Microperforated Glass

Turning the innovation into a marketable product

Olga Tourlomousi

Delft University of Technology
Faculty of Architecture and the Build Environment

TU Delft

Master Thesis

2017

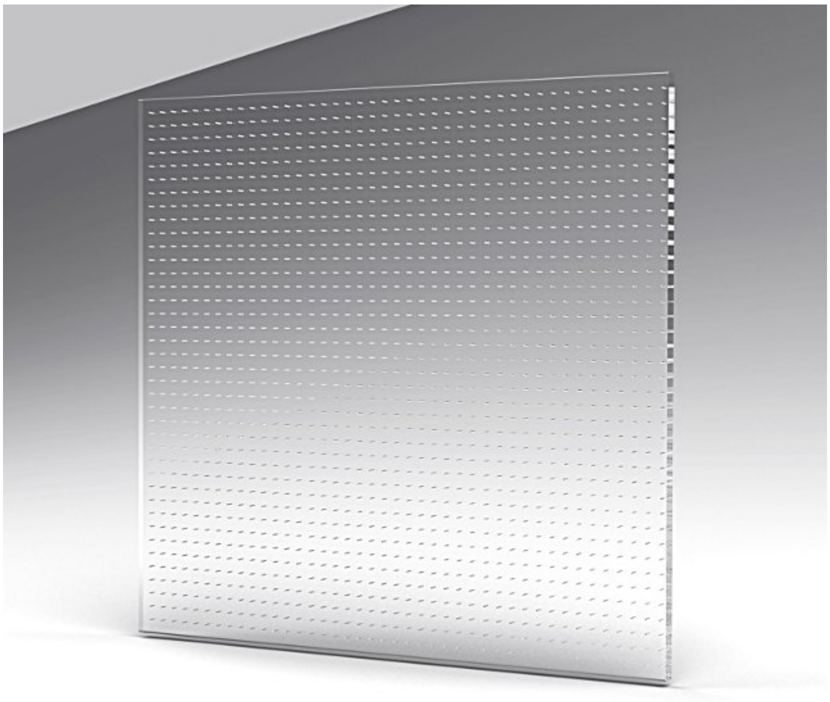


Photo source: http://s-plasticon.gr

Microperforated Glass

Turning the innovation into a marketable product

Olga Tourlomousi

Delft University of Technology
Faculty of Architecture and the Build Environment

Master Thesis
2017

Mentors:
Tillmann Klein
Martin Tenpierik
Ate Snijder

External Examiner:
Ab Straub

MSc Architecture, Urbanism and Building Sciences
Track Building Technology

Brief Contents

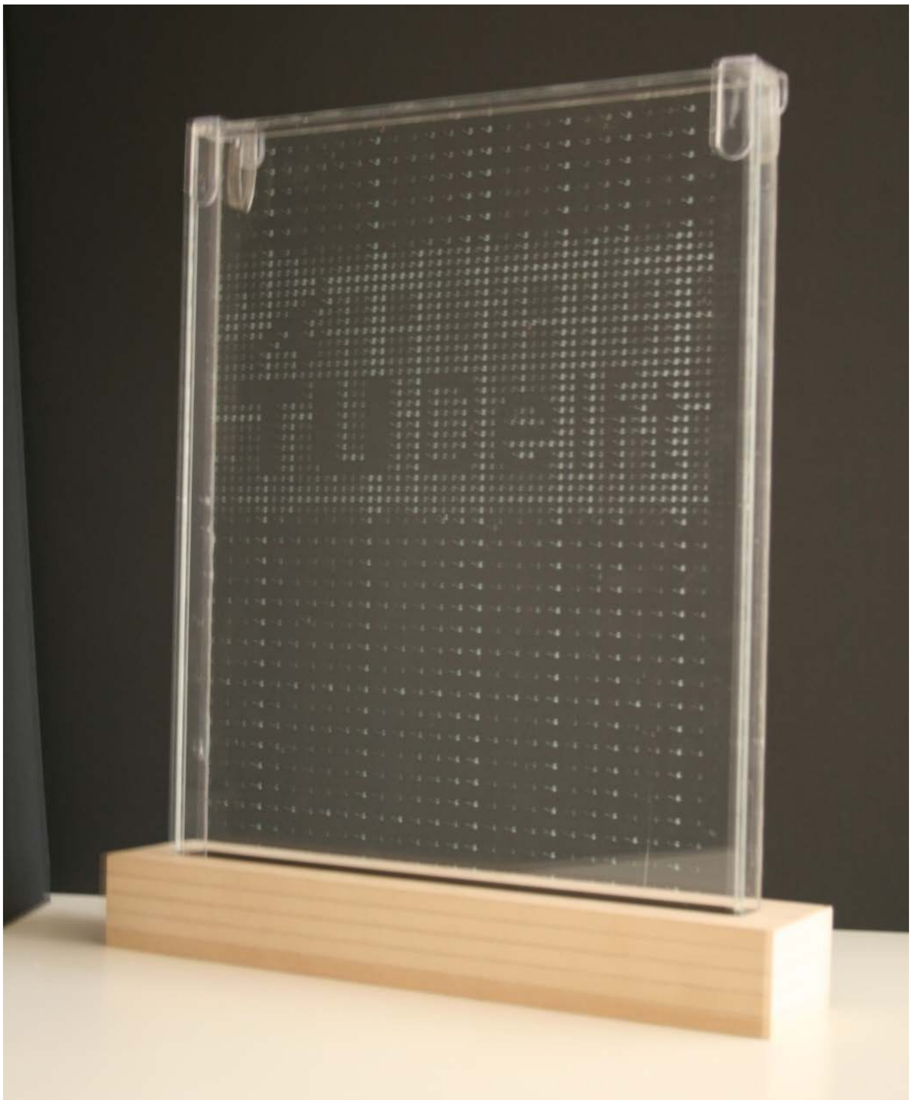
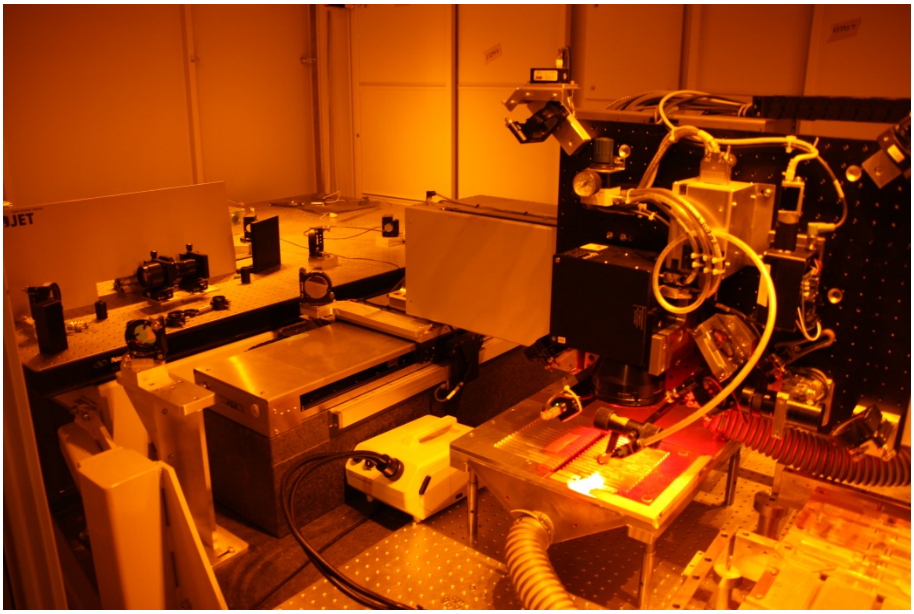


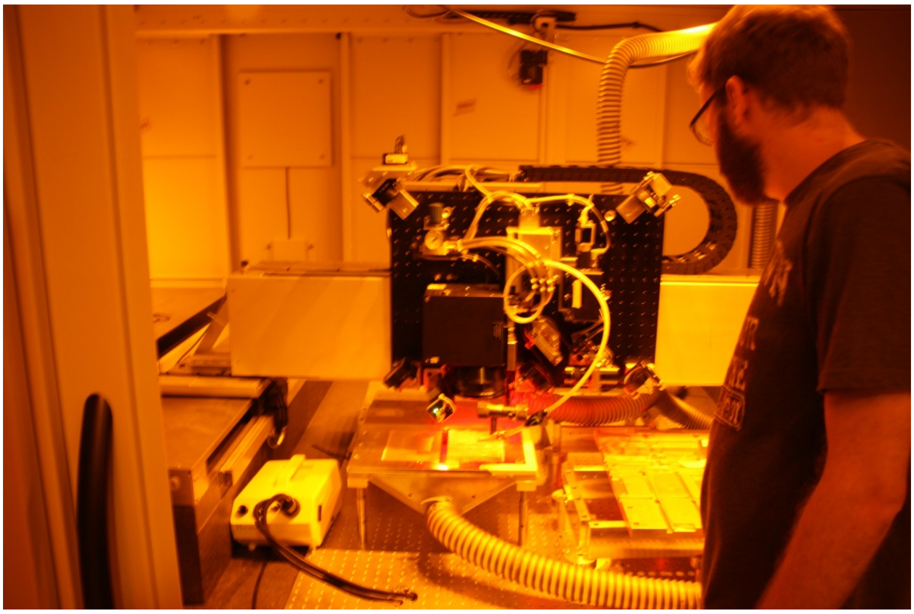
Figure A-1 Microperforated glass prototype which was fabricated in 2016-2017 for the needs of the 4TU.Lighthouse research program “Sound Absorbing Glass”. (Photo is taken by A. Struiksma)

Abstract

The potentials of glass as building material are continuously researched by experts in the field. With this thesis, glass, as sound absorber in room acoustics is presented. This function can be achieved by exploiting microperforation to glass, which is still a complicated and expensive process today. The innovative concept of a glass sound absorber was proved in 1960s and since then, no commercial product exists in the market. The objective of this research is to study how this innovation can finally become a marketable product. To do so, a structured method is followed which is divided in two phases. Firstly, the potentials in the market, the technical capabilities and limitations of the microperforated glass technology are researched in detail. Concluding from there, that the cost of production is too high, however, the advantage of great quality allows for customized solutions as façade-front applications. Following this guideline, the concept of “Sound absorbing glass louvers” is developed, based on market needs. The product is demonstrated in detail for the pilot project the “Co-Creation Centre”. The advantages of easy maintenance, flexibility in performance and customizability define the product success.



a.



b.

Figure A-2 Photos of the NS-green laser machine getting ready to microperforate glass. The photos are taken during our visit in 4JET; a company based in Germany specialized in micromashining technology. (Photos are taken by A. Struiksma)

Contents (Extensive)

- Chapter 1 -

- Chapter 2 -

- Chapter 3 -

- Chapter 4 -

- Appendices -

Research Definition

CHAPTER ONE

1.1 Introduction

This chapter introduces the topic of the thesis which refers to **the product development of an innovative glass sound absorber made out of the technology of microperforated glass.** The feasibility of producing a microperforated glass panel and the interest of the market will be initially assessed in order to decide the final product design. The assumption which exists is that the fabrication of a microperforated glass panel is limited by the brittleness of glass and the high cost of the process. The structure of the thesis follows methodologies from product development literature. The selected pilot project is the “Co-Creation Centre”, an all glass cubic lecture theater to be realized in TU Delft campus. A detailed product solution will be demonstrated in this building at the end of the product development process.

1.2 Background

Acoustics is an engineering discipline of great importance which contributes in a sustainable environment of good listening conditions, both indoors and outdoors. Focusing on **room acoustics** in this research, t**he problem is identified on how to manipulate the reflections of the sound from walls, ceiling and floor so as to ensure optimal indoor acoustical comfort.** The so called, **absorbers and diffusers** are installed at room boundaries and affect the way the sound propagates and is ultimately perceived by the user. For this purpose, a big variety of products exist in the market. These products differ in technology, performance and morphology. Depending on the function and the form of the space and on the architectural intent the suitable **acoustical product** is selected. Acousticians together with architects and designers are those who primarily are involved in the decision making process. Due to the increased general expectation for better performance, better visual aesthetics and more sustainable solutions, researchers and manufacturers are challenged in developing innovative acoustical materials used as absorbers and diffusers.

1.2.1 Towards Invisible Acoustical Room Performance

There are few trends in contemporary architecture, which underline the ever more growing **demand for quality transparent acoustic solutions** for building interiors.

First trend is the fact that the portion of glass facades and ceilings in office and public building projects is growing. Glass is no longer only used as infill material for conventional windows but as a primary material used to build beautiful, high, **wide glass facades and roofs**. However, the hardness and the stiffness of the material cause the repeated reflectance of the soundwaves, resulting acoustical problems such as high reverberation and echoing. The problem becomes more critical in concave glass surfaces where the sound is concentrated to the center of the curvature.

Second trend is the wish of the architect to use **bare sound-reflecting surfaces** made out of concrete, natural stones or wood neglecting acoustical implications. Any opaque solution such carpets or curtain that would cover the architectural finishing of the exposed material is declined.

Nowadays, there is another trend which calls for acoustical solutions that occupy **minimum space** and allow for **design freedom**. The attempt of the developers and architects is to increase the business value of the spaces by designing for maximum useful area and by preserving flexibility and adjustability in transforming the interiors. As a result, absorbers which are permanently mounted, opaque and require big thickness, like conventional porous materials do, are in this case less economical and undesirable.

Summarizing the above comments, two are **the main conclusions**:

a. The extensive use of materials with **hard reflective surfaces** like glass, concrete and natural stones reduce the acoustical room comfort. The preservation of the visual finishing of the material is the primary concern of the architect.
b. Maximum rental space and flexibility in transforming offices in minimum cost is the **new business model**. This means that acoustic material should occupy less possible space, be effective and doesn't add extra maintenance and replacement costs in case of change.

1.2.2 The Transparent Absorber: From Polymers to Glass

In projects, where for instance, extensive glass surfaces are used, the architect tends to do concessions in the concept, in order to satisfy the acoustical requirements. Such concessions would be either to replace glass components with non-transparent, sound absorbing elements, or by placing opaque absorbers or reflectors near the glass surface (see Figure 1-1,1-2). Transparency, lighting and unobstructed view through glazing are lost due to the opaque acoustic material.

Figure 1-1 Acoustic curtain in front of glass, source: http://newatlas.com/

Figure 1-2 View of Beurs van Berlage in Amsterdam, source: http://www.telegraph.co.uk

In such cases, transparent absorbers suspended or integrated in building components such as the façade would satisfy better the architectural demand.

A variety of transparent or translucent absorbers exist currently in the market. These are clear microperforated plates or foils made out of **polycarbonate, PETG, ETFE or fabrics**. Figure 1-3 shows a selection of them. However, these materials present few drawbacks, which could hamper their widespread application in buildings. **Plastics are flammable, scratch easily and become slightly yellow or deform within the time.** Additionally, the clearness of plastic is reduced at oblique angles due to **white edge effect of the holes**.

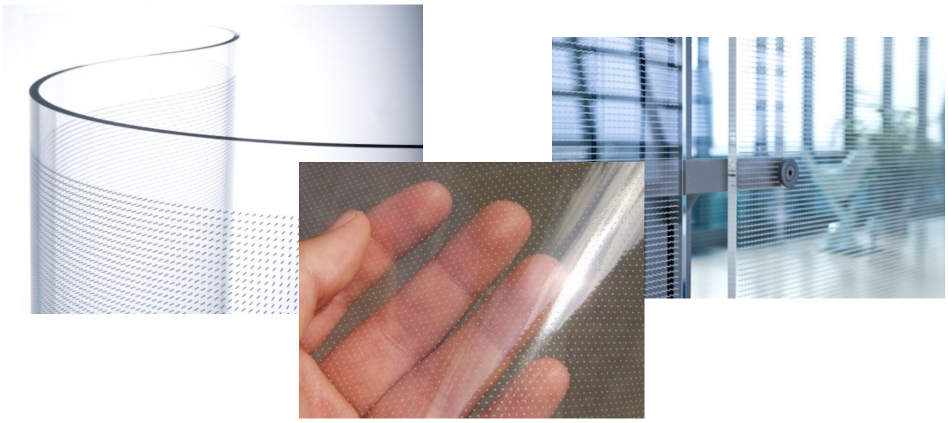


Figure 1-3 Various transparent sound absorbing materials that exist in the market and are made out of ETFE, plastics or acrylics.

The **lack of high quality transparent absorbers** from the market encourages the research in alternative transparent material such glass. Indeed, **glass, has better thermal and scratch resistance than plastics and if microperforated performs acoustically similarly**[1] **as microperforated plastics do.**

Therefore, the development of an innovative product which combines the attractive qualities of glass and the acoustic absorption function into one device offers something new in the catalog of existing sound absorbers. **The thesis intents to define what are the potentials of the innovative glass absorber in the market of building acoustics and how it can turn out to be a successful product.**

[1] The acoustical performance of these structures is largely independent of the material used, provided the material does not significantly vibrate (Cox & D' Antonio, 2009)

1.3 Problem Statement

A micro perforated glass plate if placed at a distance from a hard surface is **an effective acoustical absorber for mid to low frequencies**. Such a device can be useful to improve the acoustic quality of a space with long reverberant noise. The efficiency in the performance is proved in various publications. The following diagram (see figure 1-4) illustrates the resulted measurements of a microperforated acrylic plate as presented by Fuchs and Zha (1996). As mentioned before the performance is largely independent the material used so **a similar efficiency is also expected from a normal glass plate**. A peak is found around the resonance frequency of the material with relatively narrow frequency band absorption.

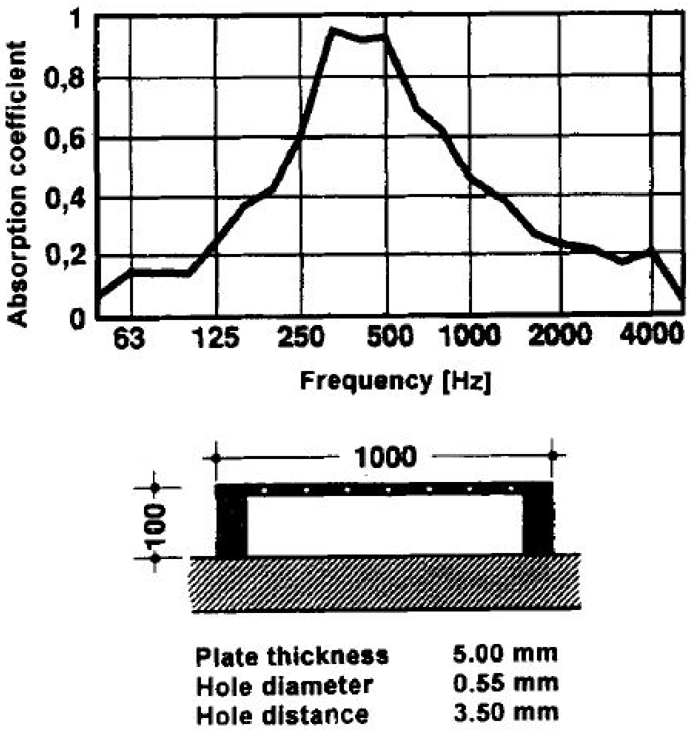


Figure 1-4 Absorption coefficient line of a microperforated acrylic plate measured in reverberation room (Fuchs and Zha, 1997). Similar absorption line is expected for a microperforated normal glass with the same geometrical characteristics.

1.3.1 Turning the innovation into a marketable product

The technology of microperforated glass as an acoustic solution for buildings currently remains in books and no relevant device has been launched in the market. **It is the complexity and the high cost of processing microperforation in glass, compared to other transparent polymers[2] that prevent manufacturers from developing such a commercial product.**

However, *placing this solution in the market successfully* (Ulrich et al.,2015) is not solely dependent on how to overpass single manufacturing obstacles, like those mentioned above. **A collective strategic approach is needed, that combines functions from marketing, design and manufacturing** (Ulrich et al.,2015). **The product development problem is largely solved, if the final product meets the needs of the market**. Thus, the development process in real case starts with the perception of market opportunity and the customer needs and ends with the production, sale and delivery of the product.

1.4 Objectives

As mentioned above, there are various trends and requirements found in contemporary architecture that raise the need for innovative, transparent solutions in the market of building acoustics. **The phase from innovating till launching the relevant product in the market successfully requires a strategic product development process.** Product development is defined by Tooley[3] as "The overall process of conceptu-alizing a product and designing, producing, and selling it".

---

[2] The cost of microperforated glass is 1000Euro/m^2 as specified by 4JET company in Germany when a sample was requested by TU Delft. The cost of microperforated acrylic plate is approx.120Euro/m^2 considering the DeAmp acoustic product.

[3] Tooley, M., (2010). Design Engineering Manual, Elsevier Ltd., United States

The main objective of this research is to turn the innovative technology of microperforated glass into a marketable acoustic product.

The **final design objective** is to demonstrate the new glass product to solve the acoustical problem of the "Co-Creation Centre".

Figure 1-5 3d Visualizations of the Co-Creation Centre (by Tim Jonathan, Green Village project)

1.5 Research Questions and Methodology

The thesis is based on the following **hypotheses**:

The brittleness of glass constrains the placement of a microperforated glass sound absorber in the market because first, it raises concerns about glass safety and second, it increases the cost of production dramatically.
Without a strictly market-oriented, product development approach that seeks ways to balance the high cost by satisfying market needs, the new product will not gain market success.

A **two-phase product development method** is used to ascertain the hypotheses.

