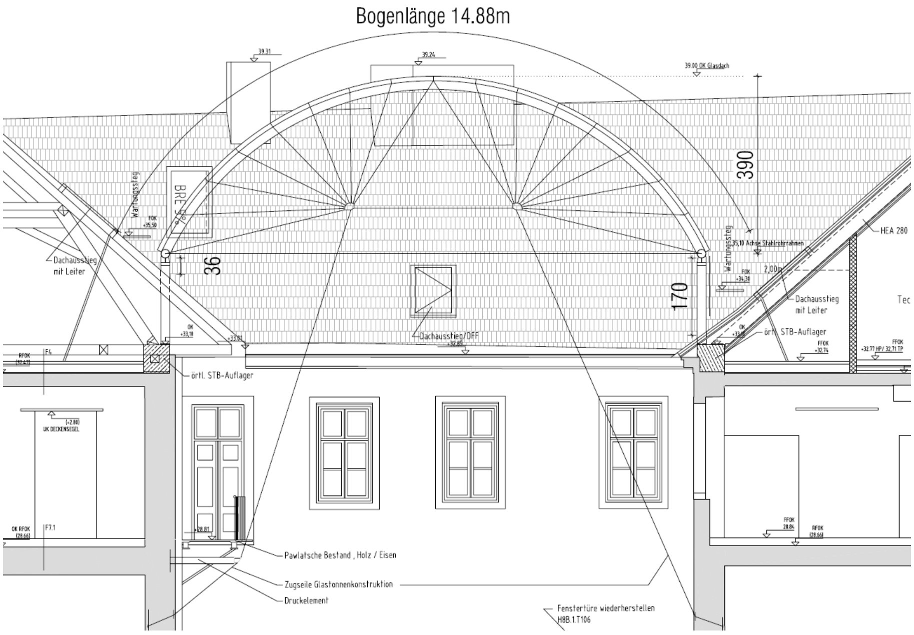

Figure 2: Cross sectional view

An additional challenge lay in the investigation of the required pre-tension force in the cable, in conjunction with the assembly sequence and the structural conditions. That the roof had to be assembled approximately 35m above the ground also meant that equipment had to be planned and manufactured. After some initial difficulties, after the release of the barrel roof, the project was completed to the satisfaction of all involved and since then features prominently in the Vienna roof landscape.

Technical data:

| | |
|---|---|
| Length | approx. 20 m |
| Width | approx. 12 m |
| Arch length | approx. 15 m |
| Glass surface | approx. 250 m² |
| Glass format | approx. 815 x 1,065 mm |
| Glass structure | 2 x 12 mm TVG with 1,52 mm PVB - foil |
| Tubular steel for frame | FR 193.7 x 10 mm, S355 |

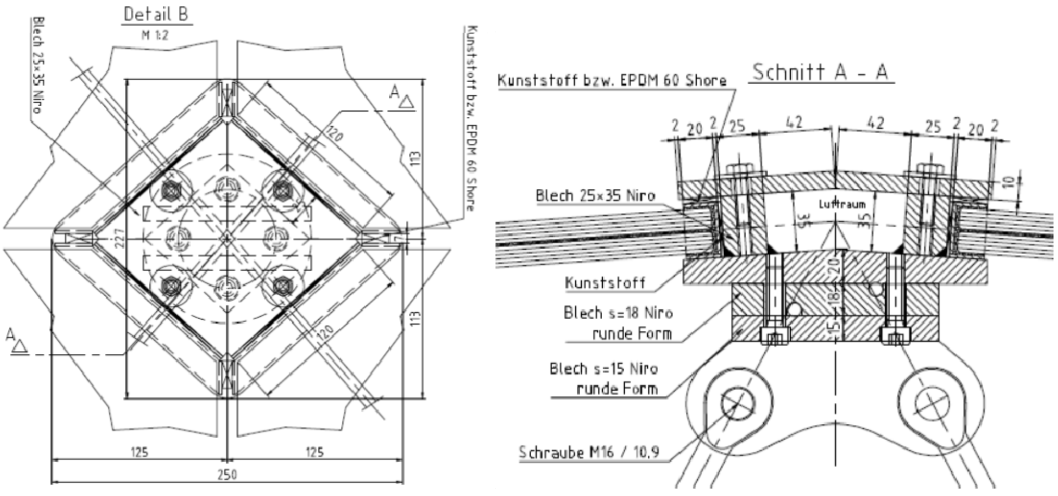

Figure 3: Central joining node

Figure 4: Large scale prototyping

Figure 5: Assembly

## 2.2 Renewal of the Funicular Railway Baku, Azerbaijan

The construction of the existing Funicular Railway in Baku dates back to the 1960s. It is currently in the process of being completely renewed. Next to a new track, the existing top and valley stations will be demolished and replaced with a new steel–glass grid-shell structure to be constructed by the Upper Austrian company GIG. The valley station is not far from the site of the event complex that will host the Eurovision Song Contest 2012. The valley station connects the Boulevard with the elevated ground that is the site where the so called “Flame Towers” are to be built.

Figure 6: Visualisation top station

The challenge in this project lay in the development and planning of wide-spanning, self-supporting shell structures. After determining the form, the next step was to determine the profile dimensions and then to agree on an optimum solution after considering the economic and business perspectives. Due to manufacturing reasons, the central connecting elements of the skeleton structure were solid steel nodes.

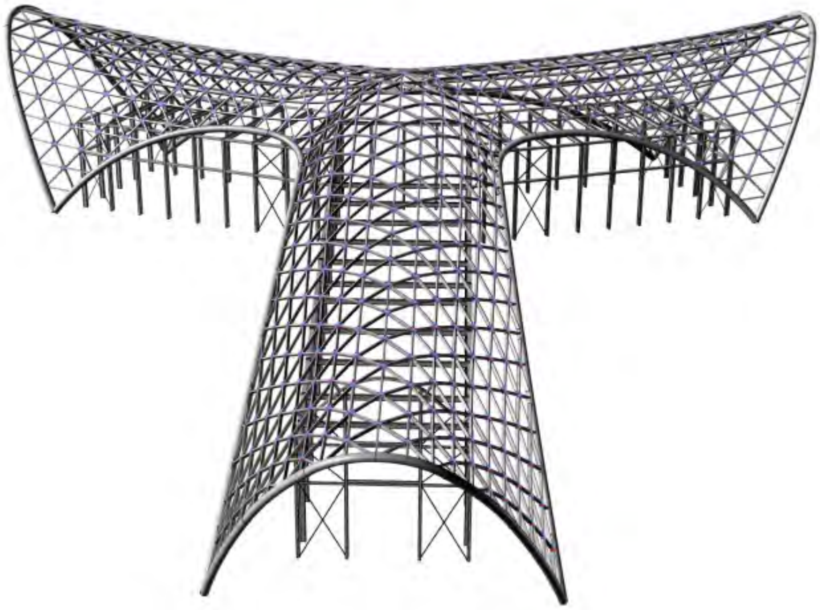

Figure 7: Rhino – Model of top station

With specialised software („Rhino“), the basis for the finishing of the nodes, glass sections and steel construction planning could be performed. As the Funicular Railway lies directly on the coast of Baku which is well known for its strong winds, a wind assessment needed to be completed beforehand. The engineering as well as the construction were all completed in Austria. The entire construction was disassembled into containers and then reassembled and then transported by truck to Baku. A particular hurdle turned out to be the interface between the substructure calculations onsite and those planned.

Language barrier, local attitude and high inaccuracies in construction were additional challenges in this project that is now in its completion phase.

Technical data (Top- und Valley station):

| | |
|---|---|
| Total enveloping surface | approx. 1,400 m² |
| Glass | approx. 1,900 pieces |
| Number solid steel nodes | approx. 900 pieces |
| Total tonnage steel | approx. 200 t |

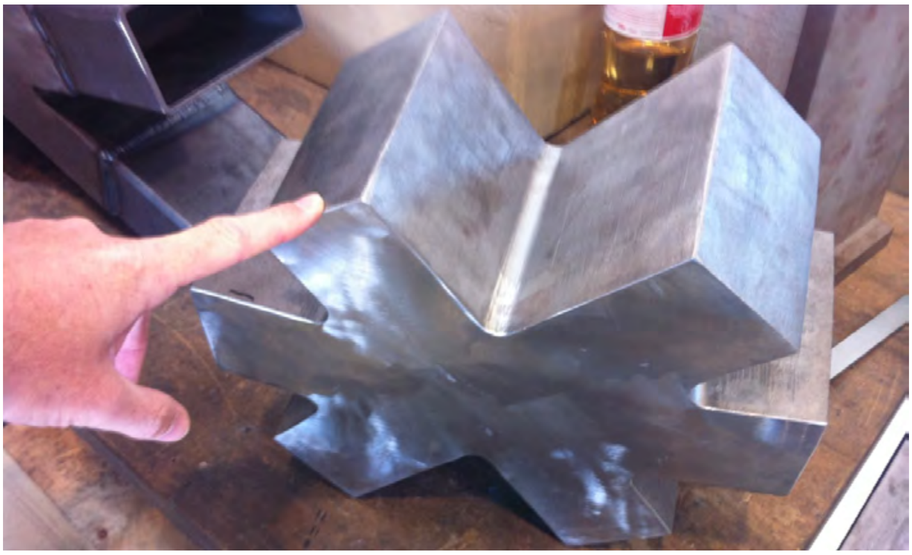

Figure 8: Solid steel node

Figure 9: Assembly valley station

## 2.3 Façade Donau – City - Tower 1, Vienna

The breaking of the ground in the early summer of 2010 marked the beginning of a new landmark of Vienna – the DC – Tower in the newest development area directly on the Danube and not far from the Reichs Bridge, the Austria-Centre and the UNO City. This new office tower will house a hotel as well as other diverse, public facilities. The DC-Tower 1 is one of the two towers designed by Dominique Perrault, and, towering 220m in height, will be the highest building in Austria and transform the Vienna skyline.

Figure 10: Façade DC – Tower 1, Status of construction end of April 2012

The façade of the tower will be constructed by the company Strabag. Thomas Lorenz ZT Gmbh was entrusted by Strabag with the responsibility to provide the detailed structural design planning. Due to the high market pressure, a most cost-effective construction was required. Particular attention was paid to the development of brackets. Numerous variations were designed and calculated, with the final decision being made on an economically and assembly perfect aluminium construction that has now been built 15,000 times.

Technical data:

| | |
|---|---|
| Maximum height | approx. 220 m |
| Façade surface | approx. 45,000 m² |

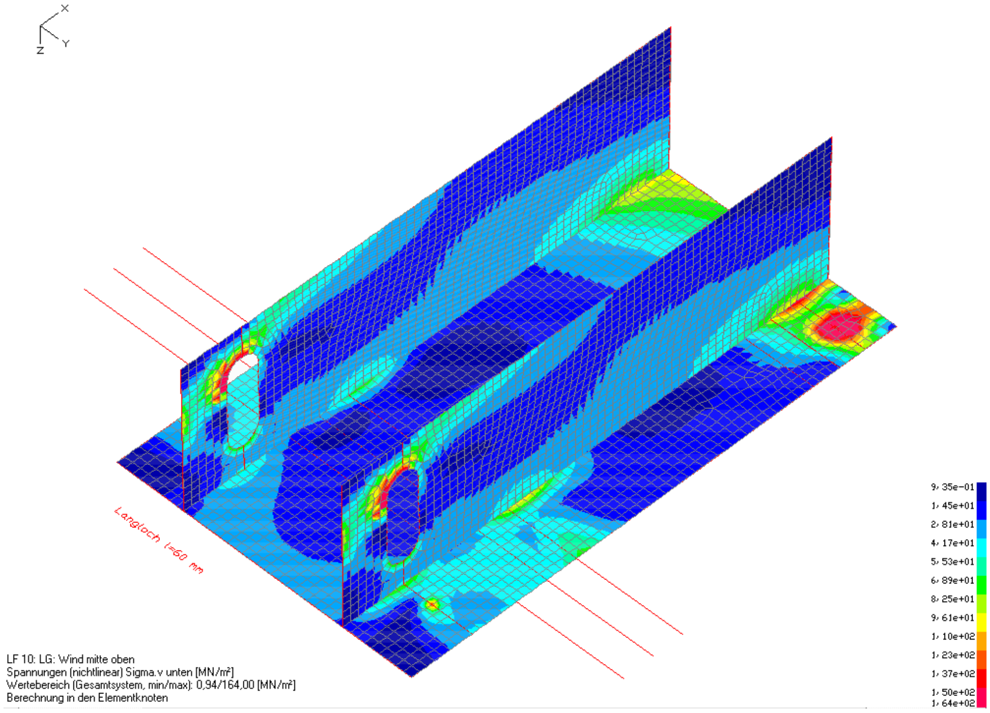

Figure 11: 3D – Bracket calculation

Figure 12: Detailed bracket DC Tower 1

## 3 Summary and Conclusion

As structural support planner on behalf of leading steel and glass construction companies and under time and cost pressures, to be able to plan and calculate in detail remains one of the largest challenges. With a good cooperation between construction managers, architects, structural support planners and leading management, demanding projects can be realised within budget, time schedule and to the satisfaction of all involved – as this contribution proves.