Firstly, the technical capabilities, the limitations in fabrication and the market potentials of the innovative microperforated glass have to be researched. Based on that, the opportunity of developing a sound absorber successfully can be assessed and

decide whether it worth to continue the product development or not.
As long as the green light is given, the second phase of the product development process will start, aiming to the design of an innovative glass sound absorber.

Accordingly, the **main research question** of this thesis is:

- ***How can an innovative sound absorber be developed using the microperforated glass technology, in order to be successful in the marketplace?***

1.5.1 Two-phase methodology for product development

Phase A': Assessment of Product Opportunity and Planning (Chapter 2)

Chapter 2 focuses on the **preliminary work** that needs to be done before the actual product development phase. It aims to decide at this early stage, whether or not, it worth the investment of money to develop a glass sound absorber for the market and if it does, what type of development process has to be followed.
An **explanatory literature study** is conducted regarding the product development methodologies, design and manufacturing of glass, acoustics and product engineering. A **survey** is conducted in "Bouwbeurs 2017", a fair for technical materials, in order to ensure a link between the market and research activities.

Subsequently the following questions have to be answered:

- ***What are the potentials of the innovative microperforated glass to succeed in the market of sound absorbing materials?"***

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

- ***What type of product opportunity there is and what guidelines are implied for the next phase?***
- ***What are the criteria to assess product success in the marketplace?***
- ***How can the microperforated glass be compared against its competitive materials?***
- ***What capabilities and what limitations exist in the design and production of microperforated glass?***
- ***What is the cost and what are the expectations in the future?***
- ***Looking into the whole process of product's lifecycle, what actions can be taken in order to increase product value?***

Finally, this preliminary phase ends by deciding what type of product development process has to be followed in the next phase in order to increase the chances for product success:

- ***What type of product planning can lead to market success?***

Phase B': Product Development (Chapter 3)

Chapter 3 describes the actual product development process for the design of an innovative glass sound absorber. The design starts using as guidelines the conclusions of the first phase:

- ***What guidelines are derived from the first phase?***

The next question to be answered is how the product design process should be structured.

- ***How can a structured product design process be formed in order to ensure market success?***

A methodology which focuses on identifying market needs must be related to the product design process. An exploratory survey is conducted addressing to architects, acousticians or glass experts who hold the decision-making role. Additionally, benchmarking with competitive products can provide an overview of the materials today. Thus, a strong market-oriented approach is the base of the final product design. Chapter 3 aims to demonstrate the final product solution in a detailed level in the occasion of the “Co-Creation Centre”. At last, this allows answering the following research question:

- ***How can a glass sound absorber be designed for the “Co-Creation Centre” so as to meet the acoustic requirements and preserve room transparency?***

Conclusions (Chapter 4)

Chapter 4 draws a conclusion by formulating the characteristics of a marketable sound absorber that embodies the innovative technology of microperforated glass.

1.6 Structure of the thesis

The thesis is made up of four chapters which describe four main research units each:
The first unit (Chapter 1) analyses the research problem, sets the objectives and describes the methodology to be followed.
The second unit (Chapter 2) focuses on analyzing the technical capabilities, the limitations in fabrication and the market potentials of the microperforated glass technology. An assessment of the potentials of this innovation in the market of building acoustics will define whether it worth to proceed to the next phase of product development.

Chapter 3 represents the third research unit which deals with the design development of a glass absorber for the pilot project, the "Co-Creation Centre".
Finally, chapter 4 concludes the research and seeks to answer the main research question.

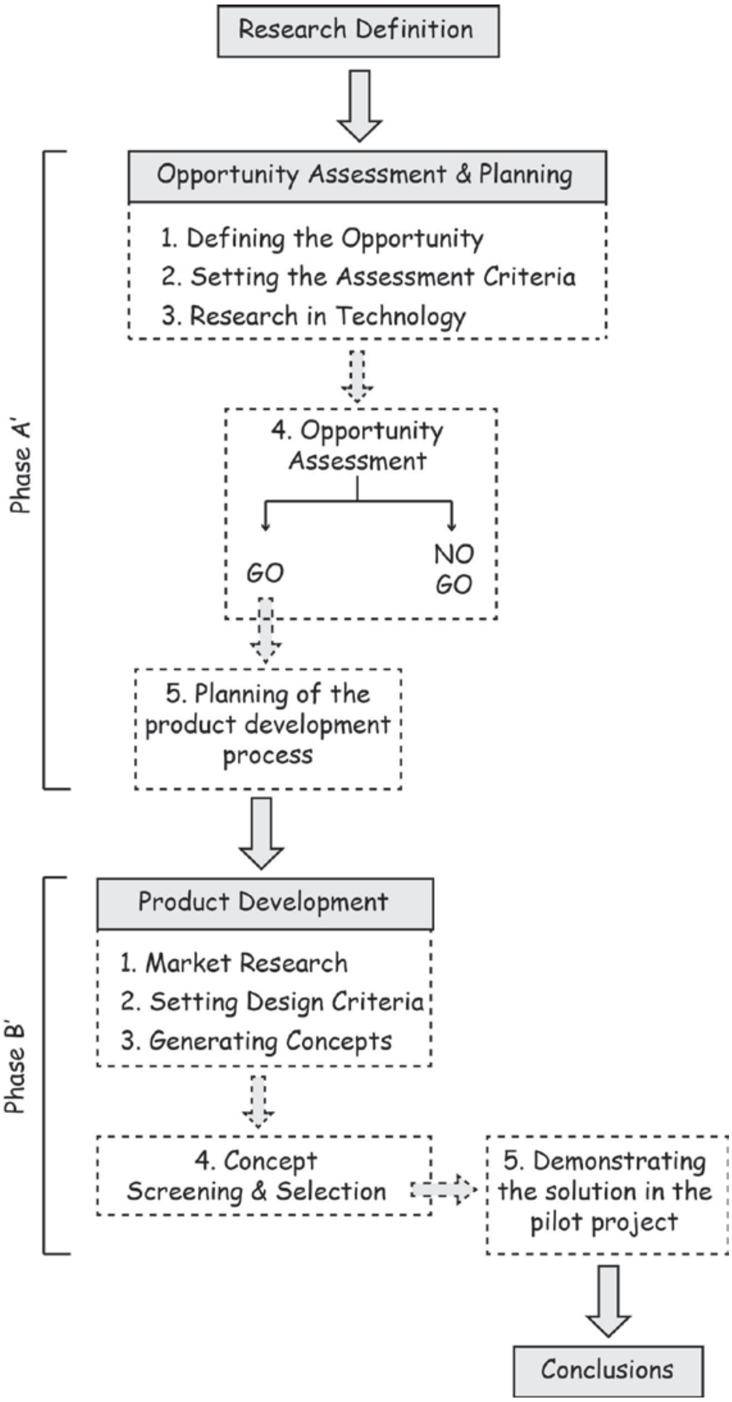


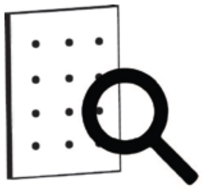
Figure 1-6 Schematic of the thesis. (By the author)

Activities of each phase	
-Phase A- **Opportunity Assessment** **& Planning**	**-Phase B-** **Product Development**
Market • Preliminary market research so as to form the assessment criteria • Define market size • Map market segments • Decide whether the technology can be successful in the market **Technology** • Demonstrate available technologies in acoustics and glass manufacturing • Research in technical capabilities, requirements and constraints • Assess manufacturing feasibility/limitations **Product Design** • Define the product type and development process	**Market** • Define market needs • Benchmark with competitive products **Product Design** • Define Product Requirements • Generate and Evaluate Concepts according to Product Requirements • Select a concept for further development **Case Study** • Define the acoustic requirements • Calculate how much acoustic material is needed • Demonstrate the design solution

Figure 1-7 Table which provides an overview of the main activities of each phase of product development.

1.7 Relevance

Developing an innovative acoustical product which is fibreless and made out of glass adds to the catalog of building materials a solution with new technical specifications. First of all, the new product allows architects to design buildings fully transparent or buildings that the architecture is not defined by the finishing of the acoustic material. Secondly, scientific knowledge regarding the design possibilities and applications with glass is gained. Microperforation is a process which is unexplored when it is applied in glass. Although this research is not focusing on the structural behavior of glass, some basic knowledge will be provided. Last but not least, there is a societal value in this research. The aspect of sustainability is promoted since the solution doesn’t entail any fibrous or porous material as common absorbers do.



Opportunity Assessment & Planning

CHAPTER TWO

2.1 Introduction

In this chapter the preliminary phase of product development process is presented. **The aim here is to decide in early stage weather the innovative microperforated glass can succeed in the market of acoustic solutions or not.** The assessment is based on input information regarding the technical capabilities and the limitations of manufacturing. The action plan starts with defining the opportunity and the decision criteria for a successful product in marketplace. The criteria are formed based on literature study and preliminary exploratory survey. Following to this, technical information is collected and presented in a meaningful way using comparison tables, graphs, etc. The final outcome of this phase is an overall assessment of the new opportunity and the decision to proceed or not to the design of a glass sound absorber. **The preliminary work which is done here obviates significantly the chances of product failure in the development process**. The following scheme presents the main steps to be followed in this phase.

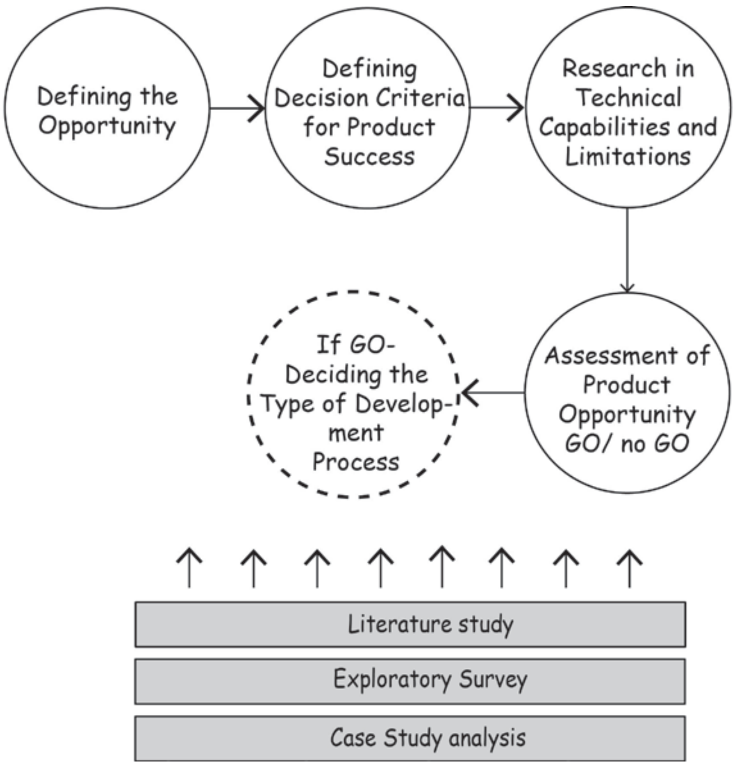


Figure 2-1 Scheme which illustrates the sequence of steps to be followed in the "Opportunity Assessment & Planning" phase. (By the author)

2.2 Defining the Opportunity

The scope of this step is to understand the type of new opportunity that exists for the market. The type depends on the context of the specific project. Understanding the nature of market opportunity will lead us in useful conclusions regarding the product development process that needs to me followed.

The opportunity exists for **a sound absorber that integrates the microperforated glass technology.** That is the type of an opportunity that the new product **is pushed by an innovative technology.** The innovation exists in processing micro perforation in glass and using the processed glass as a safe building component. The proposition of using this technology for building acoustics comes from the market, since various microperforated materials exist already such as wood, metals and polymers, functioning as sound absorbers. Consequently, the microperforated glass panel enters as a new variant in the existing family of microperforated plates used for building acoustics, as illustrated in the following scheme.

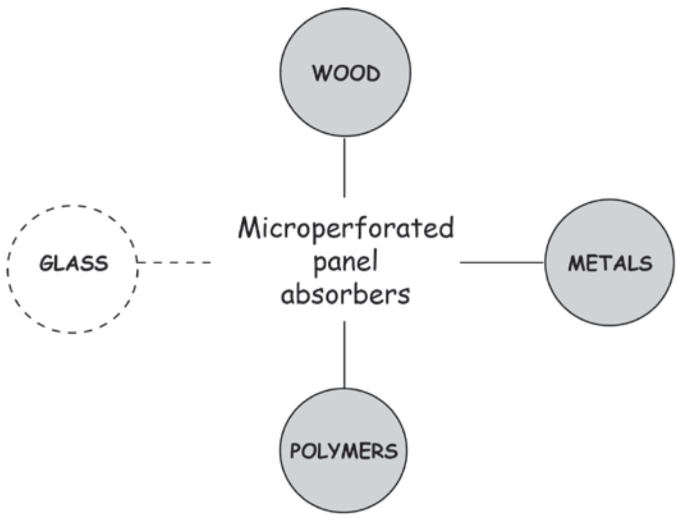


Figure 2-2 Scheme which shows the types of materials that exist today in the market as microperforated panel sound absorbers. Glass as indicated differently is the new market opportunity. (By the author)

The **"technology-push" product** is likely to succeed in the market if **an appropriate market is found**. As it is mentioned above, a market for microperforated plate absorbers already exist in the building industry. What we need to do, is to identify if there is a demand for an acoustic panel particularly made out of microperforated glass. To do so, **the clear competitive advantage** of the microperforated glass absorber must be defined in the next steps. The **market input** during all phases of product development process is necessary in order to ensure that the product satisfies the market needs. Especially in this preliminary phase of assessing the opportunity, doing a preliminary market survey will be useful to set market-oriented, assessment criteria.

2.3 Defining Assessment Criteria for Product Success

The aim of this activity is to define the criteria in order to assess the product opportunity. As it is concluded in the previous section, a strong market oriented methodology is required to ensure product success in marketplace. For that reason, a literature study on what defines successful product development methodologies and a preliminary exploratory survey will be conducted. The outcomes of this research will be a set of criteria which at the end of this phase will be used to evaluate the microperforated glass technology.

2.3.1 Cost and Quality

A definition for a successful product is given by Tooley [2016] with the following sentence: "*A business should develop the high-quality products the market desires quickly, economically, easily, and efficiently*." This definition is selected because it focuses on the product development process and not on the profit margin[4] that a company achieves at the end. Assessing profitability of the product wouldn't be feasible in this thesis because it takes time since sales grow slowly. Thus, based on the above mentioned definition and considering the context of this research, it is concluded, that the product's success is function of two main parameters, cost and quality:

What is Cost?

By saying cost we defin**e the cost of producing the product plus the cost of developing the product from concept to**

[4] Definitions such as "Product that sell and make a healthy profit" (Tooley, 2016) assess the product success based on profitability.

prototype. Also the cost determines the final selling price. However, the attractiveness of the product to the buyers is not solely related to the price but also to the quality of the product.

Figure 2-3 illustrates the product life cycle during the development process in relation to the cost and the profit. It is interesting to see there, that *the product does not become profitable until the costs are fully recovered during sales* (Tooley, 2016).

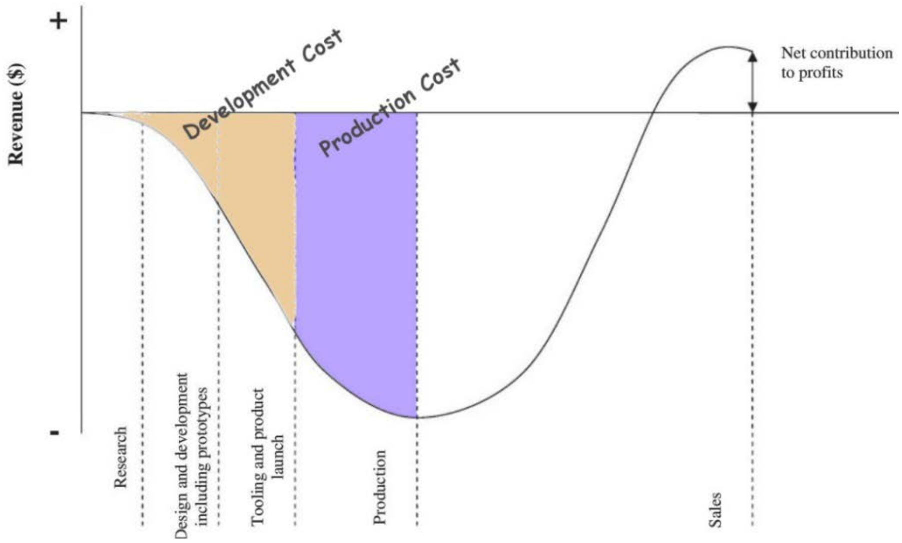


Figure 2-3 Diagram modified by the author from Tooley (2016), which shows the relationship between development/ production cost and product life cycle

What is Quality?

The product **gains value when it satisfies market needs together with providing visible benefits compared to the competing products**. Tooley claims that, *the quality of the product is the ultimate determinant of the price customers are willing to pay for it* (Tooley, 2016). To increase success rates, a thorough understanding of the market and the constant input of the market are required. At this phase t**he execution of an exploratory survey is useful to understand what characteristics define good quality in the specific project.**

Figure 2-4 illustrates schematically that cost and quality define the price of a product in the market. A good balance between these two parameters can increase the product's value.

Figure 2-4 Scheme done by the author. It shows that cost and quality are the driving factors for product success. (By the author)

2.3.2 Preliminary Market Research

A preliminary market research is conducted in order to identify **what product characteristics define its good quality based on market needs**. As it is a technology-push product, satisfying the market needs is important for product's success in marketplace. **Exploratory survey** is the selected method to conduct market research. The survey was done in "Bouwbeurs" in February 2017. On the occasion of the 3TU.Lighthouse project, the "Sound absorbing glass", samples of microperforated acrylic glass and a model of the microperforated hanging panel in a church were exhibited (see Fig. 2-5). Using the available samples to explain the technology, a semi-structured exploratory survey was conducted addressed to randomly selected visitors

Figure 2-5 Exhibition desk of "Sound absorbing glass" in Bouwbeurs 2017.

The sample was randomly selected amongst the visitors of the fair who were interested to know more about the project. The questions which were addressed to interviewees were **less directive as possible and had the form of open-ended questions**. The intension was to let people express their ideas, concerns and expectations regarding the microperforated glass absorber.

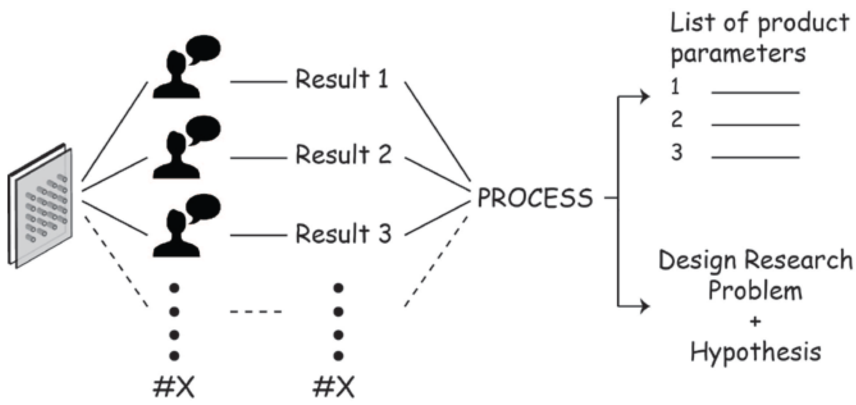


Figure 2-6 Scheme done by the author which shows the structure of the preliminary market research activity.

The questions and the responses

Initially the technology and the usage of the MPP glass have been shortly presented to each interviewee.

Questions addressed to the interviewees are:
- What is your profession/expertise?
- What is your opinion about the microperforated glass as an acoustic building solution?
- What would you like to know more about this product?
- Which type of building would you apply this?

A. Interviewees declared the following professions:
- Technician/ Builder (for housing)
- Engineer
- Architect
- Specialist in acoustic solutions for offices (ceilings, partitions)

B. The main general topics which were discussed by the interviewees were the following:

- Cost
- Method to clean from dust or water
- Condensation in the air-cavity
- Transparency advantage/ level compared to existing (plastic, acrylic) market solutions
- Type of buildings that can be applied
- Performance (in acoustics)
- Safety of glass
- Weight of glass panel

C. General opinions/ suggestions about market potentials of this product.

- Interesting innovation with glass. Existing plastic and acrylic materials are easily damaged and don't look nice.
- Very expensive solution. Not adequate for housing, maybe it is affordable for governmental or monumental buildings where the client pay for expensive solutions if they are beautiful and resistant.
- The market volume is small. If only extra characteristics (color, printed image, light) are added or other applications as a furniture or partition are thought could be more successful
- Good maintenance/ Cleaning is important/ dismantling the microperforated glass in order to clean is necessary

Processing the results

Step 1: The Word map

As a first approach in analyzing the results, a word map is developed with shows all key wording related to product properties as mentioned by the interviewees (see Fig. 2-7). The size of the words represents their frequency within the sample.

Figure 2-7 Word map of product characteristics declared by the interviewees.

Step 2: Classification and ranking of the responses

As a second step for information analysis, words having similar context are classified under main categories as shown in table 2-1. Processing the responses in limited categories would help the author to understand what are the market parameters that should be taken into consideration in product's assessment. Based on the word map and the classification table, the market parameters are ranked according to times mentioned. Thus, conclusions can be extracted about the level of importance of each which are described below.