# Tensiwall - The Case for a Multi-layered Textile Facade System

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## Summary

A facade is the interface between building and environment, between indoor and outdoor; therefore it has a functional quality. The facade is also the first component to be seen of any building; therefore it has an aesthetic quality that it needs to achieve. Currently, advanced facade materials are dichotomized in two categories: heavy and transparent materials (glass), requiring significant structural material usage; or lightweight and opaque materials, depriving the interior of natural light. This has brought about the development of Tensiwall, an innovative exterior wall system based on a textile facade. By combining the properties of various tensioned membranes, an advanced and highly aesthetic multi-layered textile building skin can function as a cost-effective, lightweight, light-transmissive, and highly insulative facade system.

**Keywords:** Textile, Fabric, Membrane, Tension, Materials

## 1 Inherent Materials Properties

Facades are constructed of various materials, and the properties of these materials create very different facade systems. This section discusses today’s materials, and how their inherent properties influence their use. The studied material groups are stone, metal, glass, brick, concrete, wood, plastic, textile, and composite. Most material groups are self-explanatory by name however it is to be noted that the textile group is not a material one but rather a compositional shape group. The two textiles researched in this group are made of one of the previously mentioned material groups, but constructed in an innovative way to produce new material application properties. The final group, composite, is once again a group of elements constructed using other material groups, creating one performative material. Figure 1 gives a visual illustration of the groupings of these different materials. As the basis for comparison, these material groups must be compared relative to their inherent properties (Figure 2).

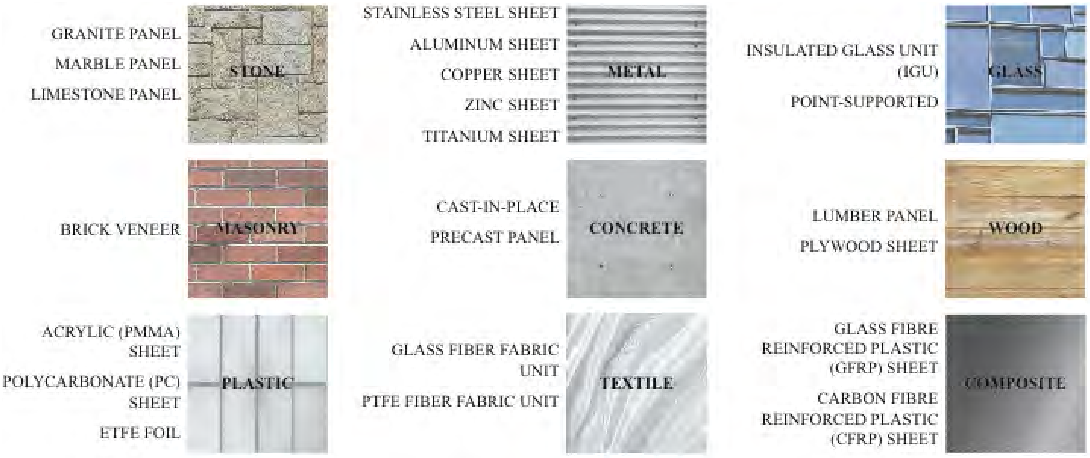

Figure 1: Materials Groups

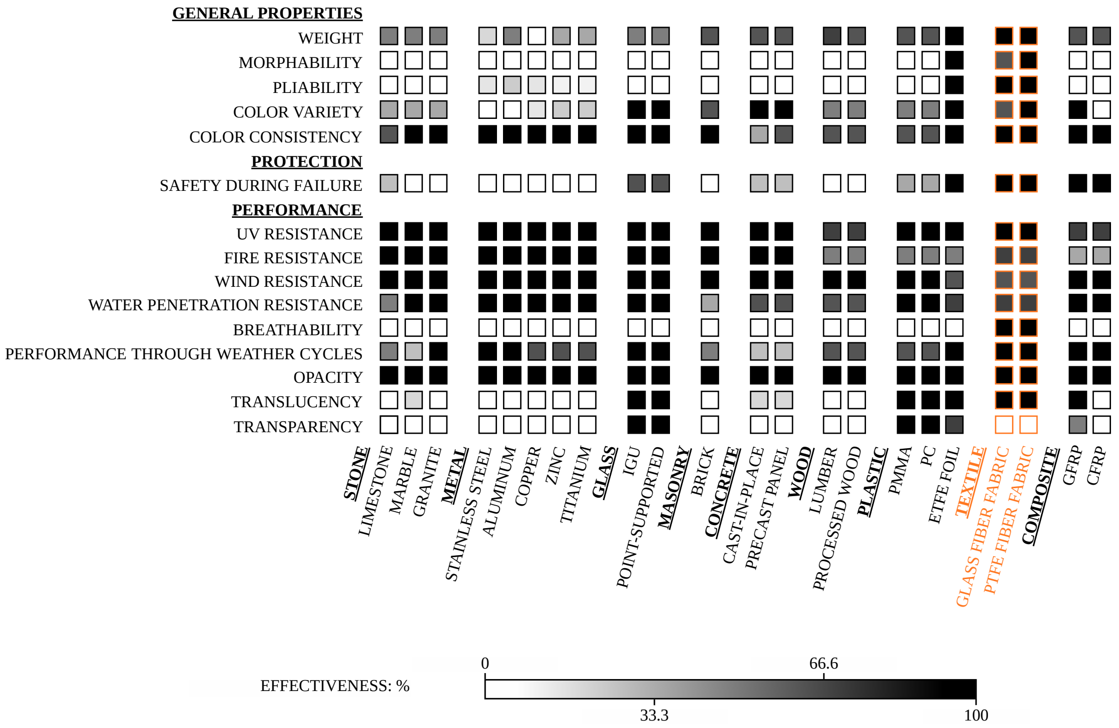

Figure 2: Materials Inherent Properties Comparison Matrix [1] [2] [3]

Textiles are applicable in many areas and in fact out-perform all other materials in some of them. Primarily, textiles offer the benefit of light penetration (something that only a few materials can do), and it should be understood that they also diffuse the light so as to reduce glare and provide an even interior lighting situation. In addition, textiles offer safety during failure (unique to fabrics), virtually eliminating hazards for interior occupants or pedestrians below during failure. Last of all to be noted is the lightweight characteristic that is inherent to textiles. Of all material groups, fabrics are the lightest because of their geometry as very thin membranes. The area in which textiles are lacking, however, is transparency. While light can penetrate the fabric, one cannot actually see through it. It is in this area that another material suitable for this purpose must be introduced into the textile facade system.

## 2 Facade Materials Properties

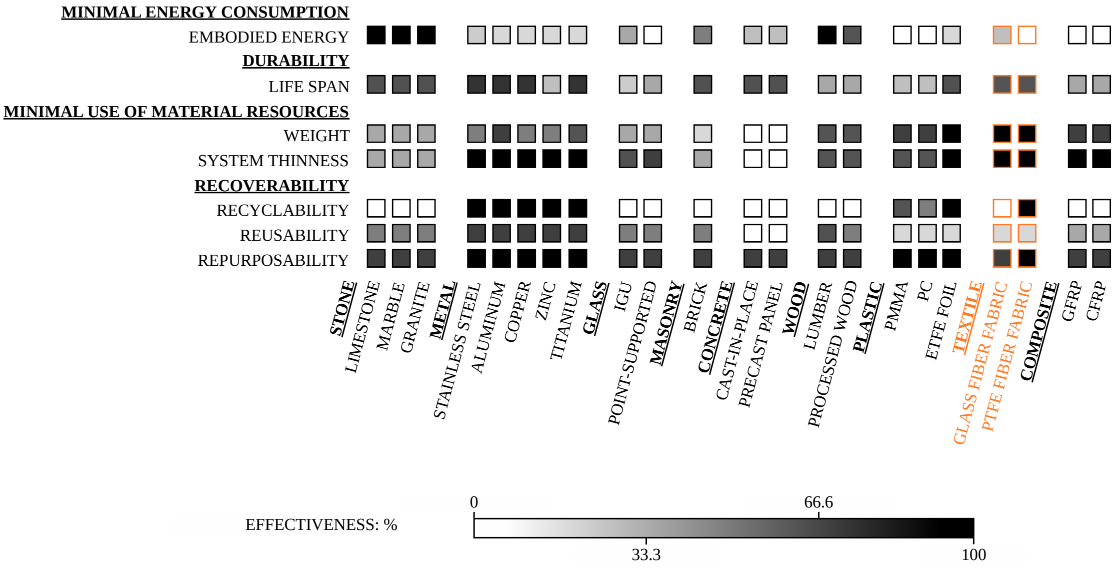

Figure 3: Materials Facade Applied Properties Comparison Matrix [1] [2] [3]

The advanced facade should be one that fulfills all of the requirements of a typical facade, but also looks ahead and functions in the context of the future market. We are confronted with a world that is affected more and more by a global awareness of energy consumption, material resourcefulness, sustainability, and recyclability. This means that the future advanced facade needs to adjust and conform its design to these ideas. The technological advances are also a major part of our society today, and along with the major advances in technology should also come a highly advanced facade design. Energy efficiency, maximum user comfort, minimal use of material resources, and recoverability are some of the characteristics that an advanced facade should consider. First, a general comparison between the material groups as they are applied to facades is illustrated in Figure 3.

Materials have inherent properties, but these properties may change as the materials are applied to facades today. This means that, for example, metals are lightweight since they are applied in thin sheets, and glass is not recyclable due to the coatings and seals applied to them. As can be seen, textiles still provide benefits in many areas even as they would be applied to facades. In this section, these characteristics are discussed relative to a comparison between the textile facade and the current facade materials.

## 2.1 Energy Efficiency

The energy consumption for every building can be broken down into three parts: the beginning-of-life energy consumption (embodied energy), the operation energy consumption, and the end-of-life energy consumption.

The beginning-of-life energy is the amount of energy required to extract, process, and fabricate materials; transport them; and put them together to construct the facade. Although relatively small, the amount of energy put into the beginning-of-life can still be reduced with careful detailing. Even more so, this amount of energy can be reduced with careful planning for its end-of-life deconstruction.

Consuming 70-85% of the energy put into a typical building, the operation energy is the amount of energy needed for the building to function properly. This means that the efficiency of the facade plays a big part in reducing this amount of energy. By producing a thermally efficient and light penetrating skin, the cost to heat, cool, and light the building can be drastically reduced. This energy need is addressed in the performance of the system discussed later.

The end-of-life energy is the energy needed to deconstruct the facade and separate its components. There is very little information on this type of energy as it is not considered in today’s architecture. However, as architects we should not neglect this phase of the building’s life. Designing a facade system that comes apart quickly and easily can keep at a minimum the amount of energy that is put into the deconstruction. The materials should then be transported to the recycling plant (if recycled) and then on to the new site where a new building can be constructed. The goal is to design a facade so as to allow for easy deconstruction, easy separation of materials, and high recyclability. The end-of-life energy consumption of a typical building is at 1-3%, but this figure only considers the demolition of the building. With a careful deconstruction, transportation, and recycling of materials, the percentage of the end-of-life energy input will rise; but the end product will be a recycled and ready to use set of materials, greatly reducing the beginning-of-life energy input of a new building. Textiles offer a benefit here because they are generally constructed in dry systems, allowing for all of the parts to come apart in a very clean manner. Tensiwall is designed with this idea in mind, providing a system that can be easily deconstructed at the end of its life, for easy recyclability and reuse of all components.

## 2.2 Maximum User Comfort

The future facade is something that should not only reduce the amount of energy required to construct, operate, and deconstruct it, but it should do all of these without the sacrifice of comfort. In order to better understand how the facade will affect this area, we should look at the conditions required for a comfortable space. There are in fact a few components to be considered when providing a highly useable space, two of which are discussed in this section: thermal and visual comfort.

Regarding thermal comfort, the interior air temperature is a function of how efficiently the facade performs. A better performing facade will prevent heat from dissipating through the wall whether from outside to inside or vice versa. A key factor in the design of the facade systems in this research is the efficiency of the system itself. Additionally, the use of transparent insulation can further boost a textile facade's performance. While adjusting the wall's insulative capabilities, this type of insulation can also allow natural light to penetrate through. Different types of transparent insulation allow different amounts of light through and perform differently with respect to U-value. Tensiwall utilizes these ideas to create a thermally efficient skin, providing maximum thermal comfort for the user. This then, greatly assists in the lowering of the operation energy required for the building.

The visual comfort at hand is regarding the amount of natural light that is allowed into the interior for optimum lighting conditions. The light quality is extremely important as it provides a visual source of information for the interior inhabitants in order that they can accomplish their work. A properly lit user space (through the use of natural light) can once again drastically reduce the amount of energy put into the operation of the building. Another item to look out for, however, is the glare produced from too much natural light. In order to reduce the discomfort that light can bring into a space, one must design the interior space so as to keep away from these light intensive areas, or some sort of shading or diffusing device must be utilized. This can be in the form of shades applied to the exterior wall, or in the case of textiles, the fabric itself. Since textiles cannot be completely transparent, and their surface is rough compared to that of a smooth sheet of glass, fabrics have the advantage of being able to diffuse light and largely reduce the amount of glare introduced to the interior.

### 2.3 Minimal Use of Material Resources

At only a fraction of the density of glass, textiles fabrics can provide a tremendous amount of reduction in the materials utilized on the project. This means that the frame used to carry the loads of the facade material can potentially be reduced as well. Further, the sizes and amount of structural materials used can be lowered due to the drastically reduced dead load of the facade materials.

Yet another characteristic to consider is the applicable thickness of a material. For example, a typical glass sheet is manufactured at a thickness of about 5 mm; and then, multiple sheets are needed to conform to the efficiency and possible safety requirements. By the end, a typical glass facade is composed of two or three layers of glass (maybe more), totaling a material thickness of about 10-15 mm. When compared to a textile facade, one can begin to see the tremendous amount of weight difference. Even with a four-layered textile system, the total thickness of fabric material adds up to about 2-3 mm (maybe even less). Figure 4 illustrates the densities of various facade materials, as well as the possible thicknesses for application to facades.

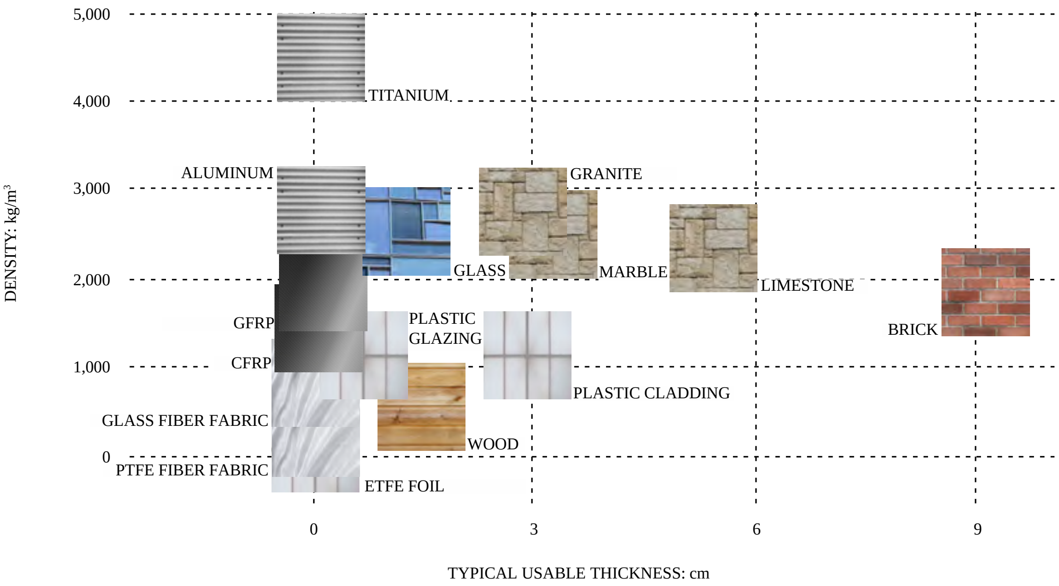

Figure 4: Materials Weight Analysis [3] [4]

Furthermore, the frame size capable to carry a glass facade unit is multiple times smaller than the potential textile facade panel. While glass units are typically limited to approximately 1-3 m x 3-5 m (3-10 ft x 10-16 ft), a textile unit is limited by the transportation requirements, allowing spans of even 4.5 m x 10-13 m (15 ft x 32-42 ft) for unitized or off-site tensioning systems, and more for stick-built or on-site tensioning systems. In addition to reducing the number of panels at installation, a larger panel size means fewer framing members applied the facade, further reducing material usage.

The last item for consideration in the reduction of resource consumption is a minimization of profile material. If the framing member section can be reduced to a minimum, a large amount of material can be saved when applied over large surfaces. This is embodied in the careful detailing and engineering of the profile (discussed later).

## 2.4 Recoverability

The recoverability of the materials used in the facade is another important aspect of the advanced facade. Recoverability can be broken into three different types – recyclability, reusability, and repurposability. Recyclability is the capability of a used material to be applied once more with its original properties and function, while requiring less energy input in its remanufacturing process than its original manufacturing. Reusability is the capacity of a used material to be applied in the same way or material state as before, while requiring cleaning and/or physical modification or cutting in order to remove unwanted matter. Repurposability is the capacity of a material to be remanufactured with little energy input in order to form a material with a different purpose and material state than its original one. See Figure 5 for a visual understanding of these three definitions; notice that not all materials are recyclable or reusable; however, all are repurposable.

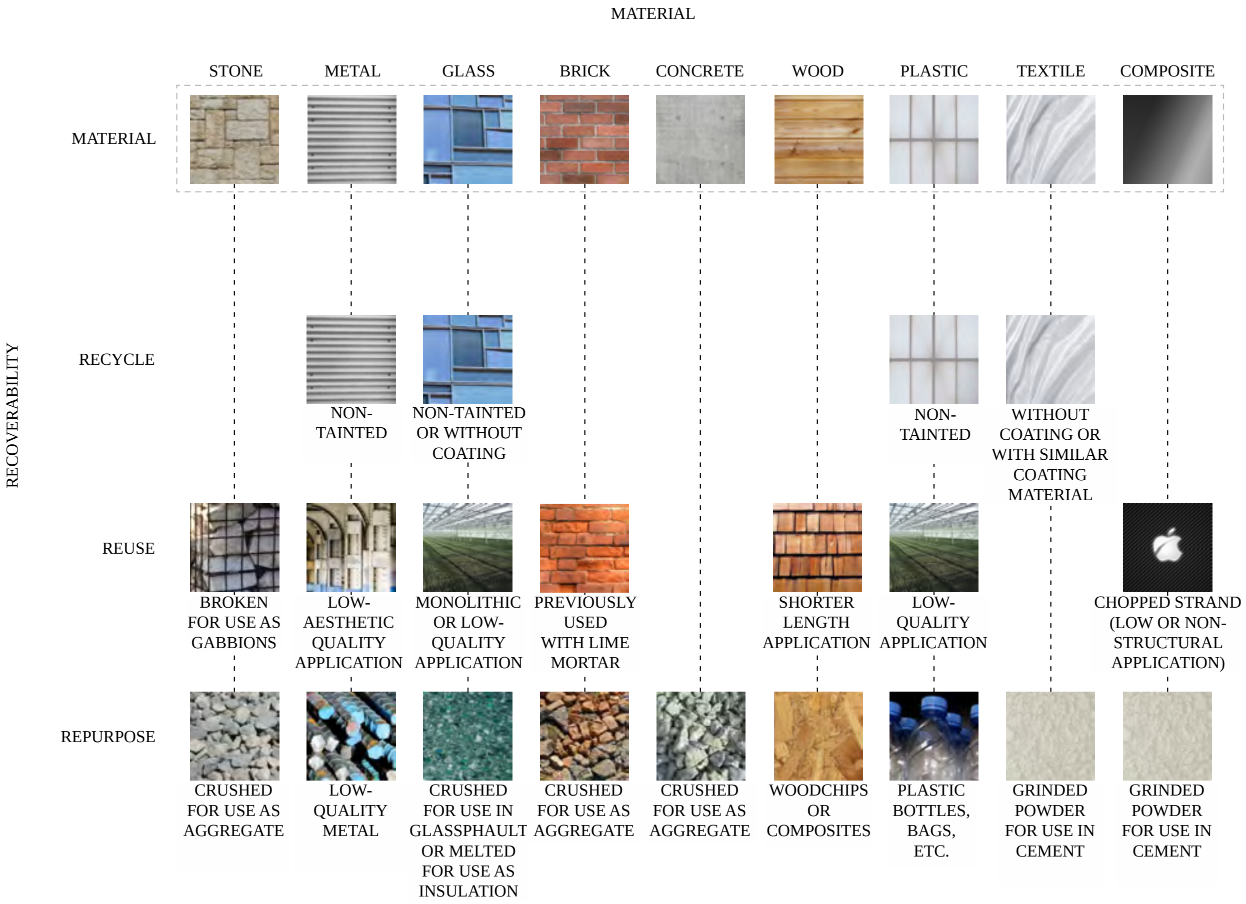

Figure 5: Materials Recoverability Analysis [5]

Metals, as well as plastics and glass, are completely recyclable in theory, but there must be no contamination of the material. As applied to facades today, glass is not recyclable - the coatings applied to the surface of the glass and even the sealants coming in contact with it take away its recyclability. Textiles, however, can be 100% recycled depending on the base material and the coating that it receives.

The reusability of a material is largely affected by the durability of the material and the ability to remove unwanted components. Glass, for example, can be reused as long as the other components of the system can still function. It, like clear plastics, can be used in greenhouse applications where aesthetics may not be a concern. Textiles have not been around long enough to find many options for reuse, but there may be possibilities in outdoor applications where aesthetics are not an item of concern. As long as the fabric has not been damaged, reuse is likely to be possible in similar low-quality applications.

All materials as applied to facades are repurposable in some way. Even textiles can be repurposed through grinding down for use in other applications. Typically a material is better recovered as a recycled material and even a reused one; therefore, Tensiwall is designed to recycle the majority of its components and reuse what remains.

## 3 Design of Tensiwall

### 3.1 Overall Design

The system panels are designed as rectangular for simplicity of manufacture, assembly, installation, and discussion. Since textiles are not transparent, but only translucent, the textile facade requires an integration of glass to provide views through the exterior wall. The typical glazing geometry of windows is circular. The reason for this is that the circular opening creates an even distribution of the forces into the membrane on all sides of the opening and greatly reduces the possibility for tear. The framing member is aluminum, similar to typical curtainwall systems. Similar to most curtainwall systems designed for use in high-rise construction, Tensiwall is a unitized system. This allows for a more precise stressing, better quality manufacture of the panel, faster assembly, and speedier installation once on site. The limitation of the unitized system is the size allowed for the typical facade panel - it is limited in one dimension to 4.5 m (15 ft) and about 10-13 m (32-42 ft) in the other. The system utilizes four layers of membranes (Figure 6).

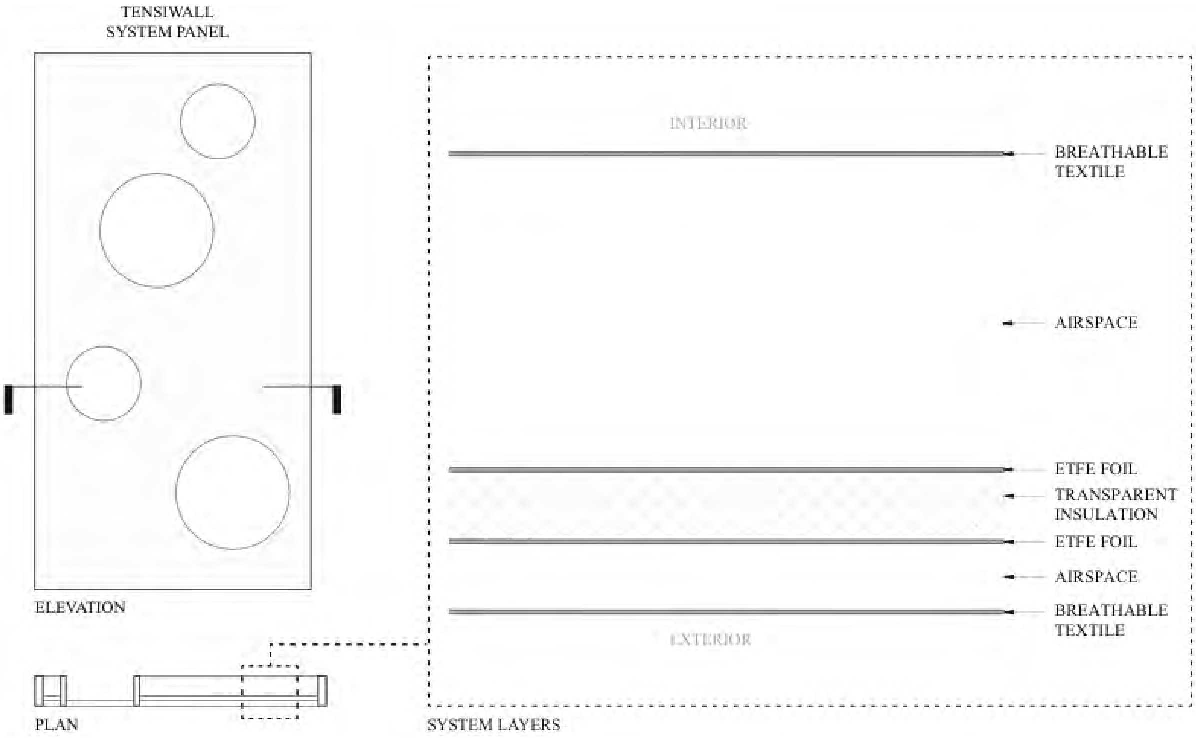

Figure 6: Tensiwall System Layers

The exterior layer of fabric is breathable so as to prevent any water from penetrating, yet still allow water vapor to pass through. This is required in order to allow water that has entered into the first cavity to evaporate back out. The interior two layers are composed of fully transparent plastic ETFE foils so as to allow maximum light penetration. These two layers function as a retainer for the insulation while also performing as a vapor barrier. The distance between the two inner layers can be adjusted to provide more or less space for insulation, depending on the performance requirements. Between the two inner layers is a transparent insulation, capable of providing high insulation values while also allowing natural light through the system. This layer of insulation is kept at a minimum in order to keep the light penetration levels as needed without sacrificing much thermal performance. The interior-most layer of fabric is once again a breathable one, in this case allowing any water that has condensed within the system to evaporate out.