Main Categories	Key-wording from interviewee responses
Performance	Acoustics, Performance, Thermal Properties, Weight, Technical Specifications
Safety	Safety, Fragile, Strength
Aesthetics	Beautiful
Durability/ Maintenance	Maintenance, Cleaning, Dust, Water, Condensation, Fragile, Connection
Flexibility	Variety, Customize, Extra characteristics, Add-ons, Transparency level, Connection, other Interior Applications, Furniture, Traffic noise
Cost	Cost, Expensive
Market Volume	Small Market, Special Buildings, Music Halls, Monuments, Governments
Sales Strategy	More technical Information, Models, “don’t know how to use…”

Table 2-1 Key-wording from interview responses classified in categories.

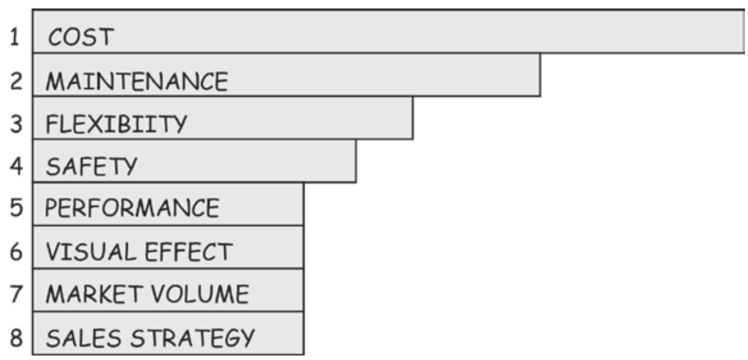


Figure 2-8 Ranking of the parameters according to times mentioned during the interview. (By the author)

Conclusions of the Interview

1. The **cost** of the product is the main decisive factor for the success of a glass sound absorber in the market. If the product is sold at low price and within the price range of other acoustic absorbers then people are willing to buy. The cost of the new glass sound absorber must be further investigated so as to have a clear view on what the cost expectation should be today and in the future (see Section 2.6.2, for detailed analysis of the cost of microperforated glass).
2. The **quality** of the product can be defined by the **market needs and expectations** as derived from the survey. The product characteristics, based on the market research that can ensure product success are:
- Good acoustical performance
- Safety of the glass component
- Attractive look
- Possibility to customize the product adding other character-ristics such as digital printing or lighting
- Easy and low maintenance

2.3.3 The Assessment Form

An assessment form is developed forming criteria to evaluate the market opportunity. It is a useful tool in order to have a clear view at the end of this process **on the strengths and weaknesses of the new product and decide whether it worth to proceed further or not.**

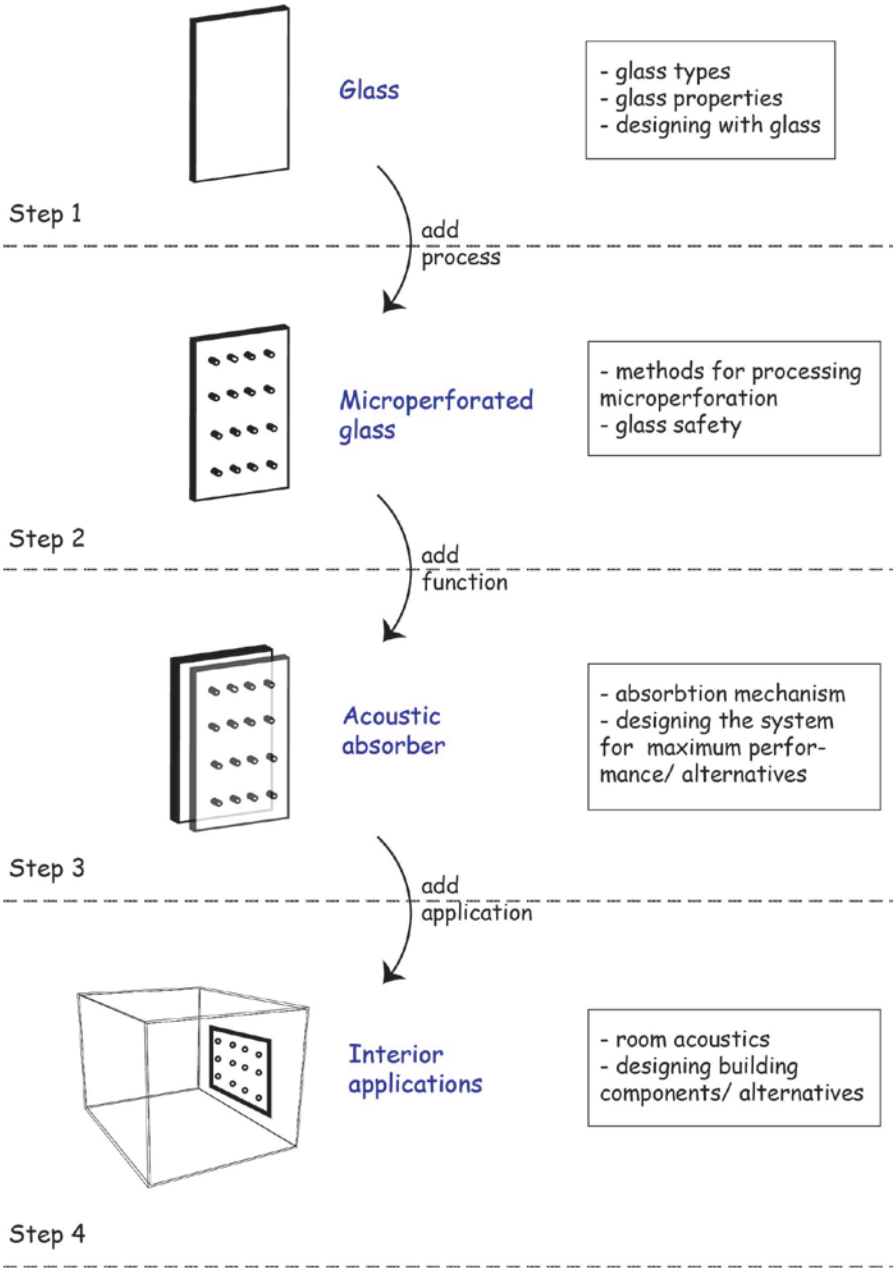
The **context of the form** is based on the outcomes of, firstly, the **literature study on what defines a successful product** and, secondly, **the exploratory survey**. Hence, it contains a list of questions which are grouped under the two main parameters that define product success as discussed in section 2.3.1; these are the “Cost” and the “Quality”. The context of the questions is formed taking into account the **market needs** as discussed in section 2.3.2 where the results of the preliminary market research are presented.

The questions are structured in such a way that "Yes" answers lead to a successful product opportunity and 'No" answers to the opposite:

Assessment Form for the Evaluation of the Product Opportunity, "Glass Sound Absorber"		
	Yes	**No**
A. Cost		
A1. Can it be produced at low cost?		
A2. Is the product feasible? Can it be produced?		
A3. Is the cost going to be reduced in future?		
Answer		
B. Quality		
B1. Is there an appropriate market?		
B2. Is there a clear competitive advantage?		
B3. Does it have a good acoustical performance?		
B4. Is it safe?		
B5. Can it be customized adding other characteristics?		
B6. Is it easily maintainable?		
Answer		
Total		

2.4 Research Technical Capabilities and Limitations

The aim of this activity is to **gain expertise on the technical capabilities and manufacturing limitations** of microperforated glass. **Benchmarking with competitive material**s will conduce to define clearly the advantages of glass. The following scheme describes the steps for a systemized technical analysis of the microperforated glass panel absorber:



2.4.1 Glass

The technical analysis starts with a brief overview of **glass as a building material**. However, it is not the purpose of this thesis to analyze any single aspect of glass technology, but instead information and data that are directly related to the specific product design.

There are many different types of glass, as presented in the following table (see Table 2-2). The difference exists in the chemical composition and proportion of substances that are mixed to produce each glass type. All of them contain as a base the quartz sand, i.e. silica (SiO_2) mixed with fluxes and stabilizers. Pure silica glass has a very high melting temperature. For this reason, fluxes are used, which reduce the melting point. Stabilizers improve the durability and hardness of glass. Besides these, small portions of other substances may be induced in order to influence properties (e.g. coefficient of expansion) and color (Balkow, 2007).

Glass Types (EUR/kg)	Composition	Advantages	Applications
Quartz (5140-8580)	Silica 96% Boric Oxide 3%	High melting point (1723C)	Windows of spacecraft
Soda-lime (1160-1370)	Silica 96% Soda 15% Lime 10%	Bulk production of this because of low melting point (400-600C)	Construction industry (eg window glass panes, doors, partitions)
Borosilicate (3430-5150)	Silica 60-80% Boric Oxide 10-25% Alumina 1-4%	High resistance to temp. changes	Household cookware
Lead-oxide (3300-5100)	Silica 30-70% Lead Oxide 18-65% Soda/ Potash 5-20%	High refractive index	Perfectly clear and flawless objects such as glassware

Aluminosili-cate (1170-1370)	Silica 5-60% Aluminum trioxide 20-40% Lime 5-50% Boric Oxide 0-10%	Withstands high temperature	Fire- resistant glazing

Table 2-2 Table which shows a list of various glass types in relation to the price, the composition, the main advantage and common applications. (By the author).

The selected Glass Types: Soda-lime vs Aluminosilicate

Amongst the aforementioned glass types, soda-lime-silica glass and aluminosilicate glass are selected as potential materials for the development of a microperforated glass plate. **Soda-lime** glass is the most **widely used glass type** today for building applications such as window glass panes. On the other hand, **aluminosilicate glass** is currently becoming known in glass industry due to its eligibility to produce **thin glass** sheets. A common application of this is as cover for phones, tablets and photovoltaic modules. Due to its high chemical resistance, aluminosilicate is adequate glass type for chemical prestress which results in a very strong glass despite its low thickness. Having the possibility to fabricate a microperforated glass sheet with **thickness less than the typical of 2mm, allows for optimization of the acoustical performance** and design of the glass absorber.
The following table (see Table 2-3) presents the advantages and disadvantages of each glass type:

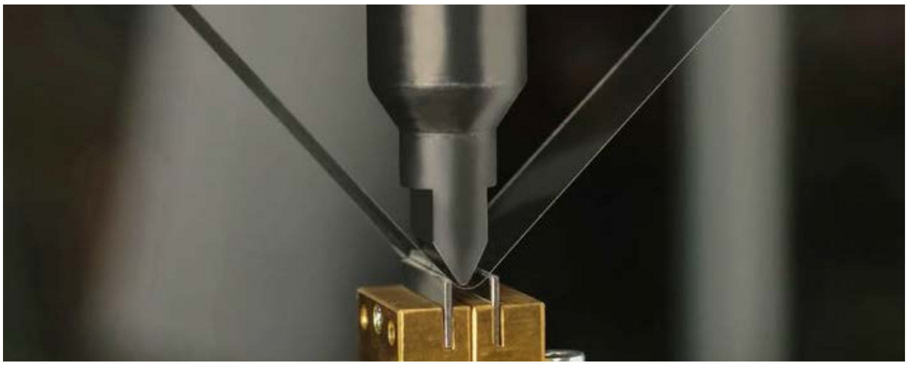


Figure 2-9 Demonstrating the high bending resistance of thin glass made out of aluminosilicate glass, source: www.Schott.com.

Soda-lime glass For glass thickness ≥2mm	Aluminosilicate glass For glass thickness <2mm
(+) 90% of manufactured glass today, widely used (+) relatively cheap (+) sufficiently hard (+) easily workable (+) Low thermal expansion (-) rapid decrease of strength under mechanical process like drilling holes (-) limited minimum thickness 1-2 mm	(+) lightweight, less material needed (+) can be deformed, easily cold bended in bigger radii (+) very high scratch resistance on its surface (+) Toughness (+) Low thermal expansion (+) Chemical durability, can be chemically strengthened (-) Not easily workable (-) Not widely used so it's still expensive

Table 2-3 Table, which lists the advantages and disadvantages of soda-lime and aluminosilicate glass. (By the author)

Material Properties: Glass Vs Polymers

A list of material properties are researched that influence the decision of an engineer in choosing glass for interior building applications. Glass is compared to competitive polymers based on each one of these properties whereas a comparison table at the end summarizes the results. The following table (see Table 2-4) presents the selected material properties together with the associated design qualities they provide to a building component.

Property	Design qualities
Transparency	Light transmittance, uninterrupted view
Durability	Optical appearance , expected degradation, find suitable applications
Fragility vs Strength	Safety, Lifespan
Thermal	Degradation, detailing
Maintenance	Required maintenance strategy, define costs

Table 2-4 Material properties together with the associated design qualities

Transparency

This property lies on the non- crystalline molecular structure of glass, which allows light to penetrate the material without scattering (Herzog, 2008). Glass also has smooth surfaces, since during the formation the molecules of the super cooled liquid are not forced to dispose in rigid crystal geometries and can follow surface tension (Haldimann et al., 2008).

Ashby presents in a useful diagram, the transparency range of most common materials against cost (see Fig 2-10). The transparency level is ranked on a four-point scale from “water-clear” to “opaque”. **Focusing on water-clear transparency, the cheapest materials are soda glass and some polymers such as polystyrene (PS), polyethylene terephthalate (PET) and acrylic glass (PMMA).**

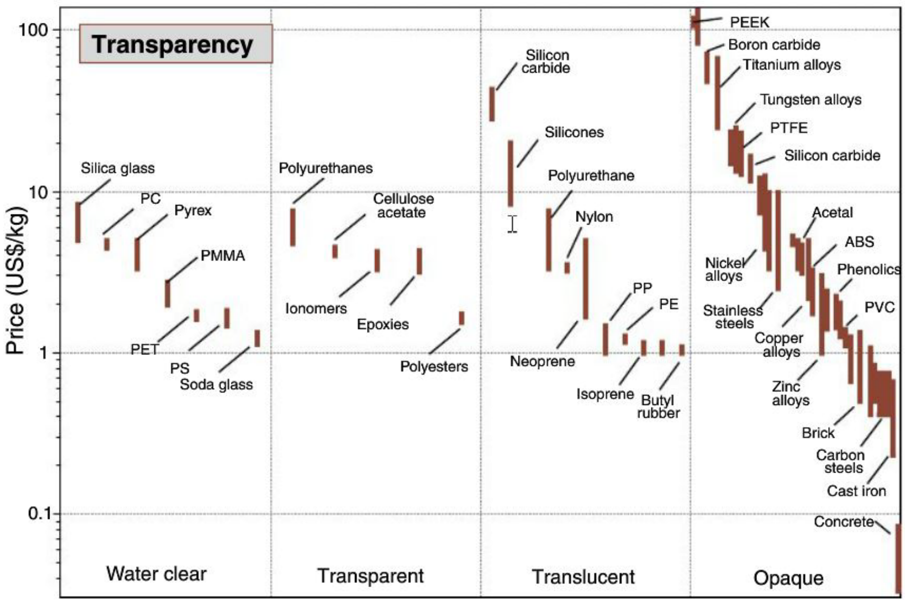


Figure 2-10 Transparency level diagram of common materials against price. (Ashby, 2002)

Durability

Glass is generally **resistant to acid and alkaline solutions** owing to its siliceous composition. However, hydrofluoric acid, hot alkaline solutions and water are excluded and can become problematic when contacting glass. If a film of **water** remains standing on a glass surface (e.g. on horizontal panes) for a long time, this leads in corrosion of glass.

Regarding **scratch resistance** we can say that despite glass is a sufficiently hard material, it is vulnerable in hairline cracks and scratches caused by hard and sharp objects. The scratch hardness measured in Mohs scale for soda–lime glass is 6 units whereas for aluminosilicate is 7. **Scratches are unwanted because they not only reduce the optical transparency, but also the strength of the loaded glass element.**

Compared to glass, the scratch resistance of polymers is very poorer, because of their low hardness. Polyethylene (PET) for example, is easily scratched due to its low hardness.

Fragility Vs Strength

Glass is a typical brittle material but on the same time appears hardness and strength. However, the strength of glass component is not a pure material property, but instead a variable dependent on the degree of damage to the surface of the glass (including edges and drilled holes) (Sobek 20007).

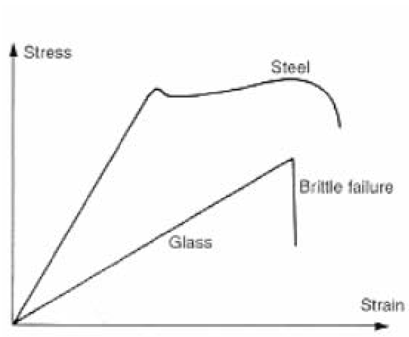


Figure 2-11 Comparing stress/strain behavior for steel and glass (source: https://www.researchgate.net

Surface damages like scratches or damages to the microstructure within the body of glass create extremely high stress concen-tration when the element is subjected to mechanical actions. Glass doesn't exhibit any plasticity contrary to what elastically deformable materials, like metals do (see Fig. 2-11). This means that glass fractures suddenly and without warning as soon as the elastic deformability has been exceeded. Since the strength of the **glass element depends on the flaws of the surface, the real material strength has limited applicability when designing with glass. A good method to measure the expected strength of a glass pane would be the experimental**

determination of the strength of an older pane. This gives an approximate value of the glass strength after it is been reduced due to the surface damaging occurred during its lifetime.

Occasions where surface flaws are inevitable and decrease glass total strength are the following:

- Edges of the glass
- Around drilled holes of any kind e.g. for glass support or microperforation
- External mechanical sources such as scratches, cleaning, wind erosion
- Mechanical or chemical treatment on glass surface such as cutting, grinding, sand- blasting coating or printing

Based on the subject of microperforating glass, it is worth to mention here that the cracks caused at the edges and at the sides of drilled holes **can’t be rectified by polishing operation** because are deep and can’t be reached.
In addition, it’s important to know that glass strength is comparable to that of steel when loaded in compression but exceptionally **weak under tension**. By inducing compressive prestress, the resistance of glass in tensile stresses can be increased by thermally or chemically strengthening the glass.

Thermal properties

Soda-lime glass, which is commonly used in buildings **has thermal expansion equivalent to this of steel but far lower than aluminum.** This fact needs to be taken into consideration when designing support connections and joints. If these are rigid and inflexible, internal stresses are generated between the two materials with different thermal expansion. This can be harmful especially for glass which **is vulnerable in high stress concentrations**. Stresses also can be caused in the joint when the components are exposed in solar radiation or artificial heating or cooling.
The **thermal expansion of polymers** is much higher than this of conventional glass under temperature differences. Polymers

elongate above 35mm for a temperature difference of 10K, whereas glass only 9mm. Fixings for plastic components must therefore permit such an expansion and contraction (Knippers et al.2016). Another critical failure of polymers when they are subjected in higher temperatures is the fact that the bonding forces between the molecular chains become weaker and their strength drops, accelerating both **creep and relaxation.** This leads to deformation and loss of their tensioning strength over time and begin to sag.

Maintenance and Resistance in UV light

If seen under the microscope, the surface of glass is rough which means that dirt and moisture are trapped. When glass is used for interior applications, mainly it is dust that is stack on the surface of the glass pane and need to be cleaned. During cleaning a wet cloth must be used and to ensure that the dry particles of dirt are not scraped across glass surface and so damage it.

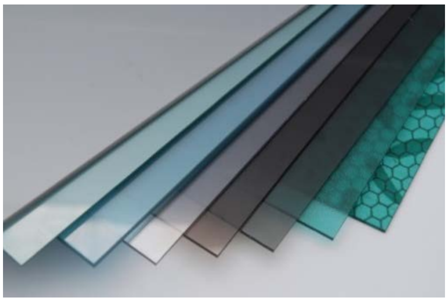
Glass is highly resistant to UV degradation compared to polymers. Polymers age when they are exposed to light (particularly to UV) causing loss of strength, stiffness and toughness and discoloration (Ashby, 2002). Intensive UV radiation dissolves the plasticisers out of a polymer which results in yellowing or embrittlement (Knippers et al., 2016). However various additives and UV stabilizers can be used outside in order to prevent yellowing.

Transparent Polymers

Commonly used transparent polymers, used as building materials are hereby presented:

- **Polycarbonate (PC)**: Is better known commercially as Lexan, Makrolon or Danpalon. PC is characterized by its extremely high impact resistance and water-clear transparency (more than glass). On the other side is more expensive, scratches easily and has poor UV resistance. UV stabilizers are required when it is used for exterior application in order to prevent yellowing.
- **Polyethylene terephthalate and glycol (PETG)**: It is colorless, soft thermoplastic with high impact strength (less than this of PC) and easiness in processing. However, it has poor resistance to scratches and UV light exposure.
- **Polymethylmethacrylate (PMMA)**: It is known as acrylic glass or under the commercial names of Plexiglas, Lucite or Perspex. PMMA is cheaper and less likely to scratch than the other plastics. However, it has less impact strength (10 times less than PC) and is more likely to chip than PC.

2-12



2-13

Figure 2-12 Polycarbonate, source: http://dama.com.sg/
Figure 2-13 Plexiglas (PMMA), source: https://www.vanderleedenhout.nl/

The following Table 2-5, presents the values of selected physical and mechanical properties for the types of glass and polymers that described previously in this section. This numerical table is helpful to formulate a **qualitative comparison between glass and transparent polymers**. Conclusions will be extracted regarding the competitive advantage of glass over the plastics.

	Soda-Lime Glass	Alumino-silicate Glass	Transparent plastics		
			PC	PETG	PMMA
Physical					
Density[1] g/cm^3	2,5	2,5	1,20	1,38	1,18
Mechanical					
Young's modulus[2] GPa	68-72	87		2.01-2.11	
Tensile strength[3] (MPa)	30.3-32.2	39.9-43.9	60-70	60-66	80
Fracture toughness[4] (MPaxm$^{1/2}$)	0.7-0.8	0.7-0.72		2.11-2.54	0.7-1.6
Hardness in Vickers[5] (kPa/mm^2)	89-98.4	477-525	12.20		20.59
Functional					
Service temp. T_{max}[6] (°C)	550	600	-	51-64	100
Thermal expansion coefficient[7] (K^{-1})	9×10^{-6}	4.6×10^{-6}	-	$120\text{-}123\times10^{-6}$	-
Refractive index[8]	1.5	1.5	1.60	1.57	1.4895
Price EUR/kg	1160-1370	1170-1370			
Available Thickness (mm)	2,3,4,5,6,8, 10,12, 15,19,25	0.55-1.3			

Table 2-5 Quantitate comparison table of physical, mechanical and functional properties, source of information CES Edupack 2015.

1. **Density** measures the weight. Minimizing the weight has much to do with clever design (Ashby, 2002)
2. **Young modulus** measures the resistance to bending, thus the stiffness.
3. **Tensile strength** is the ultimate limit beyond which the material fails.
4. **Fracture Toughness** measures the resistance of materials to cracking and fracture. It shows how brittle or not tough the material is.
5. The **Hardness** property measured in Vickers test indicates the resistance in scratching.
6. **Maximum Service Temperature** is a limiting temperature above which the properties of the material change usually for worse. Its strength falls, it starts to creep (to sag slowly over time), it may oxidize, degrade or decompose (Ashby, 2002)
7. **Thermal- expansion coefficient** measure how much the material expands when is heated.
8. Refers to the average **refractive index** for the visible range of wavelengths 380-780mm.

	Glass	Plastics
Lightweight	-[1]	+
Stiffness	+	-
Brittleness/Toughness	-	+
Scratch resistance	+	-
Impact resistance	-	+
Resistance to temperature differences[1] and heat	+	-
Degradation/ Aging[2]	+	-
Transparency	+/-	+/-
Easy to clean	+	-
Price	-	+

Table 2-6 Qualitative comparison table of glass with plastics. The symbol (+) indicates the advantage, the symbol (-) indicates the disadvantage and the symbol (+/-) indicates equal results. (By the author)

Competitive Advantage of Glass

Transparent polymers, as those described above, are the competitors of glass in the market, due to their similar transparency. Knowing what the advantage of glass is over its competitors is the initial step to ensure product's successful strategy.

The main advantages of glass are found in its better **scratch and UV resistance, resistance in temperature differences due to its low thermal expansion and better aging.**

Plastics scratch easily, especially during cleaning as their surface gets quickly marked by scratches and finger prints. Additionally to this, plastics present very low resistance to UV exposure whereas the effect is that they become yellow and lose their strength over time. This fact has an effect not only on its physical appearance, but also in its ability to be a safe building component. Due to the above mentioned disadvantages, plastics are not desirable for architectural applications.

On the opposing side, glass is more robust than plastics and presents much lower degradation in time caused by external factors. The preference of the architects in glass can be verified by the fact that glass is the most commonly used material for windows and other interior applications such as wall partitions, doors and stair balustrades.

The following table summarizes the advantages of each material:

Glass (+)	**Polymers (+)**
Robustness Scratch & UV Resistance Longevity	No fracture Cheaper Lighter

Table 2-7 The table presents the advantages of glass and polymers summarizing the analysis which is previously done into their properties (By the author)

2.4.2 Manufacturing with Glass

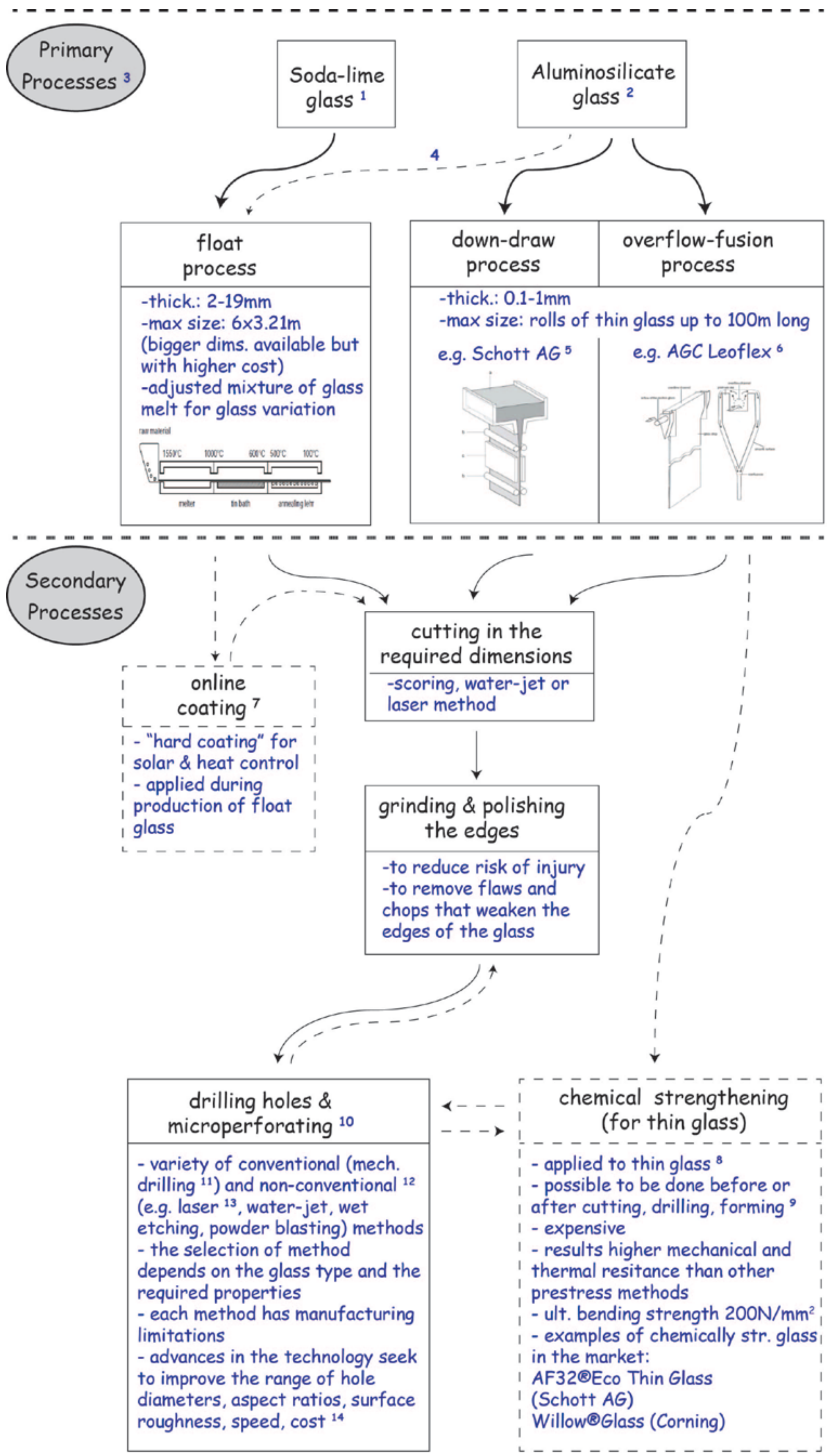
Next step of the technical analysis is to get an overview of the **possibilities and limitations that exist in the manufacturing** of a building glass component. Putting this information together will help us **define what variations in glass design** can be achieved. The features that define the product configuration and depend on the manufacturing process are the following:

Glass features	Manufacturing Process
Size	Primary float process, Cutting glass
Optical Effect	Surface treatment, Coatings, Laminating foils
Texture	Surface treatment, Coatings
Color	Surface treatment, Coatings, Laminating foils
Form/Shape	Cold/ Hot Bending
Mech. Strength	Prestressing
Safety	Prestressing, Laminating

Table 2-8 List of glass features and the process that needs to be applied for each one of them, (By the author)

A **diagrammatical plan** is developed (see Table 2-9) which illustrates the **sequence of various manufacturing processes** that need to be applied, in order to fabricate a microperforated glass component. The plan proposes two alternative methods, one for the **common soda-lime** and one for the **aluminosilicate glass**. The aim of this diagram is to give an overview of the possibilities and the limitations that might exist during glass fabrication.

Figure 2-14 Glass furnace, source: www.agc-glass.eu


Primary Processes 3
Soda-lime glass 1
Aluminosilicate glass 2
4
float process
-thick.: 2-19mm
-max size: 6x3.21m
(bigger dims. available but with higher cost)
-adjusted mixture of glass melt for glass variation
down-draw process
overflow-fusion process
-thick.: 0.1-1mm
-max size: rolls of thin glass up to 100m long
e.g. Schott AG 5
e.g. AGC Leoflex 6
Secondary Processes
online coating 7
- "hard coating" for solar & heat control
- applied during production of float glass
cutting in the required dimensions
-scoring, water-jet or laser method
grinding & polishing the edges
-to reduce risk of injury
-to remove flaws and chops that weaken the edges of the glass
drilling holes & microperforating 10
- variety of conventional (mech. drilling 11) and non-conventional 12 (e.g. laser 13, water-jet, wet etching, powder blasting) methods
- the selection of method depends on the glass type and the required properties
- each method has manufacturing limitations
- advances in the technology seek to improve the range of hole diameters, aspect ratios, surface roughness, speed, cost 14
chemical strengthening (for thin glass)
- applied to thin glass 8
- possible to be done before or after cutting, drilling, forming 9
- expensive
- results higher mechanical and thermal resitance than other prestress methods
- ult. bending strength 200N/mm²
- examples of chemically str. glass in the market:
AF32®Eco Thin Glass (Schott AG)
Willow®Glass (Corning)

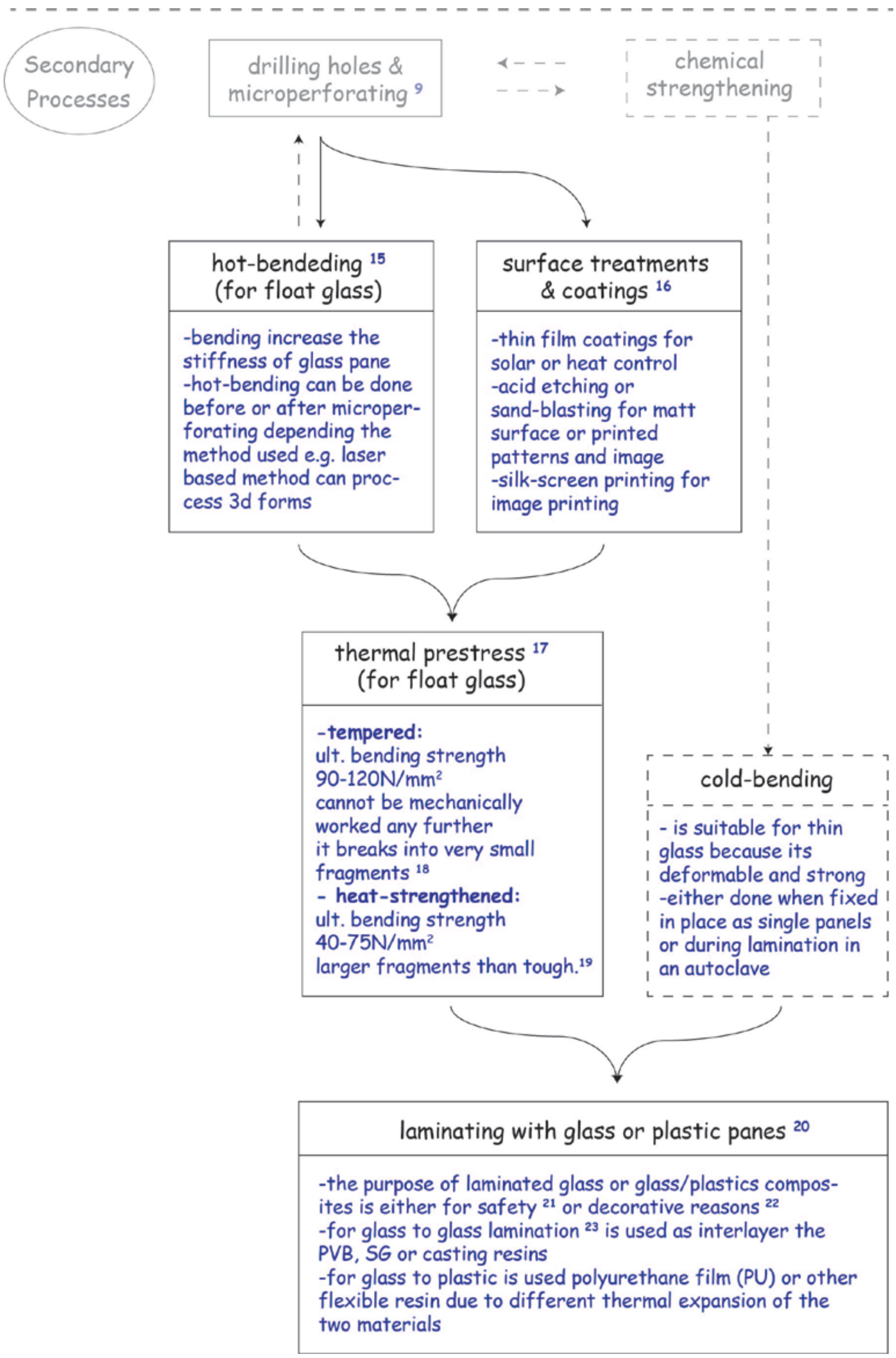


Table 2-9 Manufacturing process of fabricating a microperforated glass plate either soda-lime or aluminosilicate, by the author.
The reference numbers found in the diagram are technical explanations which are found below.

Explanations on the reference numbers:

1 *(Soda-lime glass)*

Soda lime glass is not adequate for the production of thin glass (lower than 2mm thick), due to its properties. It is less hard and less chemically resistant than aluminosilicate glass. This means that it can’t resist bending forces when having such a low thickness and also it can’t be processed with chemical prestress. Thermal toughening method is not easily applicable to thin glass.

2 *(Aluminosilicate glass)*

Borosilicate, likewise **aluminosilicate glass** has excellent chemical durability and thermal resistance. However, aluminosilicate glass is preferred for the production of thin glass because it has comparatively **higher young modulus, fracture toughness and can withstand mechanical bending**.

3 *(Primary process)*

The main difference between the three types of production processes is the final **quality of each glass surface**. In float process, the **“tin” side** is distinguished from the **“air” side** because the glass is in contact with the tin bath and thus resulting in a higher concentration of tin ions. On the other hand, the overflow process results in almost **flawless and smooth surfaces**, as the glass surface in not getting in contact with any solid as it flows for cooling.

4 *(Thin glass)*

The production of thin glass is feasible with float process up to 0.5mm thickness; this method is not preferred due to size limitations and tin/air side effect.

5 *(Schott AG)*

Down-draw process is used from Schott Glass Company to produce thin glass.

6 *(AGC Leoflex)*

Overflow-fusion process is used for the production of AGC's Leoflex and Dragontrail products.

7 *(online coating)*

The durability of the glass surface after being coated with online method is roughly equal to that of an uncoated glass surface (Balkow, 2007)

8 *(Thin Glass)*

Chemically toughening method is a process which aims to increase the surface compression of glass and is especially suitable for thin glass type. It is very hard to provide reinforcement to a thin glass less than 2mm on an industrial thermal tempering installation (Gy, 2008). **Thermal prestress** is adequate for glass plates with bigger thickness because the compression layer which can be achieved is deeper (see Figure 2-16). In a chemically strengthened glass sheet higher surface compression stress can be achieved than in a thermally one. This means that larger deflections are possible and since stiffness is lower, cold

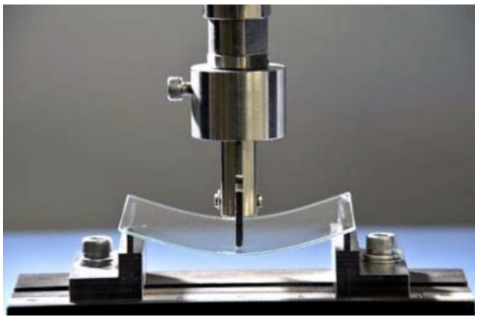


Figure 2-15 Demonstration of the resistance in bending of the dragontrail chemically strengthened thin glass, source: www.dragontrail.agc.com

bending with lower forces is feasible. The main drawback of chemical tempering is the **high cost** compared to conventional thermal methods.

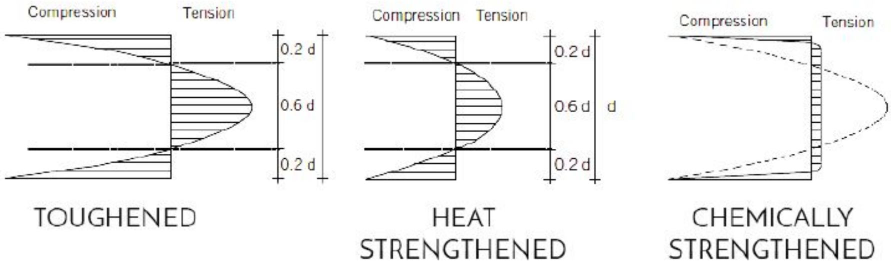


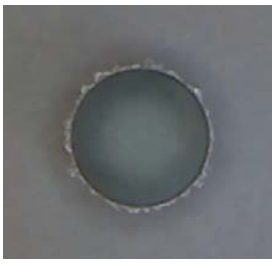
Figure 2-16 Stress distribution comparison in thermal and chemical strengthening processes, (Silveira, 2016, Ultra-Thin Glass, MSc thesis)

9 *(Cutting thin glass)*

In contrast to thermally treated glass, **chemically strengthened glass can be cut afterwards**. However, in this case the cut edge has only the strength of normal glass. Moreover, **thin glass can be microperforated before or after the chemical strengthening process.** The decision which order to follow lies on the instruction given by the manufacturer and depends on various factors such as the method of microperforation (e.g. type of laser or powder blasting) the glass type, the required properties, etc.

10 *(Microperforating)*

The main challenge in glass micro machining technology is **how to deal with the relatively large hardness and brittleness of glass.** The problem is that any treatment in glass can cause **unexpected cracking or microchipping** around the holes which dramatically reduce the strength of glass. Advancements are constantly being made in this field, **seeking ways to reduce induced stresses and improve surface roughness alongside with improving manufacturing aspects such as speed, cost and aspect ratios**.



a

b

Figure 2-17 Photo taken with microscope of 2mm mechanically drilled hole in 2mm annealed glass pane, a. at the exit of the drill, b. at the entrance of the drill.

11 ***(Conventional drilling methods)***

The most **conventional** and relatively low-cost method is **mechanical drilling**. However, this method results in chipping and **micro-cracks mostly at the exit** of the holes due to the deformation of glass by the thrust force of the drill acting at the bottom surface of the workpiece (Hof & Ziki, 2017). There are **methods proposed to reduce cracks during mechanical drilling such as decreasing thrust forces or attaching a supporting backplate with liquids**, but still the resulted surface remains rough and the speed of fabrication is getting longer. Figure 2-17 presents photos taken with the microscope of a 2mm diameter hole, mechanically drilled on a 2mm annealed glass pane. It can be seen the difference of the surface around the hole at the entrance of the drill (b) and at the exit of the drill (a). Chipping and microcracking at the bottom side is more apparent than at the top due to the reasons discussed above.

12 ***(Non-conventional drilling)***

There are a number of **non-conventional** micro-drilling methods which are ever

more progressing in order to overpass the limiting factors that exist from older techniques. These methods can be categorized as: a) **mechanical**, such as powder blasting or abrasive water jet, b) **thermal**, such as laser, c) **chemical**, such as wet etching and finally the innovative d) **hybrid technologies** which combine two or more methods for better performance.

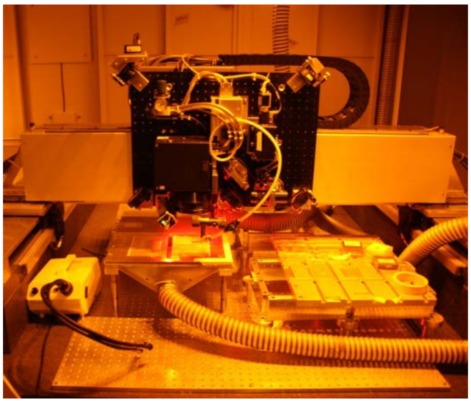


Figure 2-18 Ns green laser. Photo taken by the author while visiting 4Jet, a company specialized in micromashining in Germany.

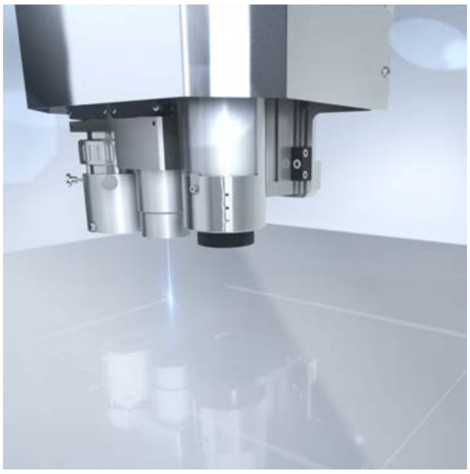


Figure 2-19 Ultra-short pus laser from Corning Technologies, source: https://www.corning.coml

13 *(Laser drilling method)*

The **laser microdrilling** process is based on material removal by thermal shock or ablation. The most c**ommonly used lasers** for cutting glass in industrial applications are the **carbon dioxide (CO_2) lasers.** This type of laser causes **thermal impact** on glass and generates mechanical stresses which lead to cracks during cooling (Hof & Ziki, 2017). Solutions to avoid this problem which have been proved to be efficient are the **local preheating of the workpiece** or heating the whole workpiece afterwards. However, this is a disadvantage of the method because it **delays the process**. Added to this, a limitation in the cutting glass thickness exist which is up to 3mm. Although the reliability of this method in glass applications is low, the **fast speed** and the **low cost** make it a good option for the market.