## 3.2 Specific System Design

Tensiwall is characterized by easy replacement of the membrane in case of failure or at the end of its life, minimal use of materials, very thin profiles, minimization of thermal weak points, and high recyclability. All of these qualities have been carefully designed into this specific Tensiwall system, allowing it to excel above other advanced facade systems of today. In order to maximize the thermal performance of this system, the length of the panel is in the vertical direction; in order to further advance the lightweight aspect of the design, Tensiwall uses the lightest materials possible throughout; and in order to push the recyclability of the system, only 100% recyclable materials are used (other than glass).

In order to achieve the thin profiles, this system is designed to function in different configurations for the various stages of installation. Once installed, each panel is attached to the adjacent ones, essentially equalizing lateral forces that the stretched membrane exerts on the frame. Since movement of the panels must happen at the head and sill conditions due to dead and live loads, this idea of force equalization happens only at the jamb conditions. A thinner profile at these conditions means a reduction of one of the weakest thermal points in the system. Therefore the panel is oriented in its vertical position in order to take advantage of the thin profiles, minimize the weaker points in the system (the head and sill conditions), and maximize the thermal performance. The frame, however, must also be stable during transportation when it is not engaged with the adjacent ones; therefore, the concept of Tensiwall is that the frame at the jamb conditions are allowed to rotate. This allows the depth of the jamb to be optimized whether the textile panel is in transport or installed.

As a result, the frame vertical mullions are always aligned to distribute the forces in the most efficient manner. During transportation, the member is aligned with the tension force of the fabric layers. Once installed on the building, the mullions engage each other, allowing the textiles to equalize the forces running through themselves. With this strategy, a very thin framing member can be achieved while still providing enough stability to resist the lateral forces of the tensioned fabric. See Figure 7 for an illustration of the design concept behind Tensiwall.

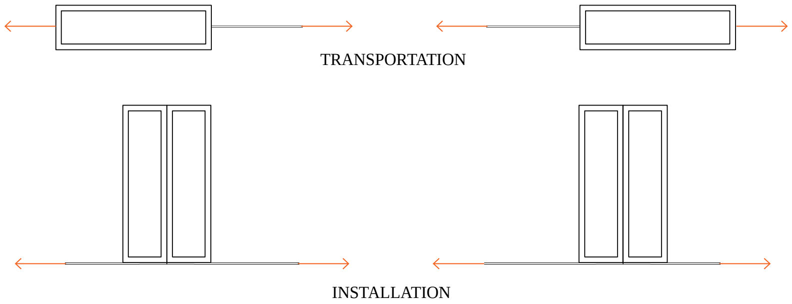

Figure 7: Tensiwall Design Concept

## 4 Comparison

As demonstrated in this work, textiles have the ability to offer an extremely lightweight alternative facade solution. In addition, the textile facade can provide natural light to the interior, while at the same time reduce glare and, through the use of transparent insulation, thermally insulate the interior spaces. Next, textiles offer the possibility of very large panel sizes, reducing the installation time required. And lastly, textiles can provide us with a fully recyclable material. Tensiwall was theoretically applied to a number of buildings across the world and compared in many performance and visual categories (see Figure 9 for a visual application of Tensiwall to an existing building).

Because the Tensiwall system previously discussed (Section 3) was designed for use in high-rise applications, this section compares it to a typical advanced high-rise facade. The comparison discussed is between another existing building facade in the United States, while the Tensiwall facade system was hypothetically applied to the building structure. Table 1 provides a detailed evaluation of the two systems, comparing various performance information as applied to 1 m$^2$ of facade area.

Table 1: Existing Curtainwall and Tensiwall System Analysis (per 1 m$^2$) [3] [4] [5] [6]

| Facade Characteristic | Existing Curtainwall | Tensiwall |
|---|---|---|
| Materials Cost ($) | Insulating Glass: 479<br>Insulation: Included<br>Glare Reduction: 392 | Membranes: 476<br>Insulation: 184<br>Glare Reduction: Included |
| Total Materials Cost ($) | 871 | 660 |
| Total Light Transmittance (%) | 58 | 45 |
| Weight (kg) | Glass: 375<br>Aluminum: 25<br>Insulation: Included<br>Glare Reduction: 25 | Membranes: 6<br>Glass: 94<br>Aluminum: 12<br>Insulation: 11<br>Glare Reduction: Included |
| Total Weight (kg) | 425 | 123 |
| Number of Panels | 0.16 | 0.03 |
| Recyclability (%) | Glass: 0 | Membranes: 100<br>Glass: 0 |
| Total Recyclability (%) | 0 | 75 |
| Reusability (%) | Glass: 100 | Membranes: 100<br>Glass: 100 |
| Total Reusability (%) | 100 | 100 |
| Repurposability (%) | Glass: 100 | Membranes: 100<br>Glass: 100 |
| Total Repurposability (%) | 100 | 100 |

Looking at a very rough materials cost only, the two systems are somewhat comparable, with Tensiwall costing less than the existing one. In fact, the cost can be reduced even further, depending on the type of textile used. This estimate is based solely on the cost of the materials, as the fabric exterior wall system has never been built. However, it does provide a general and informative comparison point between the cost of the two systems. Not only does the fabric facade materials cost less than what is currently standard in the glass curtainwall industry, it also provides more performance due to the insulation that is included. The amount of insulation within the Tensiwall panel can be selected depending on the performance requirements, allowing the price of the system to be customized in order to meet various needs.

Based on research data and multiple thermal simulations, Tensiwall seems to outperform many of the considered “advanced” facades in the present exterior wall industry. Although there are currently no proven methods to analyze exactly how fabrics perform thermally as a building skin, we have rigorously studied them with the methods available. Current results indicate that Tensiwall has a much higher performance at the vulnerable frame conditions and greatly minimizes the chance of condensation occurrence on the interior surface of the system (Figure 8). Additionally, due to the fact that the fabric facade panels are much larger than the existing ones, Tensiwall contains approximately 50% of the linear feet of aluminum compared to the existing curtainwall. This means that even the amount of thermally weak areas within the facade system is reduced by 50%, causing the overall performance to be higher.

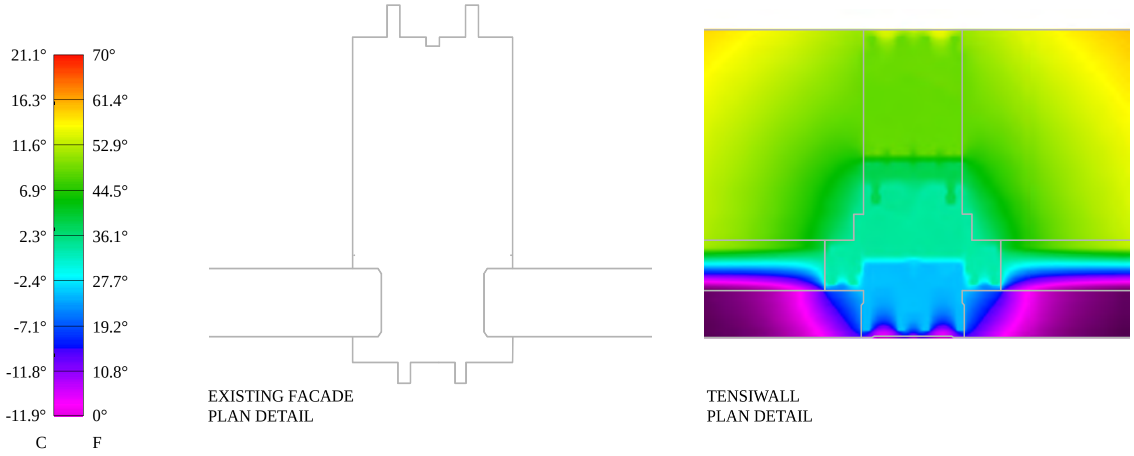

Figure 8: Thermal Performance Analysis

Comparing the light transmission of the two facade systems, this is the one area where the existing skin seems to achieve better results. However, given the amount of natural light made available for use, this set back is not very significant. It is a small price to pay for the total amount of weight removed and the money saved from all other performance areas.

Tensiwall provides an extremely lightweight alternative to the existing facade. Since each layer of the textile facade is under 1 mm thick and has a density which is many times lower than that of glass, a large amount of weight is eliminated. Compared to the existing facade, Tensiwall provides a weight reduction of over 70%. This also means a reduction in the structural elements supporting the facade, resulting in an even greater minimization of material resources.

A larger panel size also means that there are fewer panels to install. In addition, a cleaner facade is achieved, one with fewer seams. And since fabrics are not fully transparent, and the aluminum framing members are much less visible. The existing facade contains exposed aluminum components; this is not the case with the textile facade. Not only does Tensiwall have no visible framing components, it also has much smaller seams between the different panels.

Finally, consideration was given to the recoverability of the two systems. Aluminum is not included in this comparison as the amount varies per system; the comparison taking place considers the facade surface materials only. Since the existing facade utilizes glass for the full building skin surface, it has no potential for recyclability. Tensiwall is fully recyclable with the exception of the glass. Both systems, however, are fully reusable and of course, repurposable.

Figure 9: Example Tensiwall Facade

## 5 Conclusion

Textiles provide us with an extremely versatile material, one that allows for superior performance in an ever more demanding market. Currently, their use is limited to temporary applications and large-scale enclosures; however, with the further development of the use of fabrics and their associated technologies, architecture may begin to see a shift in material processes and construction methods. Utilizing this material for its strengths and designing for its limitations, the textile can become the next innovative material for use in facades.

## 6 Acknowledgements

This work would not have been possible without the assistance and partnership of Curtainwall Design & Consulting, with whom I am currently developing this work. I would also like to thank Professor Werner Sobek, for his guidance throughout the previous stages of research and design.

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# Flexible Structural Facade

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## Summary

Nature educates us about the advantages of flexibility. Allowing larger deflexions can reduce as well the impact of external forces as the development of internal forces. This way of using dynamic behaviour is not common in the building industry. At the Faculty of Building and Architecture at the Eindhoven University of Technology a research group is studying the dynamic behaviour of nature and how we can use flexibility in innovative structural design. We are questioning ourselves: how can we use flexibility as an advantage instead of a disadvantage?

The research includes the study of form-active lightweight second skins façades. This paper describes research projects in which the second skin façade is supported by the main building by a spring / damper system, and design projects where the façade structural is detached from the inner building.

**Keywords:** dynamics, flexibility, lightweight structures, second skin, energy absorbing façade, sound barrier.

## 1 Introduction

Nature developed over billions of years and, by the theory of Darwin, only the fittest organisms survived. This is probably the main reason to study nature in every part of science.
Loads are varying constantly. The wind speed and its direction changes and turbulence occur. There will be rain, snow or even hurricanes and even then a lot of organisms survive with minimum of damage. This is amazing if you think about the lightweight of these structures. Important for their resistance is their flexibility and compliance.
Nature has countless examples of these structures, they are often very complicated. We must and cannot copy nature, we have other demands regarding deflections, isolation and other building properties. But by abstracting the main principles of the use of flexibility we should come to better, lighter and more efficient designs solutions.