Apart the CO_2 lasers, a range of o**ther type of laser-based techniques** exist, which present various characteristics regarding surface quality, speed or achieved properties. The **cost** as a parameter is not much discussed here because it still remains high for all laser-based systems. A type of laser system that glass manufacturers such as Schott AG have tried in micromachining is the **ultra-short pulse (picosecond) laser.** The advantage of this system is that it can produce smooth holes without forming micro-cracks around them and thus preserve the strength of the glass. On the other side the speed is very low if compared with other techniques and the cost much higher. Figure 2-x shows the Corning Laser Cutter which drills glass in ultra-short laser pulses. Figure 2-x shows the ultra-short pulse CLT 80G laser glass tool which accommodates a glass substrate size of up to 2300mmx250mm.

Figure 2-20 Ultra-short pulse laser from Corning Technologies which is capable to manufacture glass substrate of up to 2300mmx2500mm.

14 *(Cost of microperforation)*

The following table is extracted from the research paper of L.Hof and J.Ziki (2017) which discusses the various methods that currently exist in glass micromachining. The table presents a **qualitative comparison between the main drilling methods that exist today**. This information is useful in order to have an overview of the possibilities that microperforation technology has today.

Process	Mechanical				Thermal		Chemical		Hybrid
	Mechanical Drilling	Powder Blasting	ASJ	USM	Laser Drilling	FEDM	Wet Etching	DRIE	SACE
Aspect Ratio [1]	−	−−	−−	−	++	−	−−	++	+
Machining Speed (Serial) [1]	+	−	−−	−−	++	+	−−	−−	+
Surface Roughness [2] (R_a)	−	−−		−	−	+	+	++	+
Minimum Dimensions (μm)	150	50	300	200 (10)	5	20	1	0.5	100
Rapid Prototyping (Serial Mode) [3]	++	−−	+	+	++	−	−−	−−	++
Mass Fabrication (Parallel Mode) [3]	−−	++	−	−	−	+	++	++	−−
Tooling Complexity/Costs [4]	−−	−−	−	−	++	+	−−	−−	++
Applicable to Wide Range of Glass Types [3]	++	++	++	++	+	−−	−	−−	++
Equipment Costs/Complexity [5]	++	+	+/−	−	−	−	−	−−	+

On a scale of 1 to 4, the above symbols indicate: (−−) Level 1; (−) Level 2; (+) Level 3; (++) Level 4. Level 1 and Level 4 are indicated for each column on the table. [1] low −−, high ++; [2] high −−, low ++; [3] non-applicable −−, applicable ++; [4] complex −−, simple ++; [5] expensive −−, cheap ++.

Figure 2-21 Comparison table of the drilling technologies of glass (Hof & Ziki, 2017).

<u>Discussion about the feasibility and the cost of microholing technology</u>

Based on the above comparison table and general literature study, the manufacture of a **microperforated glass component is feasible.** The most suitable technologies for prototyping are **mechanical drilling, powder blasting and spark-assisted chemical engraving (SACE)**, because these are the **cheapest** processes. However, they either do not result in good **surface quality** or they are relatively **slow**. Laser drilling is another option but it is relatively expensive. It is a beneficial choice though, when high speed, flexibility and good quality are required.

In any case, e**ach drilling technology has certain limitations and advantages**. The most suitable technology is selected based on the prioritized demands of a certain application. The technology of micro mashing in glass is continuously progressing, so the burdens that currently exist will be overpassed in the near future. May be that the cost of producing a microperforated glass plate is high today, compared to plastics or that the strength of the processed glass is uncertain due to chipped or cracked surface around the holes, but these manufacturing limitations will solved as the technology progresses.

Figure 2-22 Museum aan de Stoom (widerwalls.ch, 2017)

15 ***(Hot-bending)***

Alternatively, float glass can be **cold-bended** that is a less costly method, but the **curvature radius is limited**. Hot-bended glass can be bended in any free form shape or extreme curvature pieces and is free of permanent bending stresses. This fact allows forming glass in a geometrically stable shape which increases its **structural stiffness**. An example of this glass design strategy is the façade of Museum Aan de Stroom in Antewerp (see Fig. 2-22) that wouldn't be feasible to achieve an all transparent façade with flat glass panels due to their lack of stability.

16 ***(Coatings)***

Each coating has its own technical specifications regarding its composition, strength, durability and application and therefore their manufacturing process depends on the manufacturer's requirements. Coatings can be applied facing either the outside air or the inside air or placed between the glass panes. Some of the coatings can withstand further thermal processing for heat strengthening and toughening, some of them cannot. All coated glass can be processed further to produce safety or laminated units. The general purpose of coatings is to provide solar or heat gain control or anti-reflectance properties.

17 *(Thermal Prestress)*

Thermally prestressed float glass achieves higher ultimate bending strength and thermal stability.

18,19 *(Fracture pattern)* (see Fig. 2-23)

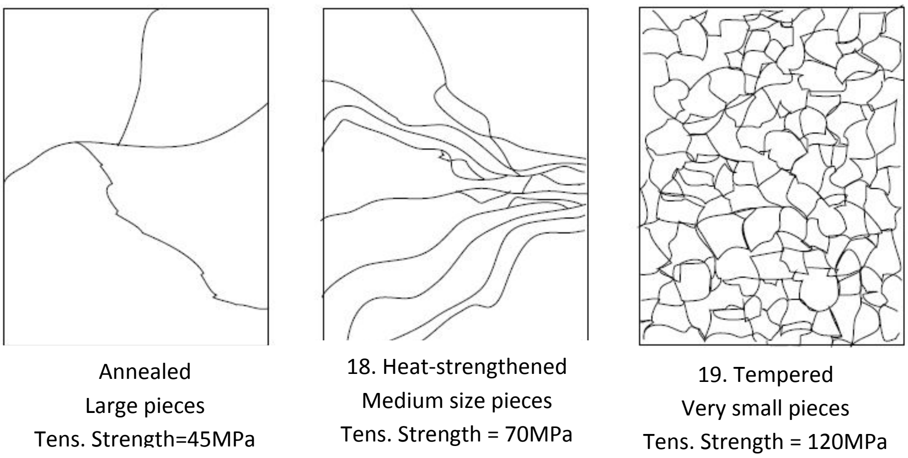


Figure 2-23 Fracture pattern differences between annealed, heat-strengthened and tempered glass.

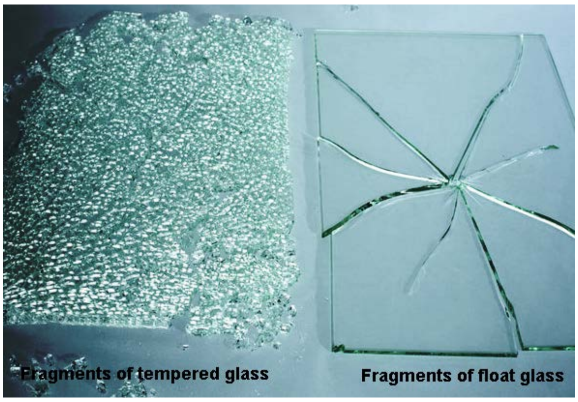


Figure 2-27 Fracture pattern differences between annealed and tempered glass, source: quora.com)

20 *(Laminating with glass or plastics)*

Lamination is the manufacturing process when two or more glass layers tempered or not are firmly bonded together by means of viscoplastic interlayer or a casting resin. Lamination can also exist

between glass and plastics under lower temperature manufacturing conditions in order to produce composites with certain requirements.

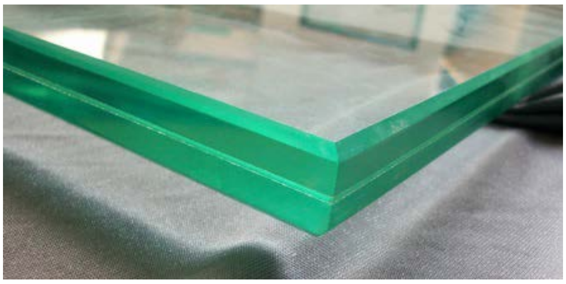


Figure 2-24 Edge view of the laminated glass product, source: http://sepio.ca/product/clear-roofs/

21 (Laminating for safety)

When lamination is done to provide safety, in case of damage, the broken pieces remain glued to the other one given that the unbroken panel is able to carry the loads. This safety concept protects people from being injured by the glass fragments.

22 (Laminating for decorative reasins)

When lamination is used for decorative reasons, a **colored or printed film** interlayer between the panes creates the required effect. This is an inexpensive way to produce laminates with a special optical effect. For example the PVB interlayer used for safety glass laminates can also be used for printing an image by an inject printing process. In this way a decorative laminated safety glass with good adhesive qualities ca ne produced.

Figure 2-25 Digitally printed image on a PVB interlayer, source: http://www.toughglaze.com/digital-printing-on-pvb.html

Figure 2-26 Digitally printed image on a PVB interlayer, source: http://coolingbros.com.au/our-products/digiglass/

23 (Glass to glass lamination)

Lamination between glass panes is done by the heat and pressure method, the **vacuum method or the UV curing method.**

A. The plastic transparent foil named **PVB** is placed between two glass panes and the whole system is pressed together in furnace up to 250^{o}C under the action of heat and pressure (see Fig. 2-27). Due to the size of the furnace, there is a size limitation for glass panels up t0 2.5 x 4.5m. PVB interlayer for glass to glass laminates is commonly used for bullet-proof glasses or window panes because of its adhesion to glass when subjected to suitable temperatures and pressure, because it is transparent and resistant in elongation under impact loading.

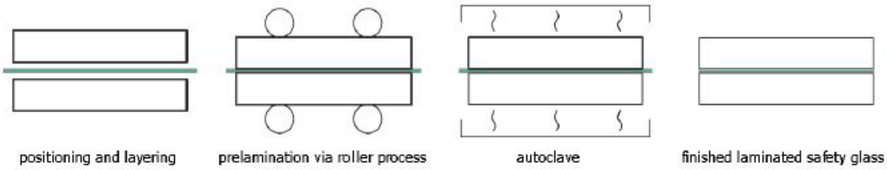


Figure 2-27 Scheme which illustrated the heat and pressure process of laminated glass with PVB interlayer (Topcu, 2017)

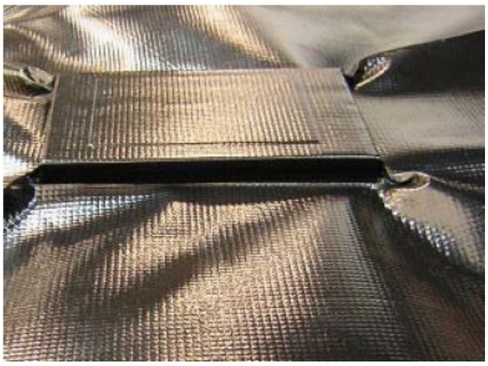


Figure 2-28 Vacuum lamination of glass

B. In **vacuum process** is used the innovative **SentryGlas** interlayer which is a special ionplast polymer used for extraordinary bonding characteristics and high structural properties. The laminate is produced in a rubber bag under 120^{o}C where the air glass and interlayer is vacuumed completely.

C. The **UV curing** process is used when casting resin in the interlayer space between the two glass panes. In this process the glass panes are cleaned thoroughly and the interlayer space is created with double tape. After the resin is pumped in the gap, is cured by exposure to UV radiation. The UV method of laminating has the following advantages:

- cheaper than the autoclave
- faster and in good quality
- follows the size of the laminates

24 (Glass to plastic lamination)

Lamination between glass and plastics is used for example to build bullet proof or car windshields, which are two cases subjected in high impact load. Bonding glass with a plastic instead of another glass produces a much lighter component whereas light-transmittance and stiffness are preserved. The difficulty in hybrid glass/plastics laminates arises from the fact that glass and plastics such as polycarbonate (PC) or acrylic (PMMA) have **different coefficients of thermal expansion and therefore expand at different rates** (Teotia&Soni, 2012). The polyurethane film **KRYSTALFLEX® PE 393 (thick. 50mm) is a commercial material used as interlayer for glass/ plastic laminates**. It offers high adhesion at relatively low processing temperature and thus preventing the thermal deterioration of plastic caused in high heating temperatures.

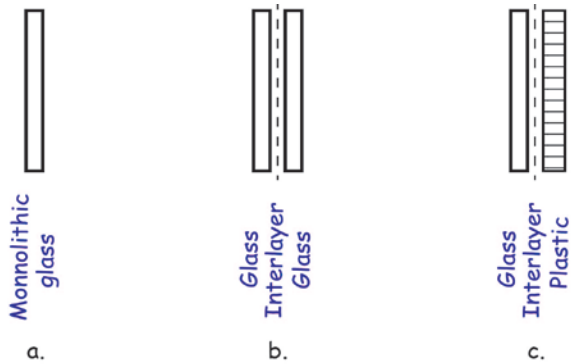


Figure 2-29 **(**a) Single glass layer, (b),(c) Laminated glass either with glass or plastic (By the author)

2.4.3 Options for Glass Customization

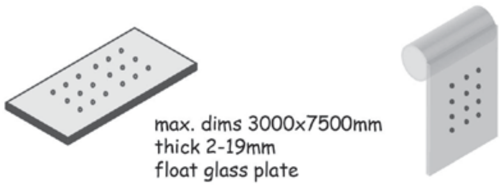
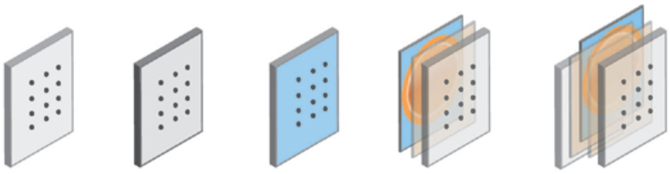
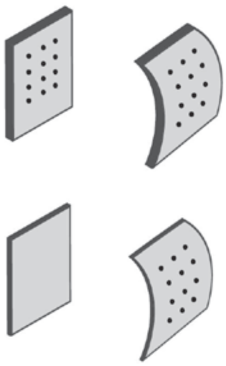
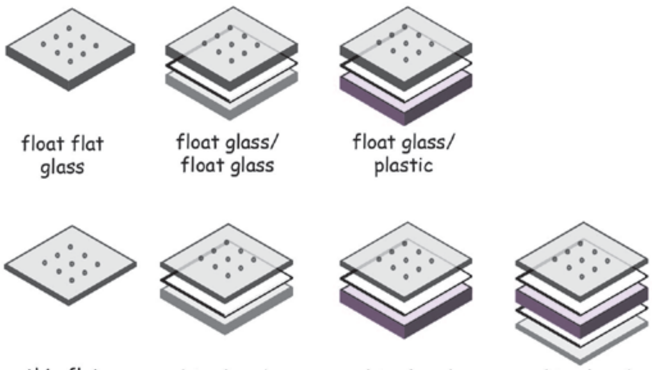
size	 max. dims 3000x7500mm thick 2-19mm float glass plate max. dims ???? thick 0.55-2mm thin glass sheet
optical quality/ texture/ colour	 transparent; matt; coloured/ textured; digital printing film; laminated digital printing film
form/shape	 a. flat/ curved float glass b. flat/ curved thin glass
mechanical strength	a. annealed glass (float glass) 40MPa b. heat-strengthened (float glass) 40-75MPa c. tempered (float glass) 90-120MPa d. chemically tempered (thin glass) 300MPa
safety	 float flat glass; float glass/ float glass; float glass/ plastic thin flat glass; thin glass/ float glass; thin glass/ plastic; thin glass/ plastic/ thin glass

Table 2-10 Table which summarizes the options that exist in customizing the design of a glass plate. (By the author)

As it is discussed before, the possibility exists to laminate glass with glass or plastics in order to increase safety and strength. However, **it is difficult to microperforate a laminated glass panel** yet impossible. It is expected that the interlayer will be destroyed due to the induced thermal energy of the laser machine. Apart this, a limitation exist in the thickness of glass piece that can me perforated, which thickness is approximately 2-3mm. On the other side, microperforating two plates separately and laminating them afterwards raises problems regarding the accurate hole alignment.

These problems can be overpassed by designing holes of much bigger dimensions in the second plate as it is illustrated in the following sketches:

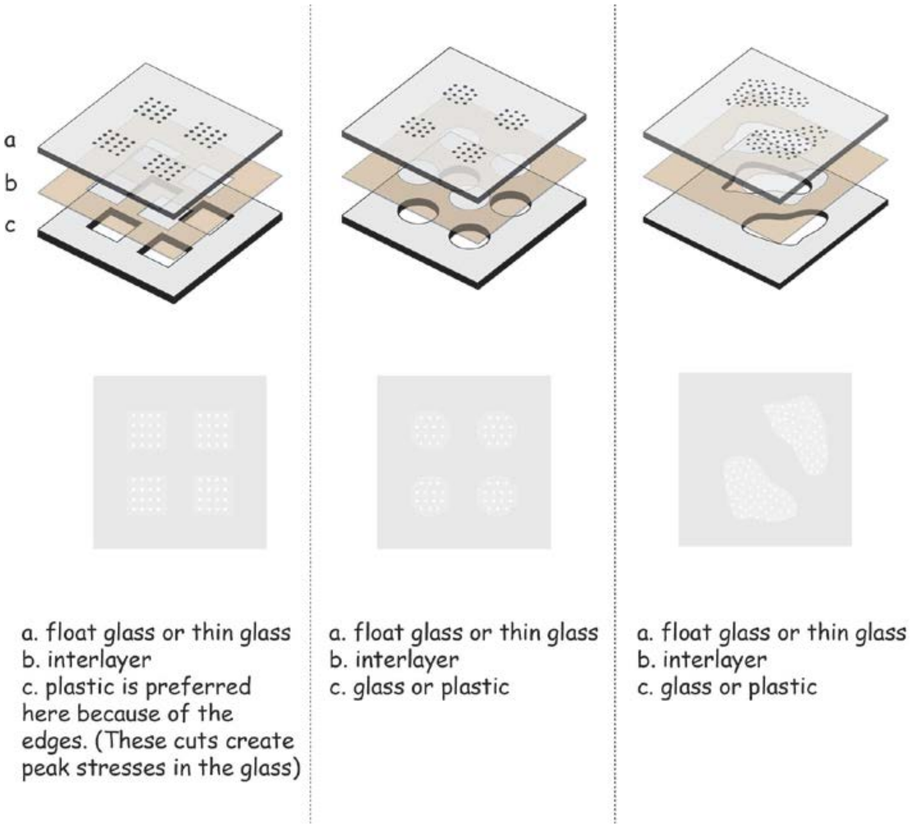


Table 2-11 Decorative patterns which show variability and customizability of the microperforated glass unit. Due to laser-based fabrication unlimited alternatives are feasible. (By the author)

2.4.4 Acoustics & Competitive Sound Absorbers

Rooms with glass boundaries or other hard surfaces like concrete suffer from **long reverberation** and **poor sound intelligibility**. Reverberation is occurred due to the repeated reflections of the sound that last more than 50milisecond. The reverberant sound reduces the clarity and the intelligibility of the sound resulting in bad acoustic conditions.