Facades and roofs can play an important role in the study of flexibility. They form the barrier between the internal space and the outside climate. In this role of building physics, second skin façades are designed to make use of the natural energy sources as wind- and solar energy, but they do not fulfil a main structural roll.

At the Eindhoven University of Technology several studies are done in which the second skin façade has an influence on the main structural system or is even part of it. In this paper we discuss:

- Façades connected by controlled spring/damper systems that, by its flexibility, influence the load transfer to the main structure of the building. The combination of spring and dampers make it also possible to absorb wind energy.

- Façades as disconnected main structural elements embracing and protecting the inner building. The disconnection allows (structurally) larger deformations making it possible to use form-active lightweight façade structures that reshape under different load patterns.

After classifying the phenomena of flexibility, the first issue above will be described followed by two projects with a disconnected form-active lightweight second skin façade.

## 2 Classification of Flexibility Phenomena

The total field of flexibility through deformation we divide in three main principles with in total six typologies.

a) Principle 1: avoiding load impact.
This principle is about hiding, forming and smoothing. Three types can be mentioned:

| | |
|---|---|
| • reducing surface loading | - changing shape to reduce the area of load impact, |
| • reducing form factor | - changing shape to become more aerodynamic, |
| • reducing friction | - changing skin texture to increase the smoothness. |

b) Principle 2: improving efficiency of material
Materials and shape will react to its loading to improve their efficiency. The following types belong to this principle.

| | |
|---|---|
| • activation of material | - elements are activated by deforming, |
| • configuration of material | - changing the type and flow of internal forces. |

c) Principle 3: spreading load impact in time
The energy of an impulse loading is spread over a certain time period so the maximum value of the force on the structure decreases.

| | |
|---|---|
| • dynamic introduction of forces | - spreading load impact over a period of time. |

When we look at a three in a strong wind, the above given classification can be seen. Large deformations to reduce the load impact (a), change in angle to decrease the bending and increase the axial internal forces (b) and the dynamic behaviour under wind gusts (c).

Figure 1: Flexible behaviour of a tree under wind load.

## 3 Dynamic Behaviour

Wind is often calculated as a static load. In reality it is a dynamic wind spectrum acting on a structure. This raises the questions “How is the dynamic load transferred to a structure?”, “Can we optimize and control this interaction when also the structure is acting in a dynamic way?”.
When a constant force (static) is pushing against a fully encastre mast, the properties of the mast does not influence the internal forces and the foundation forces. When a dynamic loading is acting on the mast the properties of the mast does make a difference. A more flexible mast will reduce the internal loading and therefore the foundation forces. You can take grass moving in the wind as a reference. It would break if reality would be static.

Figure 2: Dynamic response of grass in the wind.

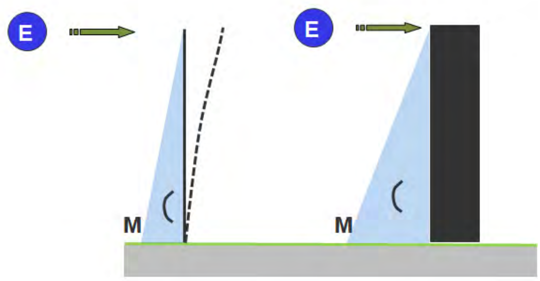


Figure 3: Impact bending moment reduced by increase in flexibility.

Beneath we compare the internal forces, the foundation forces and the deformation of a 10m high mast with different properties. At the top of the mast an impact of a mass of 15 kg with a speed of 10m/s is modelled. The following results are found.

Table 1: A comparison impact on two different mast profiles.

| **Model** | **Mast A** | **Mast B** |
|---|---|---|
| Mast length | 10 m | 10 m |
| Mast profile | Round 150x5 steel tube | Round 250x5 steel tube |
| Section area | 2277 mm2 | 3848 mm2 |
| Moment of Inertia | 600 cm4 | 2900 cm4 |
| Displacement top by 1 kN | 271 mm | 56 mm |
| Spring stiffness | 3690 N/m | 17860 N/mm |
| Kinetic force load – 15 kg at 10 m/s | 750 J | 750 J |
| Frequency | 2,5 Hz | 5,49 Hz |
| Maximum displacement at top | 640 mm | 290 mm |
| Maximum force at top | 2,35 kN | 5,18 kN |
| Maximum bending moment in mast | 23,5 kNm | 51,8 kNm |
| Maximum stress in mast | 294 N/mm2 | 224 N/mm2 |
| Kilograms of steel used | 179 kg | 302 kg |
| Maximum force on foundation | 23,5 kNm | 51,8 kNm |

The deformation of model A is larger, allowing to transfer the kinetic energy of the mass in a longer period to the mast, resulting in a lower force impact, a lower internal bending moments, lower steel usage and lower foundation forces.

Flexibility could result in a lower structural internal force and reaction force, but wind is not one gust but a constant varying loading. The question is how a structure behaves then.

## 4 Mass-Spring-Damper

When short strong gusts act on the structure the structure will react as described above. When a constant wind is acting over a longer period the structure will act more static. But in reality wind is not a single impact but a constant impact varying in time and directions also causing turbulence. The shape of this wind spectrum will influence the behaviour of the movement and therefore the development of forces in the structure. When the wind is a more periodic fluctuation, vibrations will occur that can even accelerate to a high level of deformation and reaction forces. Just lowering the stiffness of a structure by means to limit the internal forces only looking at short impact forces is therefore a risky and not the correct approach.
Also the movement caused by wind loading will directly influence the loading itself and creates an iterative process. This so called fluid-structure interaction is more and more used for flexible structures.

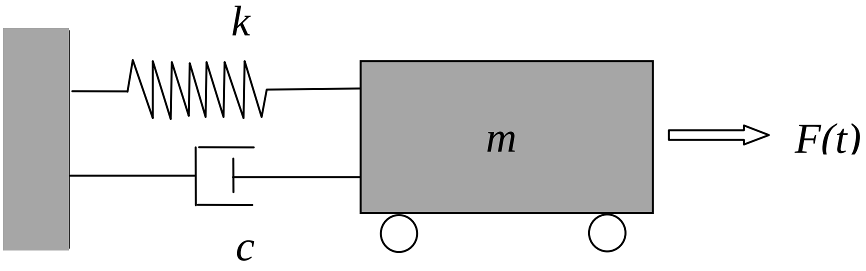


Figure 4: Mass-spring-damper system.

Although it doesn't simulate a wind loading, we started to study a mass-spring-damper system to simulate the structural behaviour of a harmonic periodic fluctuating loading on a flexible structure. When the spring stiffness (k) is endless high a static load transfer is taking place with a reaction force equal to the external load. The displacement and velocity are zero. Varying with the spring stiffness (k) and the damper coefficient (c) many different situations can be created. Limiting the damping c can result in vibrations with large amplitudes. Limiting the stiffness k too much will result in a deflection that increases in time.

Three situations are compare, all three with a mass of 75 kg, loaded with a harmonic wind load with a frequency of 3,14 rad/s and a phase of $-\pi/2$.

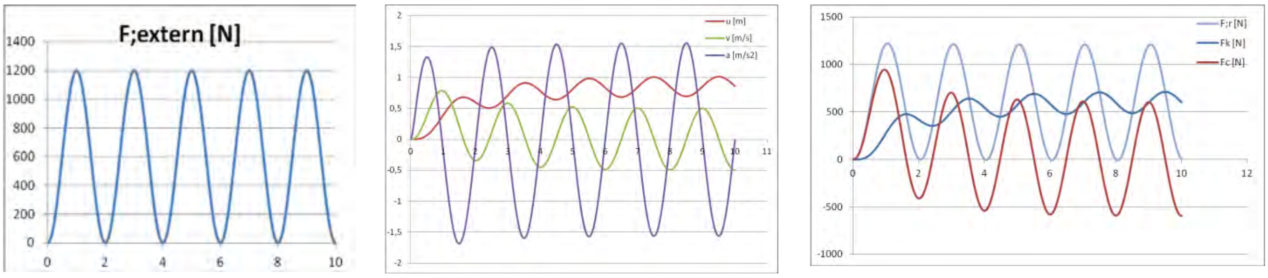
- Situation 1: maximum harmonic wind load of 1,2 kN/m$^2$. The spring stiffness k = 700 N/m and the damper coefficient c = 1210 Ns/m
- Situation 2: maximum harmonic wind load of 0,6 kN/m$^2$. The spring stiffness k = 700 N/m and the damper coefficient c = 1210 Ns/m
- Situation 3: maximum harmonic wind load of 0,6 kN/m$^2$. The spring stiffness k = 700 N/m and the damper coefficient c = 160 Ns/m

The following results are found:
($u_{;max}$ = maximum deflection, $v_{;max}$ = maximum velocity, $a_{;max}$ = maximum acceleration, $Fk_{;max}$ = maximum spring force, $Fc_{;max}$ = maximum damper force, $Fr_{;max}$ = maximum reaction force, $\Sigma E$ = sum of absorbed energy by the damper)

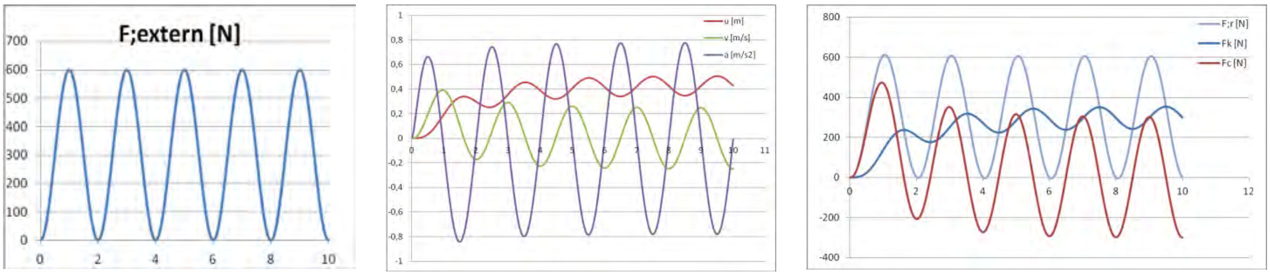
Table 2: Results variation wind loading and damping coefficient on a mass-spring-damper system.

| | $u_{;max}$ [m] | $v_{;max}$ [m/s] | $a_{;max}$ [m/s2] | $Fk_{;max}$ [N] | $Fc_{;max}$ [N] | $Fr_{;max}$ [N] | ΣE [J] |
|---|---|---|---|---|---|---|---|
| Situation 1 | 1,01 | 0,78 | 1,68 | 708 | 946 | 1222 | 1719 |
| Situation 2 | 0,5 | 0,39 | 0,842 | 354 | 473 | 611 | 429 |
| Situation 3 | 1,01 | 1,82 | 5,7 | 706 | 300 | 804 | 2431 |

Situation 1: wind load 1,2 kN/m$^2$,. k = 700 N/m, c = 1210 Ns/m



Situation 2: wind load 0,6 kN/m$^2$,. k = 700 N/m, c = 1210 Ns/m



Situation 3: wind load 0,6 kN/m$^2$,. k = 700 N/m, c = 160 Ns/m

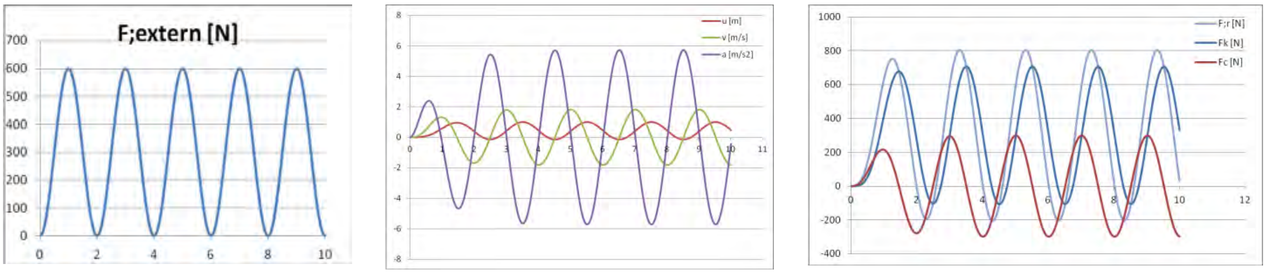


Figure 5: Results of mass-spring-damper calculation with varying  loading and damper coefficient

The results of the research in general show that a harmonic loading will limit the possibility of reducing the internal forces unlike with a short impact force shown before. But interesting in these results is the use of structural capacity to increase the energy absorption by the damper. In situation 2 only half of the maximum deflection and half of the maximum internal forces of situation 1 occur. By reducing the c-value in situation 3 the deflection and the internal force increases within limits but the energy absorption is increased by 560%. This means by making the c value an active value we could optimize the structure to absorb energy.