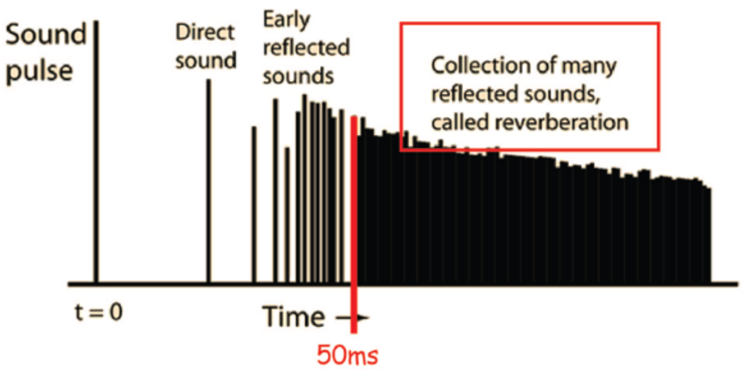


Figure 2-30 Diagram which shows the type of sounds that occur within a room, source: http://homerecordingpro.com/sound-reverberation/ modified (By the author)

What is most commonly done to confront the acoustical problem caused by long reverberation is to place heavy curtains in front of the glass or other hard surfaces. The disadvantage of the porous absorbers which are widely used today is that are opaque and thus destroying the architectural concept. The Chinese acoustician Maa found the solution in this problem by exploiting **microperforation**. With his idea of placing microperforated panel absorbers at a distance in front of a rigid wall, he developed new acoustical elements that **don't require porous damping materials.** The effectiveness of these panels is **independent the material used** and can be **exactly adjusted by modifying the geometric parameters** (see 2.4.5). Accordingly, transparent sound absorbers made out of acrylic or even normal flat glass can developed. The following image is extracted from Fuchs and Zha (1996) publication and shows the performance of an acrylic microperforated plate measured in a reverberation room:

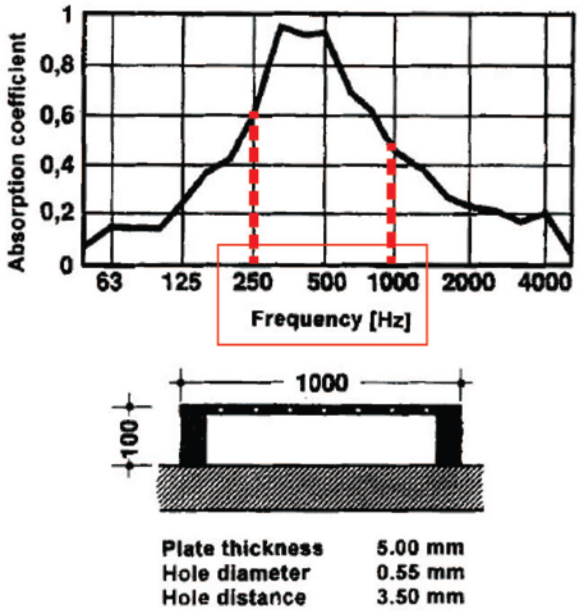


Figure 2-31 Absorption coefficient of a microperforated acrylic plate. (Fuchs and Zha, 1996)

The family of sound absorbers that exist in the market are the porous/fibrous materials, the Helmholz resonators and the membranes. Each one of them achieves absorption in different bandwidth. The following diagram (see Figure 2-32) compares the absorption coefficient of the microperforated panel with the other type of absorbers:

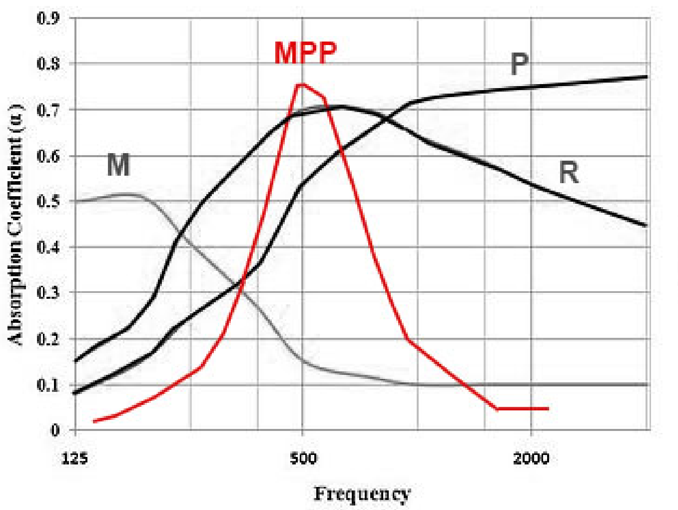


Figure 2-32 Typical sound absorption coefficient for all type of absorbers, **M= Membranes, P=Porous, R=Resonator, MPP=Microperforated plate**, modified by the author from https://en.wikibooks.org/wiki.

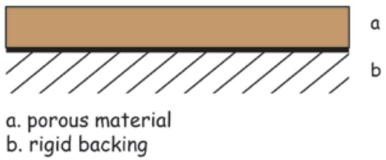
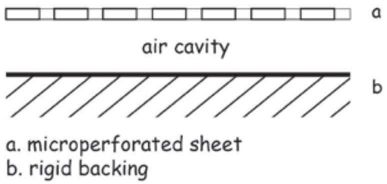
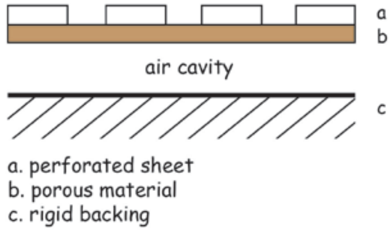
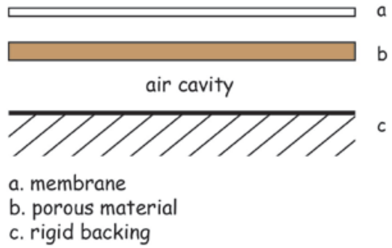
	Porous Absorber	Microperforated Absorber	Helmholz Resonator	Membrane/Panel Resonator
System sketch				
Targeted frequencies range	Mid to high frequencies 500-2000Hz	Mid to low frequencies 300-1500Hz	Mid to low frequencies 300-1500Hz	Low frequencies 50-500Hz
Description of the mechanism	Friction is caused in the pores of the material and the sound energy is converted into heat	Viscous losses occur in the neck of the very small holes as the air passes through. (no porous/ fibrous material is required)	Mass-spring system: Mass is the air in the holes. Spring is the air in the air cavity. Porous material is used for damping the sound energy.	Mass-spring system: Mass is a sheet of material which vibrates and spring is the air in the air cavity. Porous material provides damping
Technical requirements of the system	-Material thickness or distance from wall is ¼ of the wavelength -Choose material with relatively low airflow resistance	-Small hole diameter close to the size of the boundary layer δ -Perf. Ratio 0,5-2% -Hole spacing, hole diameter, material thickness, air cavity depth are adjusted to each acoustical situation -Tilting, curving, shaping the panel improves its performance	-The porous material in the air cavity lowers the absorption coefficient but increases the freq. range -Hole spacing, hole diameter, depth of air cavity and the porous material regulate the performance	-The porous material should be placed in a distance so as not to block the movement of the membrane -The porous material in the air cavity lowers the absorption coefficient but increases the freq. range
Comments	-Soft and delicate materials that need to be protected against mech. damage -Get easily dirty	-Fiber less solution -More robust than porous materials -The performance can be predicted accurately	-The performance can be predicted accurately	-The performance is difficult to predict without error

Table 2-12 Comparison table of the four different types of absorbers. Microperforated panel is found in-between porous and Helmholz resonators.(By the author)

	Porous/ Fibrous materials	Microperforated panel	Resonator Helmholz	Resonator membrane or panel
typical materials used	-fabrics and textiles -fiberglass -rockwool -aerogel -cotton	-wood -metals -polycarbonate, etfe foil -plexiglas, petg sheets	-mdf boards -metals	-rubber -mass loaded vinyl -plywood -aluminum sheet
commercial device	-acoustic ceiling tiles -panelized systems: -mounted on wall or ceiling -partitions -carpets -curtains -furniture & fixtures	-micro-perf and micro-slit panels - with air cavity behind: -suspended in front of a window -mounted on wall or ceiling -integrated in window mullion -one or double layer of stretched foil -integrated system with lighting, --heating, air conditioning, sprinkler system -sandwich panels used as partitions	-perforated/ slotted panels with damping material behind -mounted on wall or ceiling -slotted concrete masonry unit	-bass trap membrane absorber - mounted on room corner, wall or ceiling
market products	vescom acoustic curtain	deamp® clearsorber™, microsorber® acrylic clearsorber™foil, microsorber® film	diffusorbloxr, finemicro|fm panelite acoustic, acoustic plastic glass|pg	modex tm bad™ panel
most common applications	-everywhere except environments where bacteria and fiber contamination is a problem	-atria, glass surfaces in general wherever fibreless solution is required	-speech & music halls -theaters -offices	-ventilation systems -small rooms

Table 2-13 Comparison table of the characteristics of four different types of absorbers. (By the author)

2.4.5 The Microperforated Glass Sound Absorber

The principle

A glass plate containing holes in submillimeter range is placed at a distance from a hard reflective surface. Absorption occurs because **the vibration of the air in the tiny holes is damped by shearing forces at the neck of the holes**. Porous or fibrous material to be placed in the air cavity is not required because damping occurs inside the small holes. However, it does improve overall absorption behavior if placed in the cavity. The efficiency of the system depends on the mass, the stiffness and the inherent friction whereas these **parameters can be adjusted** following the specific acoustic requirements. Consequently, if the diameter of the hole, the distance between the holes, the thickness of the panel and the distance from the back wall are correctly designed, a relatively wide banded sound absorber consisting out of glass can be developed.

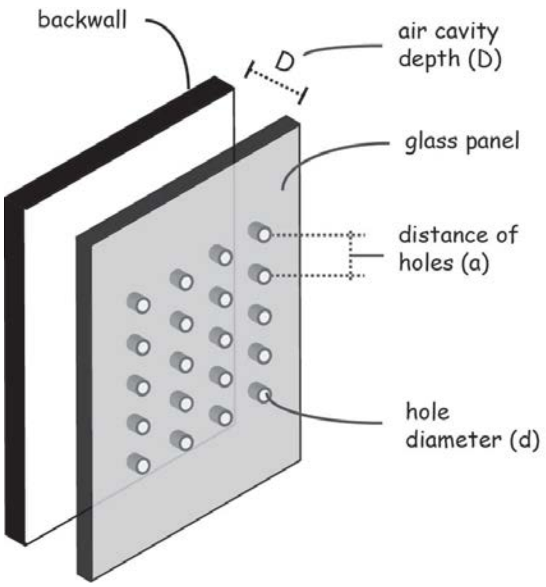


Figure 2-33 Schematic of the system of a microperforated glass absorber. (By the author)

The system

Fuchs and Zha (1997) provided in their publication a qualitative and quantitative description of the system in order to achieve optimum efficiency.

- **Material Type of the panel**

The performance of the system is largely **independent of the material** used given that the panel doesn't vibrate. Panel vibration causes the relative velocity of the vibrating air in the hole to drop and thus the absorption efficiency is reduced.

- **Hole diameter**

Accepted range is 0.1-3mm, but in the lower range of **0.1-2mm** the system has its maximum effect. Fabricating this range of holes in glass is feasible. The size of the holes and the thickness of the panel to be perforated define the suitable manufacturing processes.

- **Distance between holes**

Optimum distance between holes is **2-20mm**.

- **Panel thickness**

The system is efficient in the broad range of 0.2-30mm. When using float glass, taking into consideration the constraint of minimum thickness size of 2mm, the range from **2mm to 12mm** is mostly preferred. However other technical considerations regarding the design and the manufacture ask for minimum weight and thickness. The innovation of thin glass allows for fabricating microperforated glass in thicknesses less than 1mm. This technical feasibility creates glass products with acoustical specifications, other than that of the already known float glass.

- **Air cavity**

The optimum depth is **25-100mm**. This space may be closed (see Fig. 2-34,a) or open without lateral boundaries (see Fig. 2-34,b). Absorption occurs as long the distance is small compared to the length and width of the front panels (Fuchs & Zha, 1997). However, keeping the edges closed has the advantage of less maintenance due to dirt and dust.

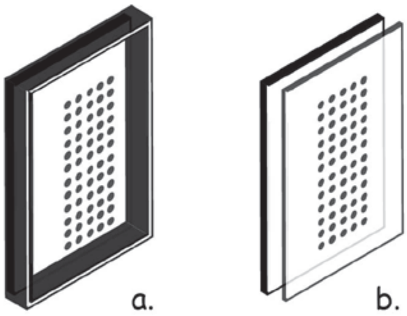


Figure 2-34 Closed (a) or open edges (b). (By the author)

Performance

The microperforated panel absorber performs well in the sound spectrum of **low to mid frequencies** (250-1500Hz). It is characterized by a **peak around resonance frequency** and more broadband damping than this of a conventional perforated-panel (d>4mm) absorber with no additional porous material. This tendency can be seen in Figure 2-35 where the acoustic line of a microperforated panel is indicated in red and this of a perforated panel resonator with no damping material, in blue.

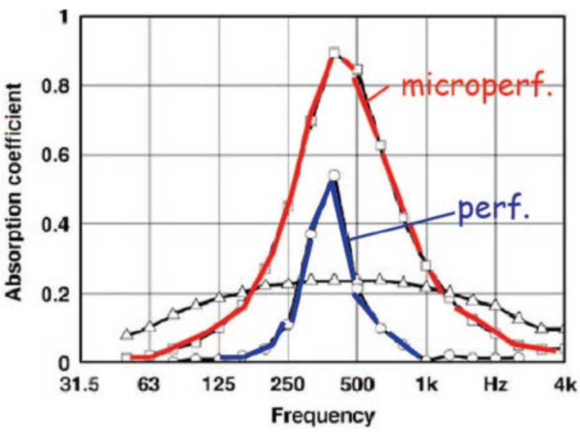


Figure 2-35 Characteristic absorption line of a microperforated (hole diam.=0,45mm) and perforated (hole diam.=3mm) panel resonator, made out of 3mm thick plates with the same perforation ratio 0,14% and distance from wall at 50mm. (modified by Fuchs, 2013)

2.4.6 Methods to improve the performance

The shortcoming of the microperforated panel option is that its absorption frequency range is **limited to a narrow band around the resonance frequency**. Alternative panel configurations will be discussed to overcome this problem by **widening the absorption band and preserving transparency.** There are four options to be presented here which are summarized in Table 2-14 and analyzed further below.

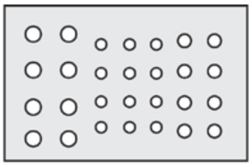
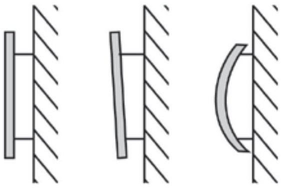
1	Adjusting and combining the geometric parameters (hole diameter, perf. ratio, glass thickness, air cavity depth)	
2	Tilting, curving, shaping the glass	
3	Combining layers of glass sheets with different geometric parameters	
4	Variations in hole cross section of a thick* panel, straight or tapered (*thick is considered the panel >1mm)	

Table 2-14 List of possible methods which improve the efficiency of a single microperforated glass panel. (By the author)

1. Adjusting the geometrical parameters

In microperforated absorbers, the air in the holes, as a mass together with the air enclosed in the space of thickness D as a spring, oscillates in the manner of a spring/mass system (Fuchs & Zha, 1996). It is important though that the size of the individual hole is so small that approaches the size of the acoustic boundary layer δ, see Figure 2-35. damping occurs due to the viscous losses as air passes through the tiny holes. These losses can be varied by choosing the geometrical characteristics of the plate which are: ***the diameter of the holes (d), the thickness of the panel (t), the distance between the holes (b) and the depth of the air cavity (D).*** By varying the above mentioned parameters of a single microperforated panel, the optimum design can be determined and calculated in every detail for the specific problem.

The optimum hole diameter is defined by Fuchs (1997) with the following rule and it is illustrated in the scheme (Fig. 2-35):

- When **r0/δ>>>1**, then the panel functions more like a Helmholz resonator and no sufficient damping occurs if no porous material is additionally used.
- When **r0/δ~1**, then the optimum damping occurs due to internal friction. The hole is designed in submillimeter range in order to approach as much as possible the boundary layer δ.

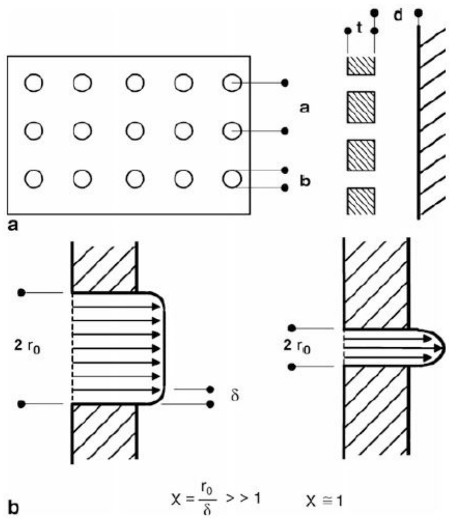


Figure 2-35

Left: the hole is big, $r_0/\delta>>>1$ and fits to a Helmholz resonator.

Right: the hole is very small in sub millimeter range, $r_0/\delta{\sim}1$ and the optimum damping is achieved functioning as microperforated panel.

Following to this, an overview will be given on how the absorption curve of the panel shifts when each one of the geometric parameters changes.

Panel thickness (t)

In section 2.4.5, the acceptable panel thickness is found in the broad range of 0.2-30mm. For glass, the thickness is limited from 2-12mm due to manufacturing constraints. Looking at the following Figure 2-36 from Prasetiyo et al. (2016), when the **thickness of the panel increases, the peak absorption is shifted to lower frequencies.**

Material	t (mm)	σ(%)	d (mm)	D (mm)
Acrylic	1.5	0.79	0.9	50

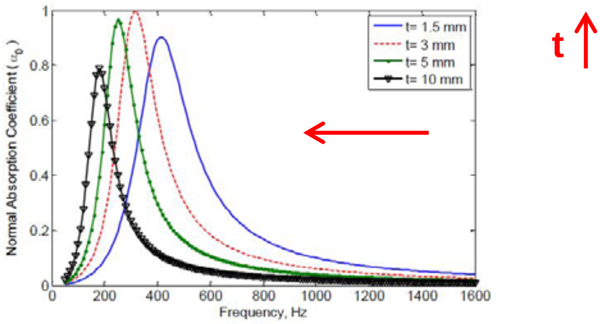


Figure 2-36 Absorption coefficient comparison for different panel thickness t with aircavity depth D=50mm (Prasetiyo et al., 2016).

Perforation ratio

For microperforated plates a relatively small perforation ratio is chosen of 0.5-2% (Fuchs and Zha, 1996). By doubling the number of holes per m^2, the maximum absorption coefficient shifts by about half an octave from 500-750Hz..

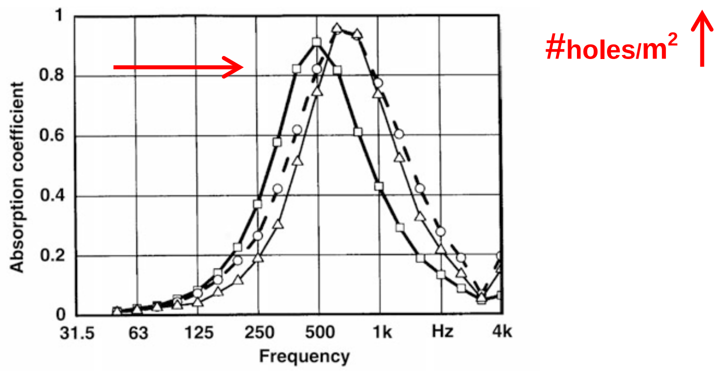


Figure 2-37 Absorption coefficient comparison for panels with different numbers of holes per m^2, □154.000 holes/m^2, ◊ 309000 holes/m^2, (Fuchs and Zha,2013)

Air cavity depth (D)

The air cavity depth defines the stiffness of the spring. **Increasing the depth of the air cavity** the stiffness of the spring is reduced and thus the absorption curve **is shifted to lower octave bands.** Placing several panels with increasing distance from the wall has proven to be advantageous (Fuchs and Zha, 1997).

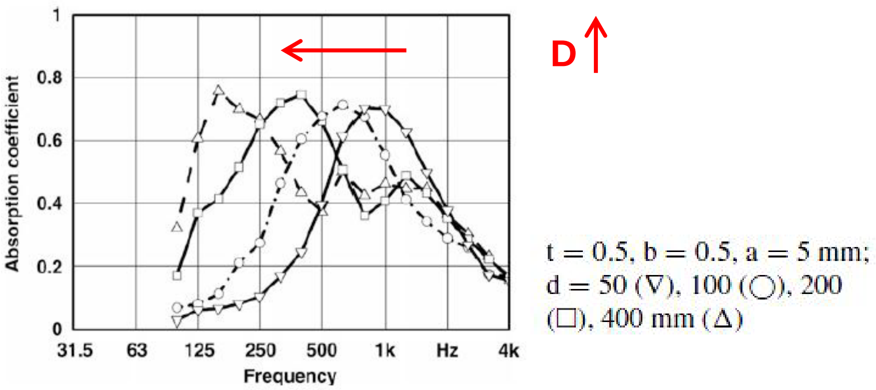


Figure 2-38 Absorption coefficient comparison for panels with different air cavity depths, (Fuchs and Zha,2013)

Conclusion

By choosing the geometrical parameters, the performance of a microperforated panel can be determined and calculated exactly in every detail. Hence, the design of the panel can be adjusted to the specific acoustical situation. **Combining** different geometrical parameters in a single glass panel (see Fig. 2-40, a) or between several panels in a room (see Fig. 2-40, b), we can achieve absorption in a **broader bandwidth.**

As for an example, the absorption comparison graph of three plain glass plates of 5mm thickness and different hole diameter and cavity depth, is presented below. If the three different panel types are combined, the final absorption line is indicated in red. It can be seen that a wider band width is achieved having peaks at the resonance frequencies of each panel configuration.