The graph in figure 6 shows that reducing the c-value would first increase and then decrease the amount of energy absorption. The minimum amount of c= 160 Ns/m is taken limited by the chosen amount of allowable deformation.

In this case the k-value is chosen so that resonance occurs. In case the frequency of the loading is different the values in table 2 will be lower. Making also k an active and controllable value will give us a better opportunity to optimize for minimum displacement and force and/or maximum energy absorption.

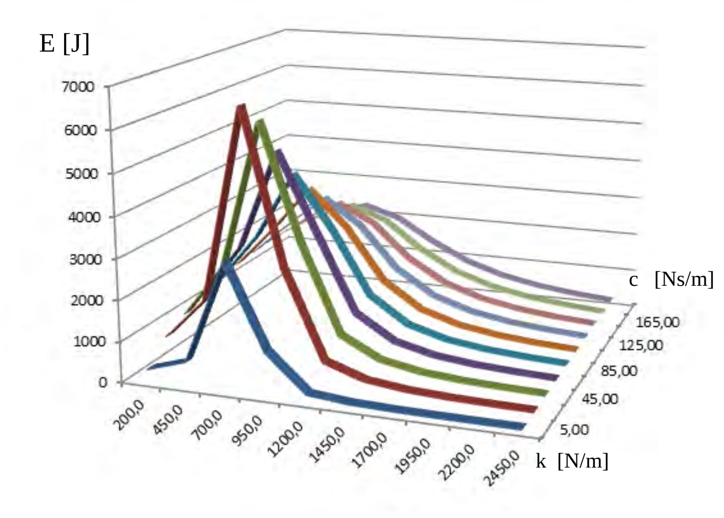


Figure 6: Amount of energy absorption as a function of k and c.

The unused structural capacity is large for lower wind speeds. When we multiply this with the occurrence percentage of the wind it is clear that almost during the full lifetime of a building a large unused structural capacity can be allocated to absorb energy.

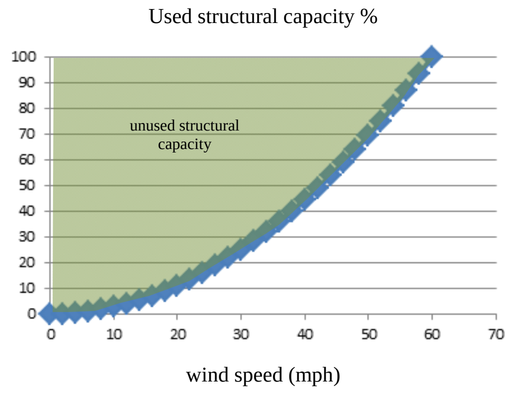


Figure 7: Used structural capacity

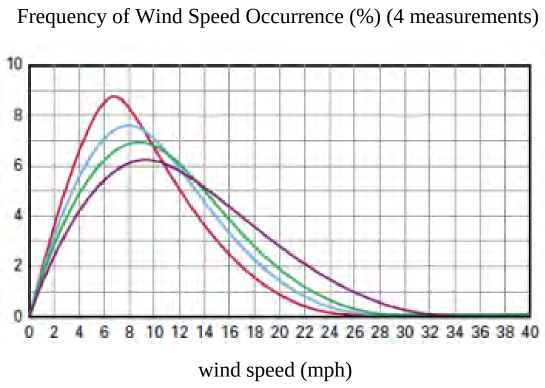


Figure 8: Frequency of Wind Speed Occurrence [5]

## 5 Split of Structural Functions

Buildings are mainly static structures hardly moving in the wind. This is because movement of floors can create unpleasant horizontal acceleration that a person can feel. This restriction in movement can have a high impact on the sizing of the stabilizing structure. In the previous part of this paper, reduction of building forces where discussed by connecting a second skin façade by spring-damper connectors to the building. But would it be a good alternative to design a form-active façade as an independent structure protecting the inner building? The structural independence allows larger deflections in the second skin façade, making it possible to increase the efficient use of materials. In this way the independent façade embraces the internal space, and prevents horizontal wind forces to act on the internal structure reducing unwanted acceleration. This design approach asks for a new way of looking at the overall stability of structures.

In 1971, a feasibility study called “City in Antarctica“ showed us an air-supported building over a city. The building, a climatic shell spanning 2km, protected the buildings underneath from rain snow and wind. At the same time, it also functioned as a first physical facade.

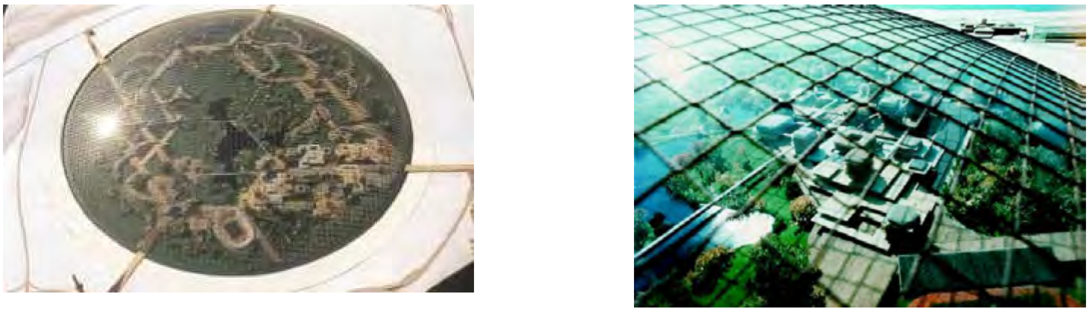


Figure 9: ‘City in Antarctica’; study of Frei Otto, Kenzo Tange en Ove Arup & Partners [4]

Although this is a futuristic design, imagine a building placed within a protected space, embraced by a structural independent skin. The scale is reduced, but the principle stays the same.

The protection against external influences will reduce the structural requirements of the building within, and increase both the efficiency in use and the architectural freedom. Part of the structural requirements have moved towards the embracing structure. Because of the structural independency between the building and the embracing skin, the horizontal movement of the embracing structure is not limited by the value of acceleration that is acceptable to people. Consequently, the allowable deflections and accelerations in the embracing structure can be higher. This opens a whole new field of structural possibilities, especially within the field of using lightweight structures.

Two of the authors design projects based on this principle are presented beneath.

### 5.1 Project 1 – Hyperbolic Office Tower

A 150m high hyperbolic office tower is embraced with a structural second façade, that protects the building in a structurally independent way. The second façade is made from a hyperbolic cable net structure with a central mast, clad with pneumatic membrane elements.

The cable-net structure is a form-active structure that will deform when loaded by wind. This deformation will limit the impact of wind gusts. Internal forces are axial forces only. Together with the high material strength of the cables slender elements are used giving a more transparent façade.

Figure 10 shows impressions of the design of the building.  Columns are only located along the inner floor edge, although the main stability structure is located in the façade.

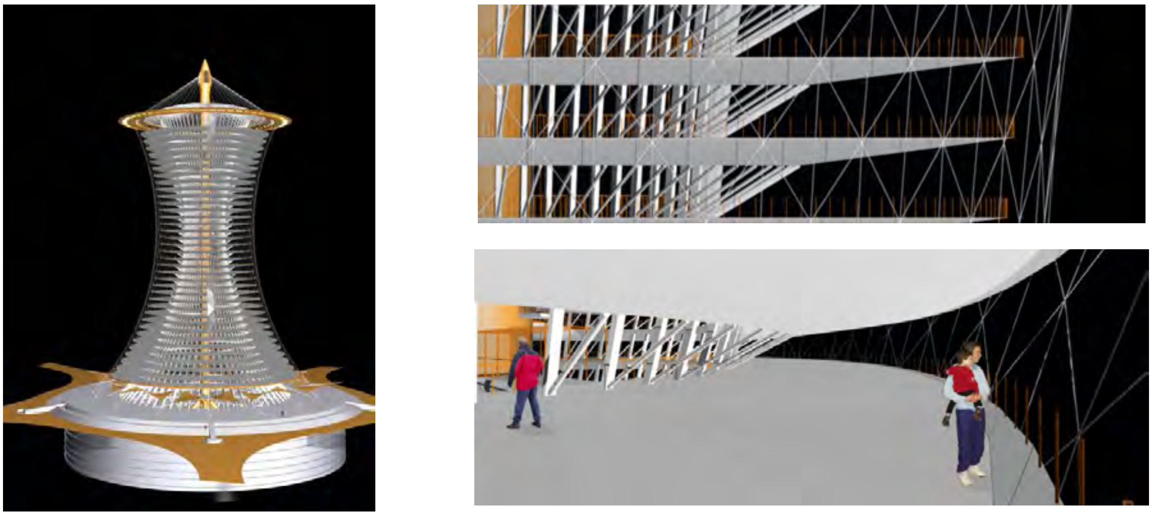


Figure 10: Impressions of the building design [3]

The internal space within the cable-net can be used freely for the design of the independent internal building.

The cable net structure is prestressed to prevent cables to go slack and to reduce the deformation. In figure 11 the deformation is calculated to be maximum about 900mm. Between the second skin façade and the building flexible connections are made capable of bridging these differences in movement, but to control the air movement within the cleft.

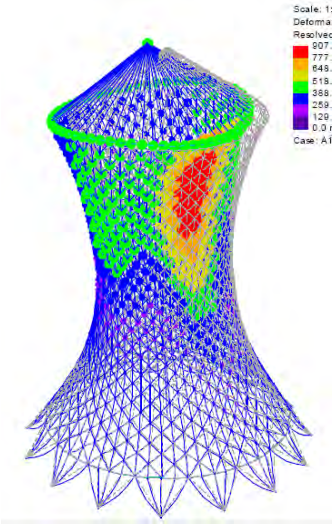


Figure 11: Model of a hyperbolic cable net structure [3].

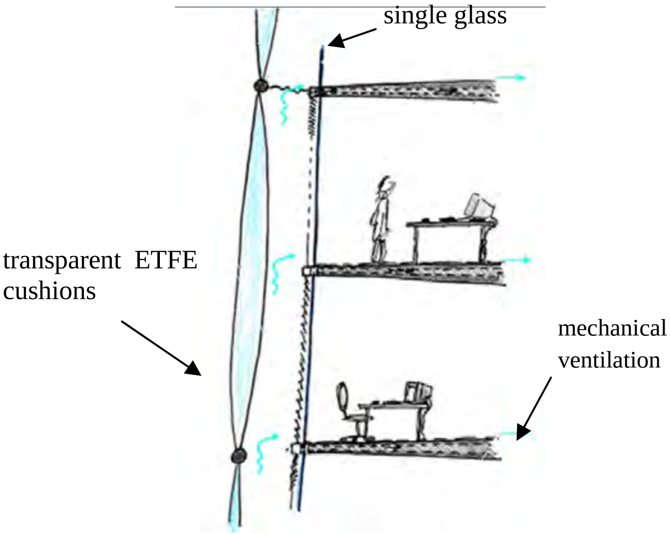


Figure 12: Section of the pneumatic independent façade [3].

Together with the basement and foundation structure the cable net is designed as a structurally closed system. The tension forces in the cable net balance the compression forces in the pylon by connecting them in the basement. This excludes pre-stress forces on the foundation. Figure 13 shows that the internal forces balance in a 3-dimensional way.

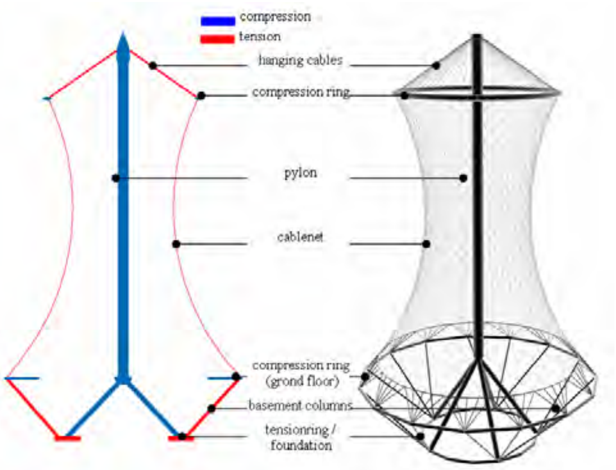


Figure 13: Structurally closed system of the embracing hyperbolic cable net skin structure [3]

## 5.2 Project 2 – Pneumatic Sound Barrier

Occupants of Hoofddorp in the Netherlands experienced for many years noise nuisance from the low frequent sound produced by planes during their take-off at Schiphol.

Natrix is a design for a pneumatic sound barrier that symbolizes the particular Dutch relation between land and water. The noise barrier is a fluent arc of water carried by air referring to the high see level and air as the supporting medium of airplanes.