(mm)	T	d	b	D	P%
Type 1	5	0.5	2.5	25	3.14
Type 2	5	0.65	4	50	2.07
Type 3	5	0.80	6	100	1.4

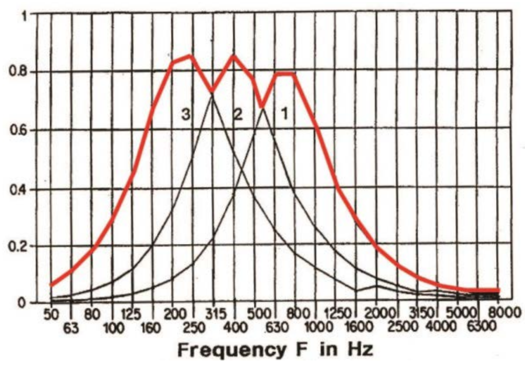


Figure 2-39 Absorption coefficient comparison for three glass panel with different air cavity depths. (Fuchs and Zha.,1997)

The following sketches propose two design alternatives on how the three above mentioned panel types can be combined in one acoustic solution for broader bandwidth efficiency:

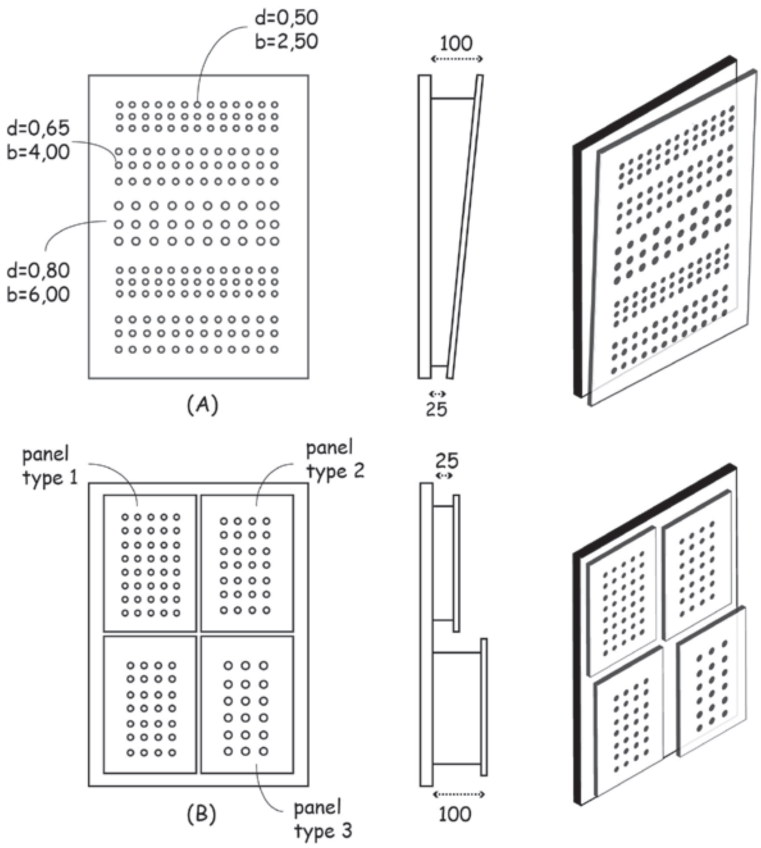


Figure 2-40 Design alternatives for combining different geometry configurations. a. Single Panel, b. Combination of multiple panels. (By the author)

2. Tilting, curving, and shaping the glass to achieve diffusion in mid to high frequencies

To augment the efficiency of the microperforated glass absorber, the glass pane can be curved, tilted or shaped within the manufacturing limitations in order to diffuse and scatter the mid to high frequencies.

Shaping the glass surface in a form other than flat parallel to back wall has two advantages: Firstly, except the absorption in mid to low frequencies, also redirection and diffusion of the mid to high frequencies is occurred. Secondly, the **variable cavity depth** achieves absorption in broader bandwidth as it is discussed in the previous section.

The possible design shapes and their effect in redirecting the mid to high frequency sound are illustrated below:

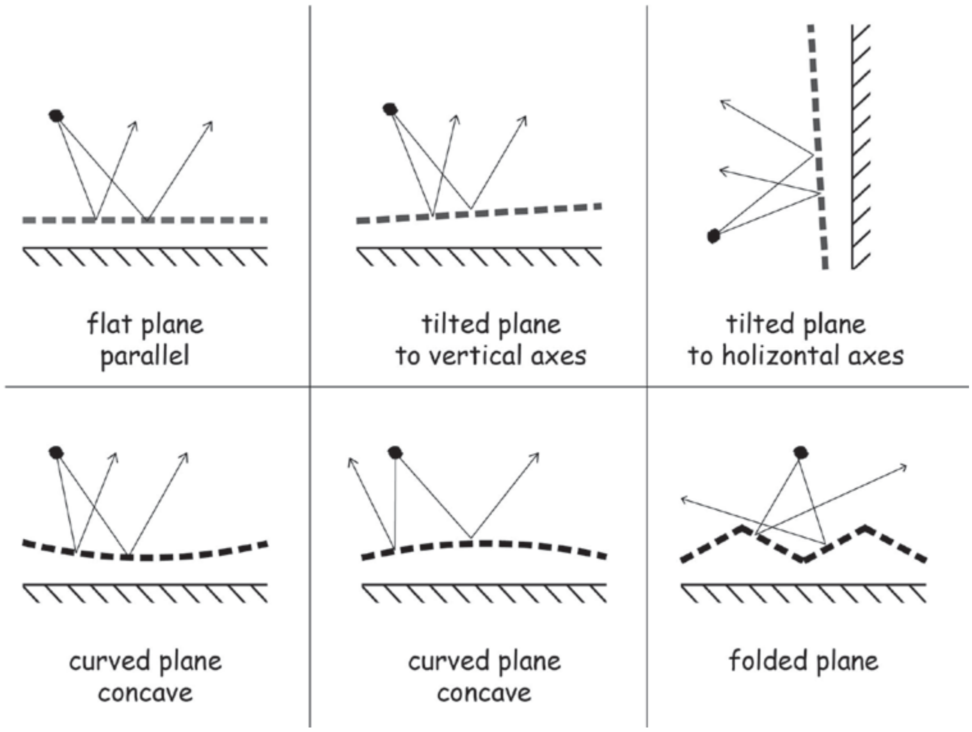


Figure 2-41 Alternative concepts for tilting, curving and shaping the glass unit in order to achieve redirection/ diffusion of mid to high frequency sound. (By the author)

3. Combining layers of glass sheets with the same or different geometric parameters

A very broadband sound absorption with multiple absorption peaks can be attained by placing microperforated panel side by side at varying distances from the solid wall. It can be a **double or triple layer system** where each panel can have its own geometrical configuration. In multilayered assembly, the microperforated absorbers can be designed in such a way that the final unit absorbs more than 80% of the significant frequency range on one (Fuchs & Zha, 1997). The acoustic efficiency of the layered structure is presented here through the absorption comparison of a single layer panel and a triple layered microperforated panel:

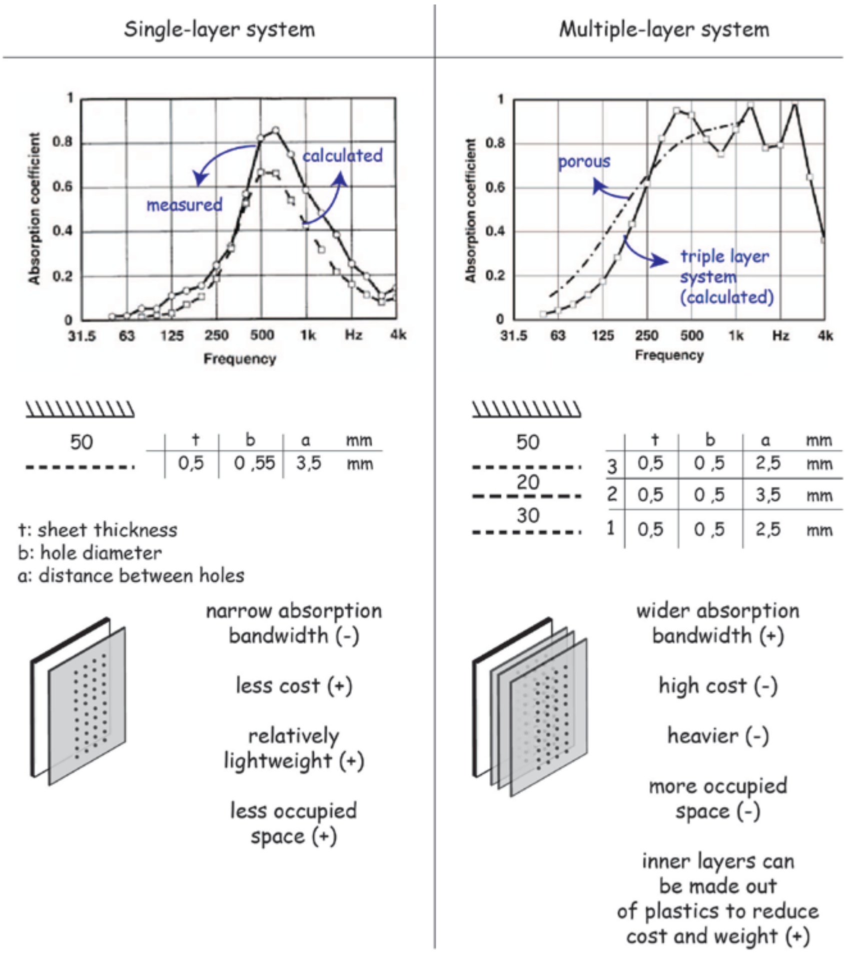


Figure 2-42 Comparison table of a single layered glass system to o triple layered system. The diagrams are taken from Fuchs and Zha (2013) and modified by the author.

Combination of glass with plastics in multi-layered structures

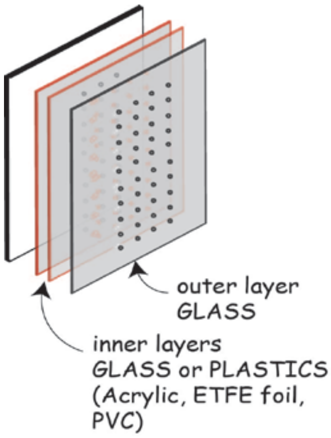
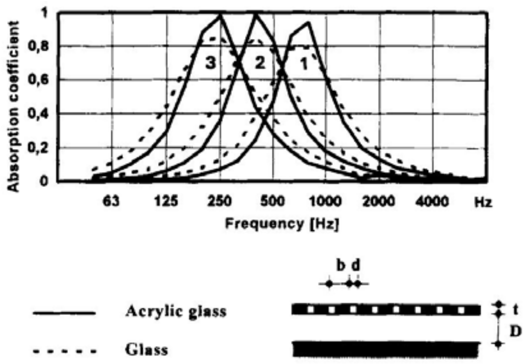


Figure 2-43 Combination of glass with plastics in the multi-layered configuration. (By the author)

In 1996, Fuchs and Zha presented in their research paper *"Acrylic-glass Sound Absorbers in the plenum of the Deutscher Bundestag"* the absorption of glass and acrylic panels in a combined diagram (see Fig. 2-44). It is seen that **the maximum absorption of glass is somewhat lower than that of acrylic, but it is a bit more broadband, due to their different thermal conductivity.** However, the deviation is small so we consider the performance of the type of materials equal.

It is proposed that in case of a multilayered absorber, the inner microperforated plates could be made out of clear transparent acrylic panel as presented in Figure 2-43. Acrylic is lighter and cheaper than glass; as a result, **the overall weight of the multilayered system** is reduced. The acrylic panels are not exposed to the risk of unwanted scratches because they are protected from the outer glass layer.



	t [mm]	d [mm]	b [mm]	D [mm]	σ
Typ 1	5,00	0,50	2,50	25	0,0314
Typ 2	5,00	0,65	4,00	50	0,0207
Typ 3	5,00	0,80	6,00	100	0,0140

Figure 2-44: Absorption comparison of tree different panels made out of glass and acrylic (Fuchs and Zha,1996)

4. Variations in hole cross section of a thick panel

Taking into account the rule for highest performance of a microperforated plate, the thickness of the sheet should be roughly equal to the diameter of the hole. If the **panel needs to be much thicker** so as to ensure structural stability, then the **performance** of a thick microperforated plate **drops**. Prasetiyo at al. (2016) proposes on his paper regarding "*Inhomogeneous perforation thick micro-perforated panel sound absorbers"* that **by modifying the section of a hole into e.g. a tapered hole, the acoustic performance of the thick plate can be improved.** From practical point of view this poses some problems which need further investigation such as manufacturing feasibility. Nevertheless, there are already available manufacturing techniques, such as the ultrasonic machining (USM), which makes the fabrication of slanted, tapered or non-round holes feasible, yet expensive.

The following table presents design alternatives related to the shape of the hole:

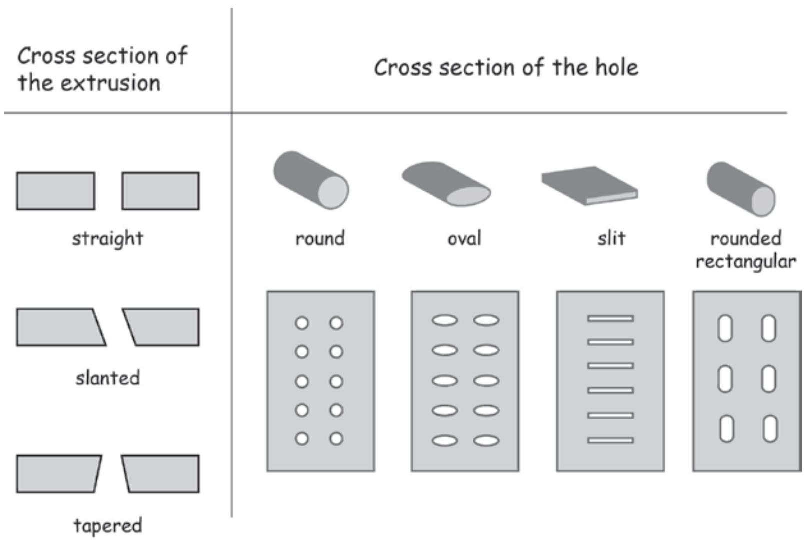


Table 2-15 Design alternatives for shaping the hole cross section. (By the author)

2.4.7 Framework for Designing the Sound Absorber

The following table summarizes the finding of the technical analysis that was done regarding acoustics in Section 2.4.6. It proposes a framework to be used as a guide when designing the acoustic requirements of a microperforated glass plate:

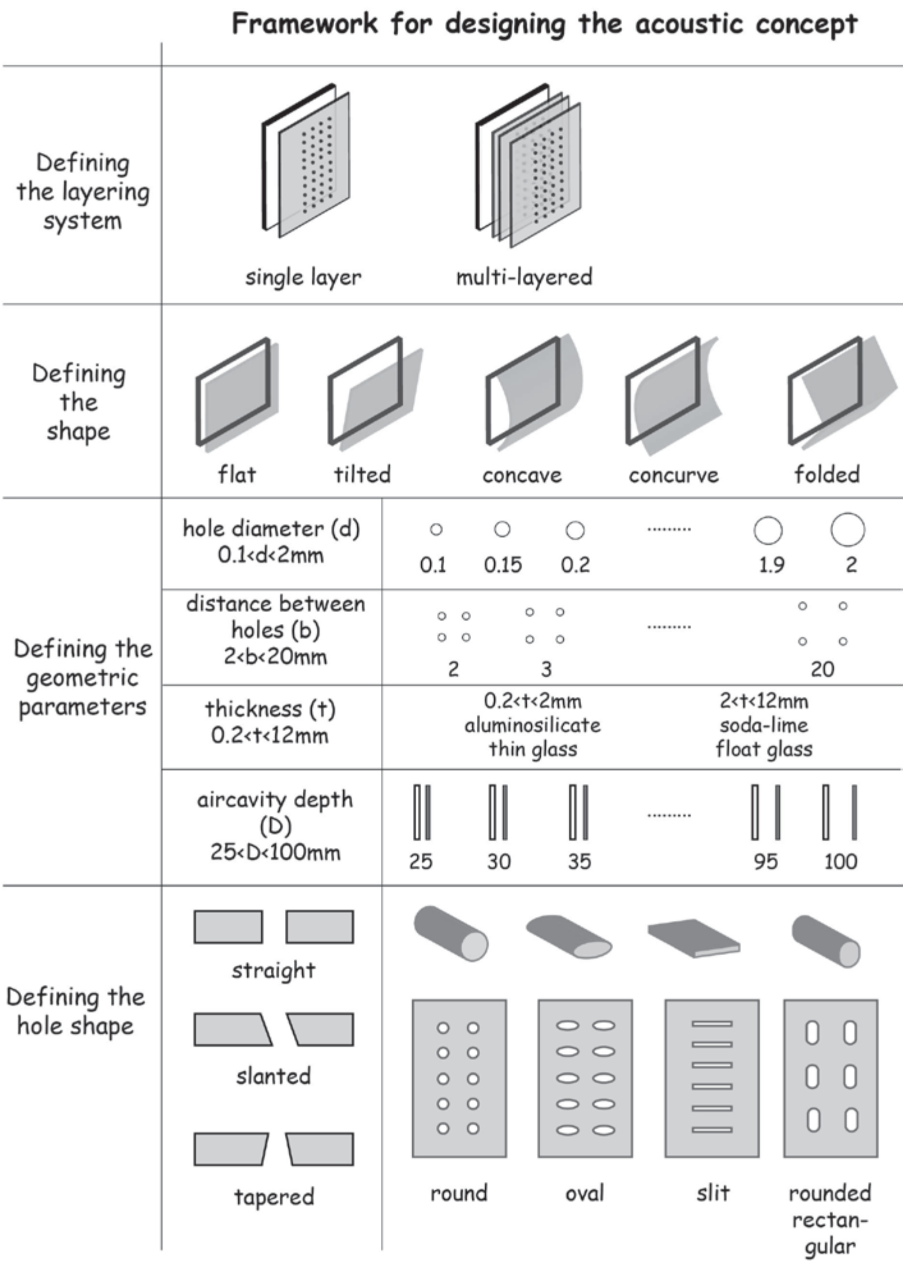


Table 2-16 Framework for designing the Sound Absorber. (By the author)

2.4.8 Interior Applications of the Glass Sound Absorber

In this section the application possibilities of a microperforated glass absorber in room acoustics will be discussed. The research starts with the presentation of few case studies which are characterized by **large glass surfaces** and **demand for acoustic treatment due to high reverberation and flutter echo** within the space.
Researching few existing projects that integrate acoustic solutions, competitive to the glass sound absorbers will help us to **understand the market**. Firstly, a list of possible type of rooms that could require a microperforated glass plate will be presented together with their associated acoustic requirements. Then, all possible positions of the glass sound absorber in the room will be illustrated in schemes in a common table.

Figure 2-45 Plenum of previous Parliament in Bonn. In that building was the first realization of acrylic glass microperforated plates in 1992.
Source: http://www.bonn-region.de/sehenswuerdigkeiten-kultur/plenarsaal-wasserwerk.html

Case studies

1. German Historical Museum in Berlin

	 View of the yard of the Historical Museum in Berlin. (source:https://www.flickr.com/photos/henmagonza/6170433108)
Problem	Long reverberation (8-10sec) Flutter echo
Type of space	Historical building Atrium with glass roof
Solution	Two layers of translucent micro perforated plastic foil suspended under the glass roof, concave shape
Product	Clearsorber™ Foil -0.1mm thickness -polycarbonate -translucent -easily installed 
Acoustic Result	Reverberation dropped 4 seconds

2. Glass Music Hall in the Beurs van Berlage in Amsterdam

View of the music glass box in Beurs van Berlage in Amsterdam.

Problem	Long reverberation (5sec) Focusing of the sound
Type of space	Concert hall
Solution	-one of the two side walls is not parallel -metal perforated absorbing panels suspended on the inside side walls in 20cm distance -large polyester sails suspended on the side of curved wall -acrylic domes in the ceiling
Product	No info.
Acoustic Result	Reverberation dropped in 1,5 seconds

3. Van der Mandelezaal courtyard in Prinsnehof Museum in Delft

View of the courtyard in the Prinsenhof museum in Delft

Problem	Long reverberation Flutter echo
Type of space	Historical building Atrium with glass roof Multifunctional public space (music hall, speech hall, exhibition hall)
Solution	sound baffles suspended from the ceiling
Product	No info.
Acoustic Result	No info.

4. Het Scheepvaartmuseum in Amsterdam

	 View of the courtyard in Scheepvaartmuseum in Amsterdam.
Problem	Long reverberation Flutter echo Low sound intelligibility
Type of space	Historical building Atrium with glass roof Public space
Solution	Acoustic flooring system
Product	Customized product: 9cm travertine slabs with very thin cross-shaped openings 
Acoustic Result	Communication improved

5. Museum Voorlinden in The Hague

	 View of the indoor space of Voorlinden Museum in The Hague (source: http://www.kraaijvanger.nl/nl/projecten/453/museumvoorlinden/)
Problem	Long reverberation Echoing
Type of space	Museum
Solution	Two layers of stretched ceiling. The lower is a translucent foil and the upper is a transparent microperforated ETFE foil, both suspended under the glass roof.
Product	Stretched ceiling: -ETFE -translucent/ transparent -easily installed
Acoustic Result	Improved the acoustics quality of the indoor high ceiling space

Possible Room Functions

The analysis of the above mentioned case studies gives some interesting information according to the type of spaces that suffer from bad acoustics in lower frequency range and the demand for an acoustic solution is necessary. These are large indoor spaces or spaces with **high ceiling with extensive glass** surfaces or other hard materials. Usually they accommodate a **special function** such as music or speech hall that require careful acoustic design in order to achieve the correct values of reverberation time (RT) and sound clarity (STI). On the other side it can be a public space for gatherings or exhibitions where the communication is difficult due to the multiple sound reflections.

The following table summarizes a list of type of spaces where the microperforated glass absorber could be applicable together with the required reverberation time (T) and most common positions within the room. The reverberation values are taken from the diagram below, see Table 2-17.