The 1800m long Natrix has the shape of a snake, built-up with an inner and outer skin. The inner skin consists of pneumatic air arches spacing 6m with in between PVC-coated polyester membrane. On top of the inner membrane water tubes with a diameter of 28mm are placed side by side for sound absorption and as medium to store and transport sun energy.

Figure 14: 3D–visualization birds eye [1]

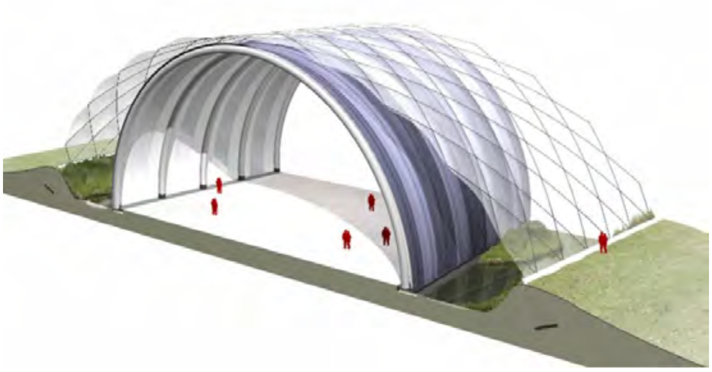


Figure 15: 3D–visualization – section part [1]

The outer skin exists of transparent foil called ETFE strengthened by a cable net and stabilized by an overpressure between the ETFE-foil and the PVC-coated polyester membrane.

The inner and outer skin are fully disconnected from each other. By the application of the two layers, a cleft is created that acts as an insulation layer. Also the overpressure is only between the outer and inner skin, meaning the inside area is not under overpressure and available for all functions.

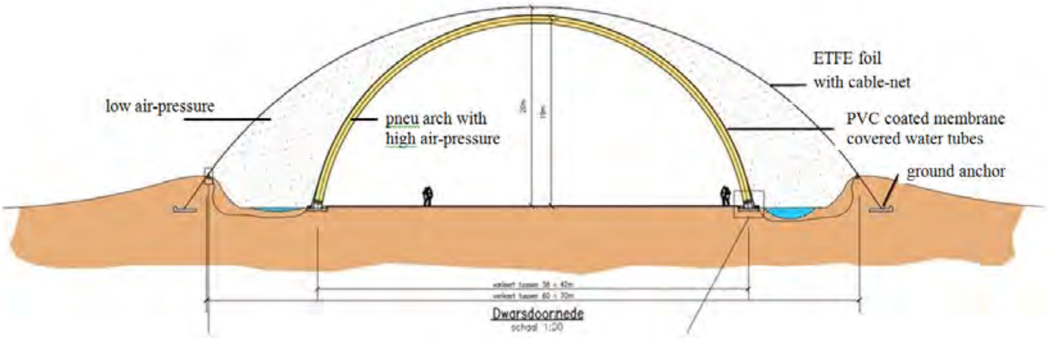


Figure 16: Cross section [1]

Figure 17: Testing the screen of water tubes in the sound lab [1]

The pneumatic build-up of the structure will result in an external membrane that will deform by wind loading, while the internal membrane hardly moves. This is because the outer and inner skins are structurally not connected and deformation differences will be absorbed by air movement in the cleft. Studies at the Eindhoven University of Technology confirm this behaviour.

Because the people inside do not experience the deformation of the outer skin, there is no need for low deformation limitations. This results in a higher efficiency of material governed by strength.

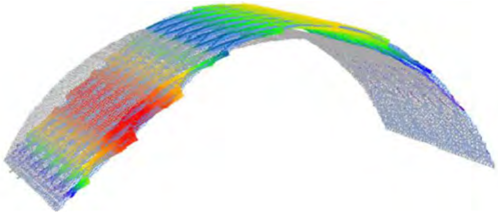


Figure 18: Deformation of external skin loaded [1]

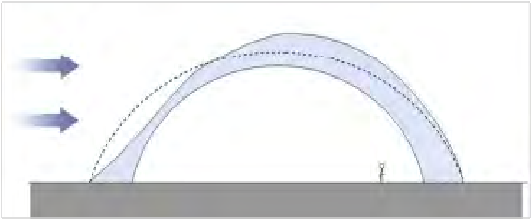


Figure 19: Outer skin deforms because of wind loading, but inner skin hardly moves [1]

Because of the independent behaviour of the external and internal skin and the air movement in the cleft the varying external loading has limited influence on the loading of the internal skin. The pneumatic arches, supporting the internal skin, therefore are mostly loaded with permanent equal divided loading: self weight, internal skin, the water tubes and the air pressure in the cleft. When the differentiation of the loading pattern on an arch structure is limited, the arch can be designed as an optimum compression arch with limited bending moments. This will make it possible to design slender and mostly axial loaded pneumatic arches.

## 6 Conclusion

The façade can play an important role in building physics, but also structurally on how a building reacts on a wind loading.

A second skin façade is discussed that is flexible connected to the building, symbolised as a mass-spring-damper system. Flexible structures reduce the internal forces and reaction forces in case of a short impact. But with a harmonic loading they can increase to a level higher than in a static situation. Wind is a constant changing dynamic load with both gusts and harmonic fluctuations. The active control of the spring and damper stiffness connecting the façade to the building, can give us better control over the force development but can also give us the possibility to optimize wind energy absorption.

To further reduce the loading on a building two designs are shown in which the second skin is fully independent of the main building. Between a fully fixed second skin façade and the fully independent façade a large variety of interactive design options between the façade and the building are possible optimizing forces and energy absorption.

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# An Instant Cost-Estimation Tool – Assistance to Designers of Form-Active Structures

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## Summary

Architectural design is mainly driven by the available budget. So for the designers' intentions and ideas to be realized, it is crucial to have knowledge about the expected costs and the economic influence of various design parameters already at the very beginning of a project.

A software tool that gives the designer an instant cost estimation of the current design could provide valuable knowledge about how to optimize the costs and bring the original design intention into reality. Surveying and quantifying the parameters within the designer's sphere of influence was the basis to create an interactive tool integrated into the "Formfinder" software package – a design software for form-active structures [1].

**Keywords:** Membrane Architecture, Innovative Design, Formfinder Software Tool, Cost Estimation, Value Finder

## 1 Introduction

In the context of membrane architecture, engineering and design are two disciplines which are complementary to equal parts. In engineering, design is a component of the engineering process. Engineering on the other hand assists design, with emphasis on function and the utilization of mathematics and science.

The American Heritage Dictionary defines design as: "*To conceive or fashion in the mind; To invent,*" and "*To formulate a plan*" [2], and defines engineering as: "*The application of scientific and mathematical principles to practical ends such as the design, manufacture, and operation of efficient and economical structures, machines, processes, and systems.*" [3]. Both are forms of problem-solving with a defined distinction being the application of "*scientific and mathematical principles*". Scientists at Xerox PARC [4], however, made the distinction of design versus engineering at "*moving minds*" versus "*moving atoms*". [5]

These definitions are the base for understanding the importance of design and for making all parties of a design team being aware of the integrated process of design at a membrane project. The foundations for successful projects are designers with extensive knowledge in as many of the important disciplines for realizing tensile structures as possible, such as design, engineering, installation, and costing.

Due to the fact cost estimation is often neglected in the design stage, time and money are spent although the realization of a building project is not finally decided at this stage. In many cases economic aspects are reason for cancelation of projects. Architectural design is often influenced by the available budget. Therefore the knowledge about the parameters for cost optimization is beneficial for designers. Rigid structures may excuse unfavorable design through local strengthening measures. The sensibility of non-rigid, flexible, form-active structures in contrary is one of the main cost driving factors. Small adjustments and modifications on the design may significantly influence the total costs of the whole project.

The more accuracy is required from cost estimations the higher its level of complexity gets. The number of parameters to be considered increases potentially. Every single factor's potential cost impact has to be evaluated.

At this point two types of parameters need to be distinguished; parameters able to be determined and such which only can be valued either by chance or by experience.

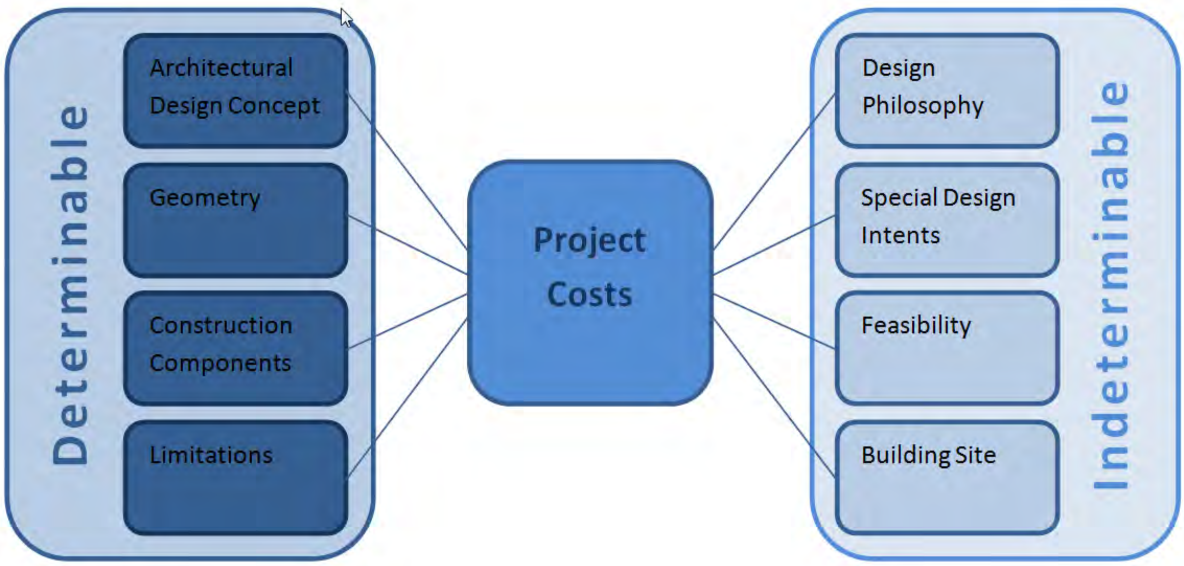

Figure 1: Examples for determinable and indeterminable parameters for cost optimization

Examples for "Determinable Factors"

- Determinable architectural design concept and intention
  (facts that can be described by designers, e.g. by sketch, by reference projects or verbally)
- Geometry described with physical models or CAD tools and readability of the structure
  (e.g. four-point sail, ridge-valley sail, high-point sail, etc.)
- Construction components and details
  ("element catalogue", alternative solutions for every component, curvature of membrane, edge cables, materials)
- Economical, legal, and geographical limitations
  (available budget, building law; external loading like wind load, snow load, and dynamic excitability; general climate conditions like weather, temperature, and local climate characteristics)

Examples for "Indeterminable Factors"

- Indeterminable architectural perception and requirements that are not part of the design concept
  (individual "design philosophy" of architect/designer)
- Special design intents
  (use of new materials or techniques, first of a kind-project)
- Feasibility of the structural concept
- Building site and infrastructure
  (construction site, accessibility of site, infrastructure, soil conditions)

As a consequence designers are able to influence the material and production costs of a membrane project the most. Not determinable parameters, however, are not directly in the sphere of influence of the designer but still can be controlled up to a certain extent at the very beginning, right after the project idea. So the design’s impact on delivery costs, installation costs, and overhead costs on the other hand is minor as they strongly depend on the parties (companies) involved but are not to be neglected.

Within the group of determinable factors substituting parameters can be defined. This subgroup contains alternative (design) solutions which can be chosen for geometric or even economic reasons without having an impact on the overall design intention.

Anticlastic surfaces with a homogeneous and well-proportionate curvature k ($k = (1/r_1) * (1/r_2)$) give higher mechanical stiffness to the membrane and further to the whole structure. As a consequence the weave needs less pretension and the deformations due to external loading are less. This results in smaller internal stresses and the material fatigues slower. Furthermore due to lower stresses and therefore smaller reaction forces in the fixation points, optimization of the adjacent structural elements and wider spans of the membrane are possible.

In general higher strain and therefore higher stresses in the membrane may require stronger material. More tensile strength is always directly related to more weight per surface area and bigger fabric thickness. Both factors have an impact on fabrication as well as on installation.

The settings of the welding machines e.g. strongly depend on the thickness of the material. The thicker the fabric the more power is needed respectively the longer it takes for achieving full load bearing capacity of the seam. The increase of the internal stresses result as well in wider seams which certainly influences the welding process in the same way.

The classification of membrane material in different Types according to their tensile strength allows as well a differentiation by the surface weight. A Type 5 material is about twice as heavy as a Type 1. From this follows that stronger fabrics may be more bulky at handling. Furthermore different fabrics require different care in general. PVC/polyester is way more flexible and less sensitive to folding than e.g. PTFE/glass fabrics.

This can result in more man needed to move the membrane, in packing in bigger pieces for the same membrane area, or the sail needs to be split into smaller bits. The more elements have to be joined on site the more time and manpower is needed. From an economical point of view the highest aim should be to prepare installation in the workshop as far as possible. The impact on transportation and installation costs is evident.

As advantageous as a big curvature is on the whole structure, more curvature means as well more time and effort in fabrication. To avoid wrinkles and to achieve uniform surfaces with less polygonal appearance, strongly curved geometries need to be assembled of membrane stripes with smaller width. The same applies to edge cables with very small radii. Welding of strongly curved cable pockets requires special care at fabrication. For avoiding wrinkles the stress-strain behavior needs to be as homogenous as possible. Therefore big variations of the warp and weft directions, meaning big differential angles of the weave of two adjacent membrane pieces, are to be avoided. For most homogenous orientation of the membrane material, the pocket needs to be assembled of small parts welded together.

When tangential forces become large in edge cables, the caused radial stress in the fabric could become critical. In this case it could be better offsetting the cable from the membrane’s edge and linking it at intervals by a sequence of straps and clamp plates. This option is used mainly for PTFE/glass fabric but also for PVC/polyester where edge spans are larger than 20m. [6]

Foundations have to be considered in the cost calculation but potentially bear high vagueness as often the final soil situation is not known before the detail design. Especially on extensive projects various foundation concepts may be required, as the local soil configuration may differ at the individual anchor points. For this reason minimizing the reaction forces always has to be the main aim. Whether a tensile roof is anchored in an already existing structure or in the ground no matter the foundation concept, high forces result in additional costs at all times.

Therefore the arrangement of struts and their guying cables is a very critical issue. The smaller the angle between the compression and tension elements is, the higher the internal forces in these construction components get. In case the available space is limited, maximization of the structure's covered area becomes a main goal. For the corners to be the closest possible to the boarders of the construction site, the angle between struts and guying cables will end up being minimized. For avoiding difficulties with high anchor forces, restraint columns could be a considerable alternative. But one has to be aware, the lightweight characteristics of membrane structures will end at soil level. Moment bearing foundations are by all means heavy-weight.

But to give an additional input on architectural design, restraint columns do not need to have structural purpose only. They could as well be part of the overall design concept. Besides the engineering requirements, it is up to the designer to transform a restraint column into (e.g.) a sculpture and make it part of a story (about the architectural intent).

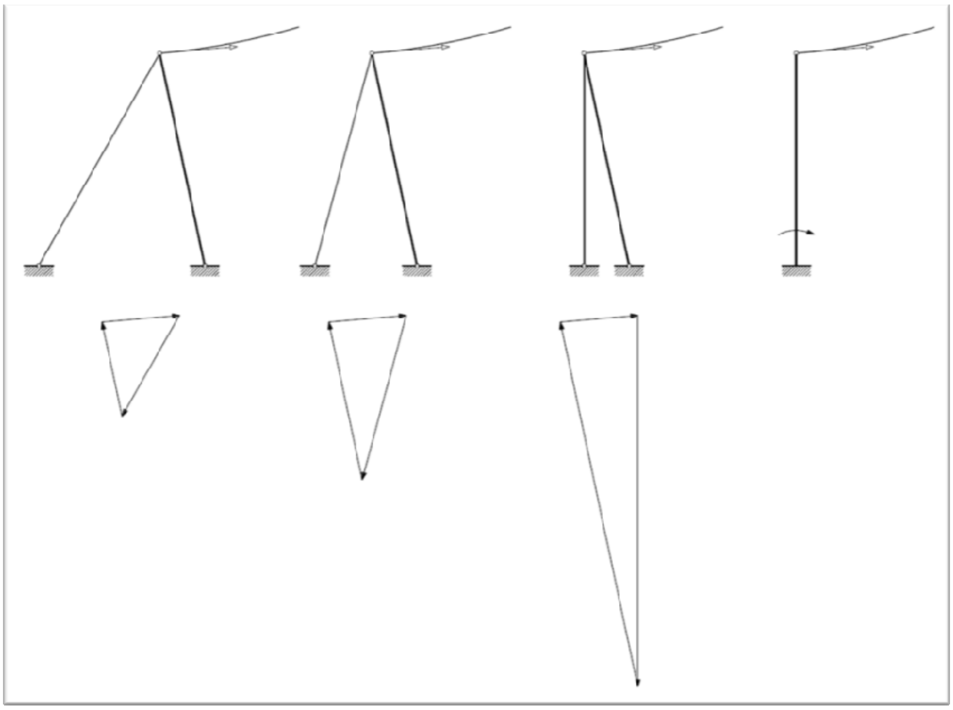

Figure 2: Different arrangements of struts and guying cables and the corresponding triangles of forces

To reduce anchor forces sometimes it may be an option to amend the design and add additional anchor points while keeping the overall appearance similar and knowing more foundations are needed.

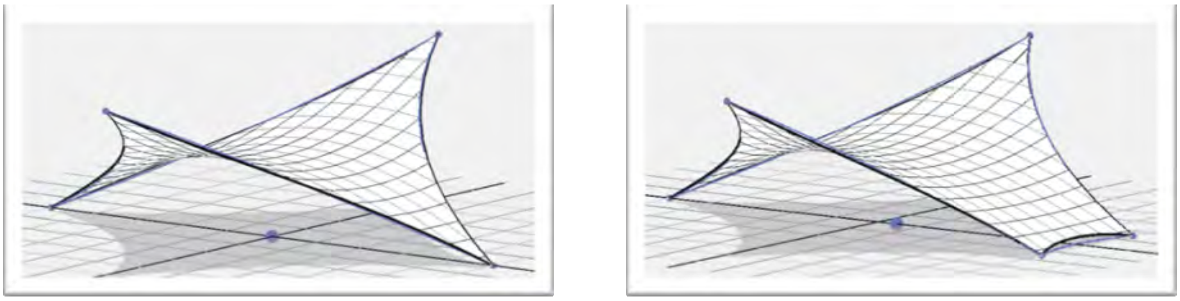

Figure 3: Implementation of an additional anchor point to reduce the anchor forces

## 2 The Tool

Goal of this tool is to visualize cost factors and to support designers to keep their own design by providing a set of positive arguments to convince the decision makers of the design intention and the design concept.

In general the process of designing consists of two steps: quantification (more ideas) and qualification (reduction of ideas) [7]. Following this approach it is necessary to decide over the final design up to a certain depth before first cost calculations can be performed. Precise cost estimation is a highly time-consuming and complex task. For conventional rigid constructions a detailed structural analysis under consideration of various aspects such as aesthetics, shape, materials, legal restrictions and requirements, etc. is needed. For non-rigid structures this complexity maximizes, since additional factors induced by the flexible nature of the membrane and its components occur; factors like additional restrictions at selecting materials, more complex aerodynamic characteristics, or influence of dominating weather conditions.

Therefore this task calls for knowledge of a domain specialist capable of handling all of these cost parameters. This however decouples the designer from the process chain. Consequently the lack of this valuable information often leads to initial designs being distorted significantly. In the past many projects failed due to this simple fact known in many engineering domains; the later design mistakes are detected in the process chain, the more expensive it may get to correct them eventually.

Our cost estimation tool is addressed in particular to designers. Surveys have shown most designers consider estimation deviations of 30-40 % to the final project costs to be acceptable. This tool allows a significant simplification of the calculation process. Reduced complexity in return increases the understanding of the cost-driving factors and the designer will find the optimum shape and design faster.

Our software program is an intelligent, self-learning tool based on databases and algorithms found on basis of theoretical design studies and of comparisons of pre- and post-cost calculations of real projects considering factors like shape, size, curvature, and material among others.

The given values, respectively the costs, are transferred into absolute values [€ / $m^2$ / year] directly usable for cost estimations or into a dimensionless factor [%] for studying and teaching purposes.

Nevertheless the user has to be aware of the limitations of this cost estimation tool. According to the parameters mentioned above the value given just reflects the production and material costs of a membrane structure. Factors like the foundations, accessibility of the building site, legal requirements, installation and geographical location only can be measured up to certain extent. Anyway the designer has to be aware of the influence of these factors.

Materials are very likely to vary strongly between different materials and products. The variation of the market prices for certain materials is also not to be neglected. Production costs on the other hand depend highly on the construction details used and the fabricator’s knowledge and technical capabilities. This is why the database is designed to be open for amendments and adjustments by the user.

In this context, also the time factor is important for evaluating the costs as for temporary/single-use roofs the time of usage differs from permanent roofs significantly. The latter remain installed over the whole material life expectancy. Therefore in terms of accounting the amortization of the whole structure runs over a longer period of time. So if a temporary construction is considered to be reusable (i.e. consideration of different load scenarios or adjustability to variations in the foundation concept) and this thought is reflected in the detail design, costs can get reduced significantly.

In a first step our model will be applicable to the four base shapes:

- four-point sail
- high-point sail
- beam supported sail
- ridge-valley sail

By default this cost estimation tool only allows for a low accuracy of the actual value. These settings reflect the most common design parameters of the reference projects used for finding the calculation algorithms. It is up to the user to narrow down the degree of detailing in the project specifications. Additional information on the design can be added. The more data is provided the more accurate the estimation gets.

In our (unreleased) software package a control panel is located on the right hand side of the screen. It contains various sliders which can be used to adjust the importance of individual factors.

On basis of a product database design parameters and material properties can be preset; involving decisions on the membrane material, whether cables or belts are used at the edges or corner details are made of standard products or individual design solutions.

Based on the geographical location and the Eurocodes the wind and snow loads for certain countries and roof types can be added automatically. In a first step loading can be generated for simple standard shapes only.

Besides the steadily growing database of integrated codes and standards, products and materials, individual calculations outside these pre-settings are allowed for.

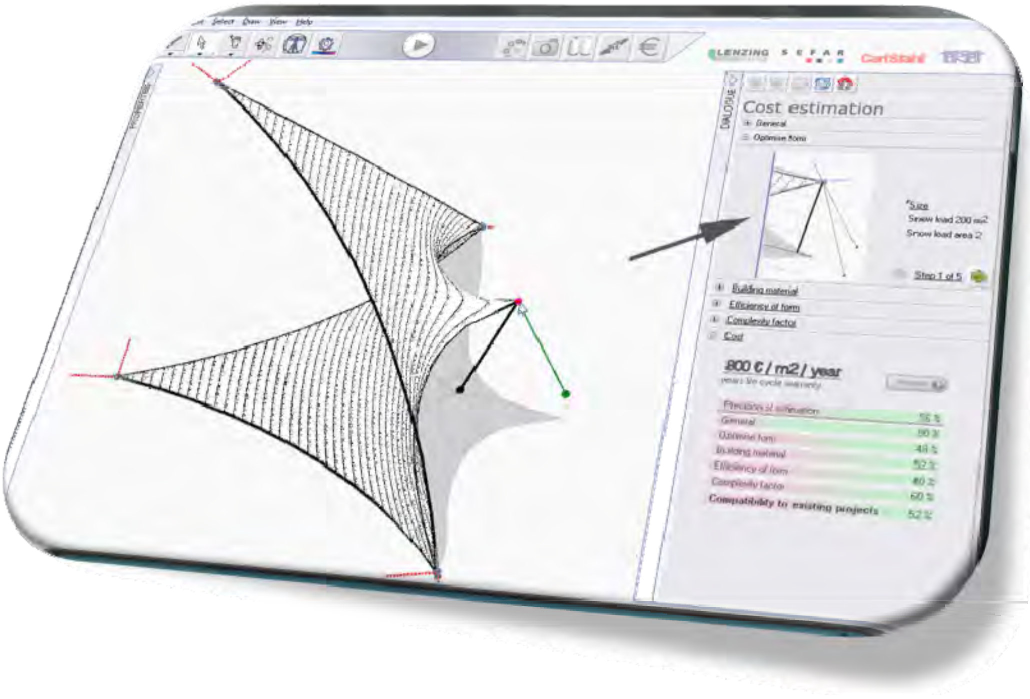

Figure 4: Screenshot Formfinder Value Finder

## 3 Conclusion

We gave a brief overview of how costs are influenced by the design and have presented a cost estimation assistant that targets designers of form-active structures. It can be used either as a pure calculation tool for first estimations or if desired expose educational facets to submit better understanding of the involved cost factors and dependencies to the designer. Even while kept simple, we believe the estimation mechanism to be powerful enough to present estimations within a range of accuracy of 20-30 %. Due to its ability to extract knowledge from existing/finished projects and to feed this knowledge back to the project database we further believe estimations to become gradually more accurate, when more projects are calculated and so more data of cost estimations and their corresponding real project costs is available.

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