Type of space	**Reverberation time (T)**
	Position in the Room
Atria for general purpose (speech & music)	T= 1.5-2.5s
	Ceiling, sound baffles
Churches	T= 1.5-2.5s
	Ceiling, sound baffles, partition on rollers
Multipurpose auditorium (speech & music)	T= 1.5-1.8s
	Wall, ceiling, curtains, seats
Concert halls	T= 1.7-2.3s
	Wall, ceiling, curtains, seats
Lecture and conference rooms	T= 0.7-1.1s
	Wall, ceiling, curtains, seats

Museums & exhibition halls	T= 0.8-1.4s	
	Ceiling, floor	
Libraries	T= 0.8-1.0s	
	Wall, ceiling, floor, between desks, curtains, furniture	
Restaurants	T= 0.8-0.7s	
	Wall, ceiling, partitions, furniture	
Open-space office	T=0.7-0.9s	
	Wall, ceiling, between desks, furniture	
Classrooms	T=0.6-0.4s	
	Walls, ceiling, furniture	

Table 2-17 Table which summarizes all type of spaces that could require for a microperforated glass sound absorber. The left column presents the associated reverberation time (according to Fig. 2-55) and the possible positions.(By the author)

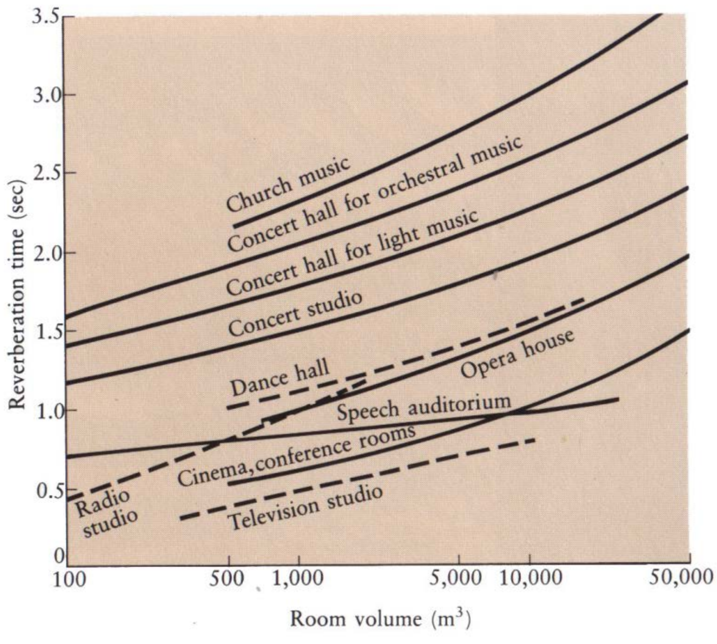


Figure 2-46 Ideal average reverberation time versus room volume for various types of rooms, source: Web.

Panel Positions within the Room

The types of possible applications are organized under three main categories as illustrated in summery in the following table:

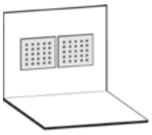
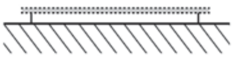
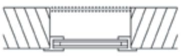
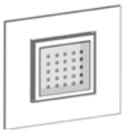
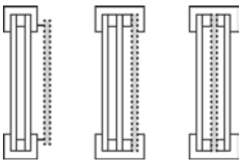
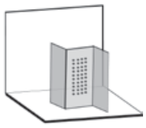
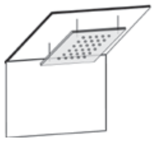
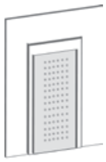
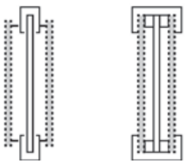
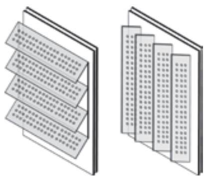
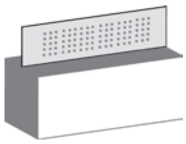
Panel absorber attached in front of building components	**Absorber integrated into building components**	**Separate building component**
 Wall panel  a. *attached to wall*  b. *in front of window*	 Windows/ curtain walls  a. b. c.	 Free-standing partition  Lighting fixture
 Ceiling	 Doors  a. b.	 Window blinds  Furniture (cupboard, phone booth, desk division)

Table 2-18 Types of possible positions of a microperforated glass panel within a room. (By the author)

2.4.9 Product Lifecycle

Apart from the research in product's capabilities, attention has to be given in the whole process. **Designing the process and not just the element can create additional value to the product and balance the high cost.** For example, the act of designing for low maintenance and easy assembly/disassembly adds value to the product and increases the price that customers are willing to pay.
Hence, the phases of product's life span are analyzed in conjunction with the considerations that should be taken at each one of them in order to increase the value.

Firstly, the following scheme illustrates the phases of the lifecycle of the microperforated glass sound absorber (see Fig. 2-47).

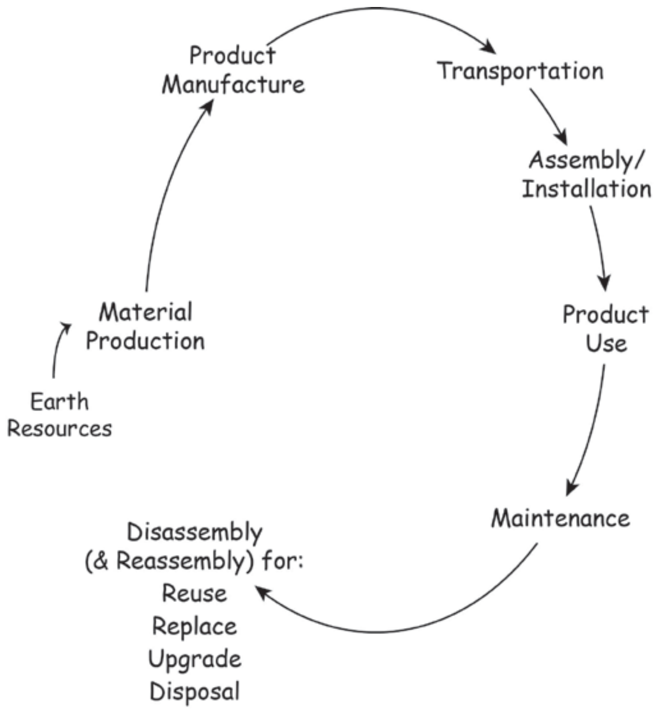


Figure 2-47 Diagram which illustrates the product process during its life span. (By the author)

Design considerations which can reduce the cost and/or increase product's value at each phase	
Process	**Design considerations**
Material Production	• Design within the standard glass size limitations and specifications
Product Manufacture	• Examine carefully which micromashining method is suitable for the specific design so to keep the cost low (e.g. In laser-based techniques, fabri-cating multiple diameters in the same glass workpiece increases the cost) • If a machine/system is required to be built for a single product, the cost per unit decreases when the production volume is increased • Use standardized connections, fasteners which are cheaper due to their availability
Transpor-tation	• Reduce the weight and the size of the elements
Assembly/ Installation	• Prefabricating a subsystem or the whole system reduces the time needed for assembly • Glass is vulnerable in breakage. Strategy to prevent failure on site during installation should be considered.
Product Use	• Easily adjustable system to increase performance targets (e.g. air cavity width, inclination, addition of extra layers)
Maintenance	• Design for low maintenance (e.g. closed edges reduce dust and dirt in air cavity, select micro holing method for smooth edge hole surface) • Standardized connections and modularity makes it easier and cheaper to replace the faulty part • Easy accessibility to the parts that need to be cleaned or repaired • Reduce the weight of the element so to make easier and less costly the operation (less people, tools, machinery needed)
Dismantling Disassembly (& Reassembly)	• Make the design modular for easy service and upgrade • Eliminate adhesives in parts that require dismantling for service or upgrade • Minimize the number of fasteners and tools to control time

Table 2-19 Design considerations which can reduce the cost and/or increase product's value. (By the author)

2.4.10 Maintenance

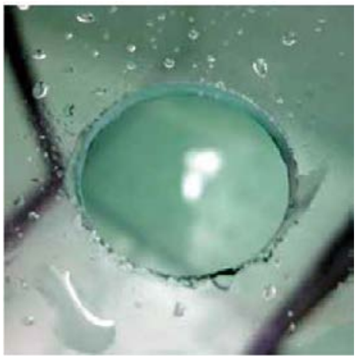
The maintenance of a building product is an aspect that should be taken into consideration early in the design process, so as to ensure that the product can be returned in its usable condition within short time and in low cost. Developing a commercial product which is not only functional and beautiful but also requires less and easy maintenance is desirable. Speaking about glass which is a clear transparent and fragile material, major maintenance activities include **cleaning** of the surface from fingerprints, dust or dirt and **replacement** of the glass piece if this breaks. Regarding the building product as a whole, additional maintenance is required for **fitting of the mechanical connection** of glass panel with the building compartment (etc. wall, ceiling or window).

Designing for maintenance means to consider in the design of the components those strategies that **reduce the frequency, the cost and the time** needed to execute the abovementioned activities.

Reducing the possibilities of replacing broken glass pieces depends on the design of the structural safety of glass. The problem of cleaning is analyzed below and maintenance strategies are assessed.

Dust at the edge of microholes

It is worth to mention here that the microholes don’t get clogged up even in very dusty environments, probably due to the vibrating plug of air within the pores (Cox & D’ Antonio, 2009). However, if the resulted edge surface of the hole after machining is not smooth enough but presents microchips, small cavities in micro scale are created which allow the settlement of dust. The problem is that this in time might cause a grey color edge effect when glass is sighted from an inclined angle. This needs further investigation and experimentation in order to describe the effect accurately. In that case, cleaning the dust from the microholes edges would be difficult because these are not easily accessible with tools. Concluding on this, selecting a



micromashining technique that causes the less possible surface roughness would be desirable not only for reducing stress concentrations in glass but also for preventing the settlement of dust.

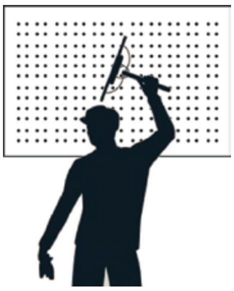
Figure 2-48 Hole in a glass pane, not polished, so all micro damages due to drilling are visible. These damages not only affect the stress distribution around the hole but also create cavities for dust settlement. Source: C. Louter presentation.

Dust and water drops on the glass surface

When glass is designed in its water-clear version, dust and dirt settlement on its surface reduces the aesthetic performance of the material. In this case frequent cleaning of both glass surfaces is required, **depending on how dusty the environment is and where the glass is placed within the room.** If for example, glass is placed in front of a window, the need for undisturbed view requires good cleaning in both sides. If the window is operable then a more frequent cleaning is required because not only dust but also dirt and humidity from the outside mess up the back surface of the glass. If on the other side, glass is attached in front of a colored wall or it is digitally printed itself then the dusty surface is less visible, so cleaning demand is low.

Maintenance strategies

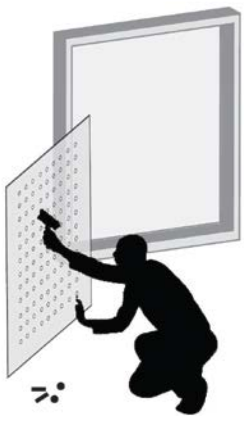
Each design project has each own demands regarding the frequency of cleaning that should be taken into consideration in the early stage of product development. The required maintenance strategy affects the design of the connections and the cost of the product. The **outside surface of glass** is accessible and can be easily cleaned by one person



using a wet cloth. The difficulty lies in the glass surface that faces the air cavity.

In the following table few possible options are proposed that ensure either accessibility to the air cavity or reduce the dirtiness of the aircavity as much as possible.

Designing for Maintenance

	**Closed/ Sealed Edges in a Frame** (+) Less dust is induced in the aircavity (-) Transparency reduced due to opaque elements (frame, sealing) (-) No access in the aircavity only if the device is dismantled in the factory ***For Low results***
	**Operable Frame** (+) Easy access manually, without tools (-) Costly solution (-) Transparency reduced due to opaque elements (frame, hinges, hardware) (-) Moving furniture when opened ***For High cleaning results***
	**Demountable Connection** (-) The access requires tools and time (-) Expensive maintenance process (-) Limitation in designing lightweight, small glass elements (+)The element can be repaired, replaced on site, dry connections (+) Flexibility in designing a frame or not, less opaque elements is possible (-) Risk for glass breakage during cleaning ***For High cleaning results***

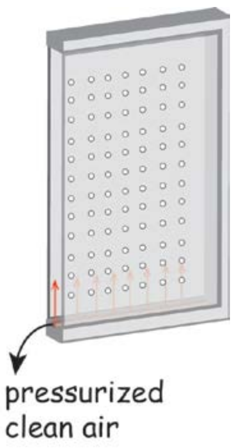
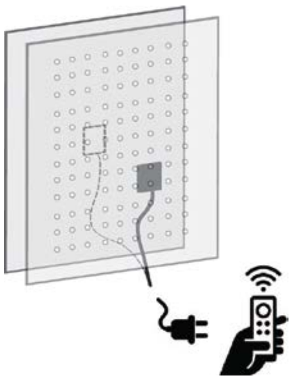
	**Pressurized Clean Air in the Aircavity** **(Closed Cavity Façade Method)**
	(+) The cavity is automatically cleaned without the need of people and tools (+) No laboratory cost (+) Designed with or without closed edges (thin seams are efficient) (+)No need for operable or demountable connection (-) High initial cost (for piping air distribution and handling system) ***For Medium to High cleaning results***
	**Robot Window Cleaner**
	(+) The cavity is automatically cleaned by the robot without laboratory cost (+) No need for operable or demountable connection (+) Allow for freedom in the design (-) Maintenance cost for the robot ***For Medium to High cleaning results***

Table 2-20 Proposed methods to clean the glass surfaces that face the aircavity. (By the author)

2.4.11 Stakeholders

Product's stakeholders are those groups of people or individuals who are affected by the product's success or failure (Ulrich & Eppinger, 2015). The list of stakeholders consists of external and internal players. External are for example the users of the space or those who make the buying decision about the product such as the client, the developer or the consultant (architect, acoustician). Internal are people who are involved in the development process such as the production or sales team. The stakeholders define the demand and the requirements of the product. Knowing who they are, it is useful in order to consider their needs at the early stage of product design so as to develop a successful market oriented product.

List of Stakeholders involved in each process

Process	Stakeholders
Buying Decision	Client/Owner Architect General Contractor
Transportation	Sub-Contractor* (or external company)
Marketing	Sales representative
Installation	Sub-Contractor*
Design	Architect/ Facade Eng. Acoustician Sales representative
Maintenance	Cleaner or maintenance company Sub- Contractor*
Production	Micromashining Fabricator Glass & System Supplier Sub-Contractor*
Functionality	Client/Owners Users

Table 2-21 List of stakeholders. (By the author)

2.4.12 Summary of the Results

In **Section 2.4.1,** we learned about the different **types of glass**, and their properties in comparison to transparent polymers such as PC, PETG and PMMA. The common soda-lime glass which is relatively inexpensive and known as a machined product for cutting, drilling is selected as the most appropriate glass type for the development of the sound absorber. However, the aluminosilicate glass type which is also known as thin glass used in electronics, has potentials in the future, due to its advantages of having small thickness, high strength and ability to be micro machined. Currently, the cost is high and not used as building material yet; that's the reason why it is a proposition for the future. If normal glass is compared to the **competitive transparent polymers**, its advantages are found in its better scratch and UV resistance, resistance in temperature differences due to its low thermal expansion and better aging. Glass is a robust material compared to the cheap view of plastics and that is the reason why, most of the architects choose for glass regardless it's higher cost. Plastics, if are constantly subject in higher temperatures creep and deform (sag), whereas if are exposed in UV light become yellow and degrade.

In **Section 2.4.2**, all the available **manufacturing processes** with glass are presented. The fabrication of a microperforated glass plate with the available technology today, is feasible. There are various techniques available based on different technologies. Each one of them performs differently regarding the cost, the speed of the process and the quality of the surface around the hole. The most suitable one must be chosen by experts considering the needs of the project. Limitations exist regarding the thickness and the size of the glass piece. Building a machine, e.g. laser-based, which can machine special glass sizes or by combining other technologies it can be e.g. faster, is possible. The technology of micromachining progresses so fast, that current limitations can be overpassed

in the near future. The fabrication of different sizes of hole diameters randomly located on the workpiece is possible since the arm is controlled by computer.
Cost of microperforating is an issue, because it's very high, resulting in a very expensive glass sound absorber. Also, cost is expected to drop in the future as the technology develops. In following **Section 2.6.2,** a more detailed analysis of the cost is presented based on the information given by an expert[5] in microfabrication in glass.

Section 2.4.3 gives an overview of all **design possibilities** that exist with glass. Microperforated glass can be **customized** with various characteristics such as color, texture, digital printing and curved form. Lamination is also possible, either with glass or plastics, overpassing the problem of aligning the holes with the proposed design of Figure 2-x.

The **acoustic efficiency** of the microperforated glass plate is analytically explained **from Section 2.4.4 up to Section 2.4.7.** The advantages of this mechanism are the absorption without the use of porous/fibrous materials and the possibility to measure the performance in detail. **Section 2.4.6** presents design methods that can **broaden the acoustical efficiency** of the system. The less costly of them is to arrange the micro perforated panels within the room in various distances from the backwall or to tilt/ curve the panel itself. The most efficient method though, is the multilayered system yet the most expensive. The cost could be reduced if plastic panels are used instead of glass referring to the inner layers.

Section 2.4.8 investigates all **possible type of spaces and positions within a room** that the glass sound absorber can get. The targeted market is found in public spaces where reverberation can be a problem. Reverberant spaces are mostly surrounded by hard surfaces such as glass or concrete or are rooms of special function like speech or music halls. Knowing

[5] Thomas Melle, Head of MicroFab, 4JET microtech GmbH & Co. KG

the targeted type of spaces, a first step in defining the market size is achieved. Similarly, listing all possible application types will help us to decide which of them are suitable in developing a successful sound absorber.

Value can be created through the **whole process**, not only to the product itself. **Section 2.4.9** looks at the different phases of product's lifecycle and proposes methods to reduce the cost or increase the quality of the product at each phase. The most **costly phase** is the manufacturing, since the technology of fabricating microholes in glass is still very expensive and relatively complicated. Creating a machine adjusted to the needs of the specific project (glass size/thickness, speed, surface quality) can reduce the cost. Opportunity to create value exists during **product's usage**, by designing a flexible system which is tuned in the acoustic demands of the space. Finally, **maintenance** is quite important for designing a glass building component. Easy access to the glass surfaces that face the cavity should be considered during the product design. **Section 2.4.10** describes analytically the requirements for cleaning.

The last **Section 2.4.11** presents the list of internal and external **stakeholders** who are involved in the whole process. Knowing this information will help us in following step to choose who will be the targeted group for conducting interviews.

2.5 Market Size and Competitive Products

The following diagram (see Fig. 2-49) presents the results of an **intense search in the web catalogs of acoustic products**. All different types of commercial absorbers are put together and classified in three main categories. Each category represents the **main purchasing intent/criteria** in choosing for an acoustic product today, according to the view of the author. The **biggest share** of the market belongs to materials that are "cheap with satisfactory performance", due to the observation that most of the leading companies in acoustic products today sell this type of solutions. **Smaller market** is found in solutions that are more expensive because they are better quality, adjustable to the architectural intent and can be customized. A much smaller market is found for acoustical products that are "fibreless and adequate for harsh or hygienic environments".

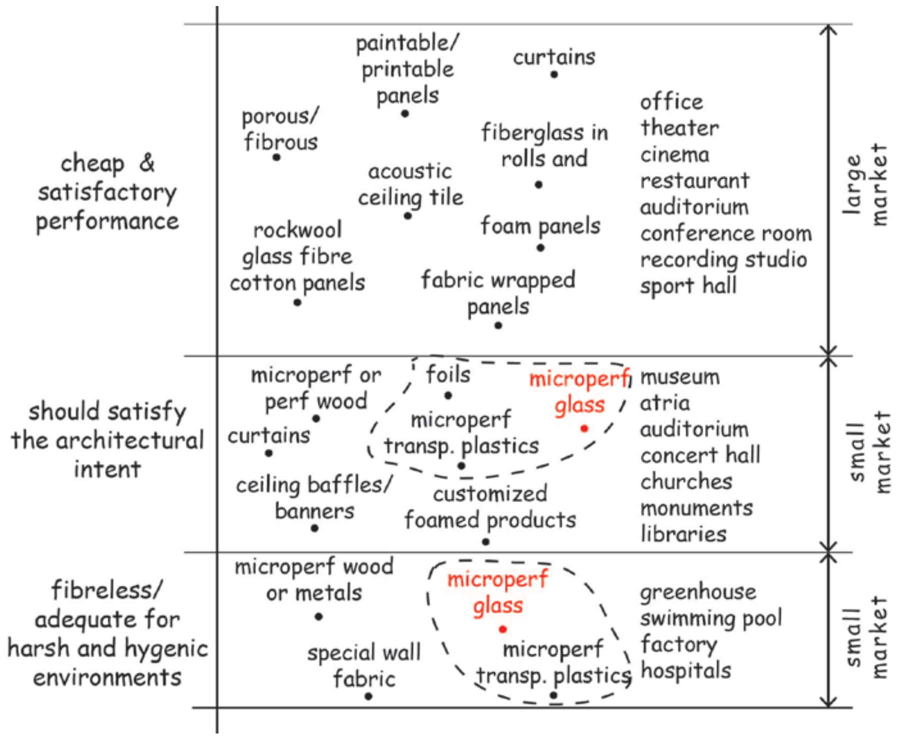


Figure 2-49 Mapping all the competitive acoustic products and classifying them into three main categories which present the buying intent of the market today, according to the author's opinion (By the author)

The above diagram helps us to draw **conclusions** about the **potential market** of the microperforated glass absorber. As it is indicated with red color, the glass sound absorber can either be chosen for its ability to satisfy the architectural intent or its fibreless advantage and thus being adequate for hygienic environments. The dashed line indicates the group of main competitive products which are the transparent solutions made out of plastics.

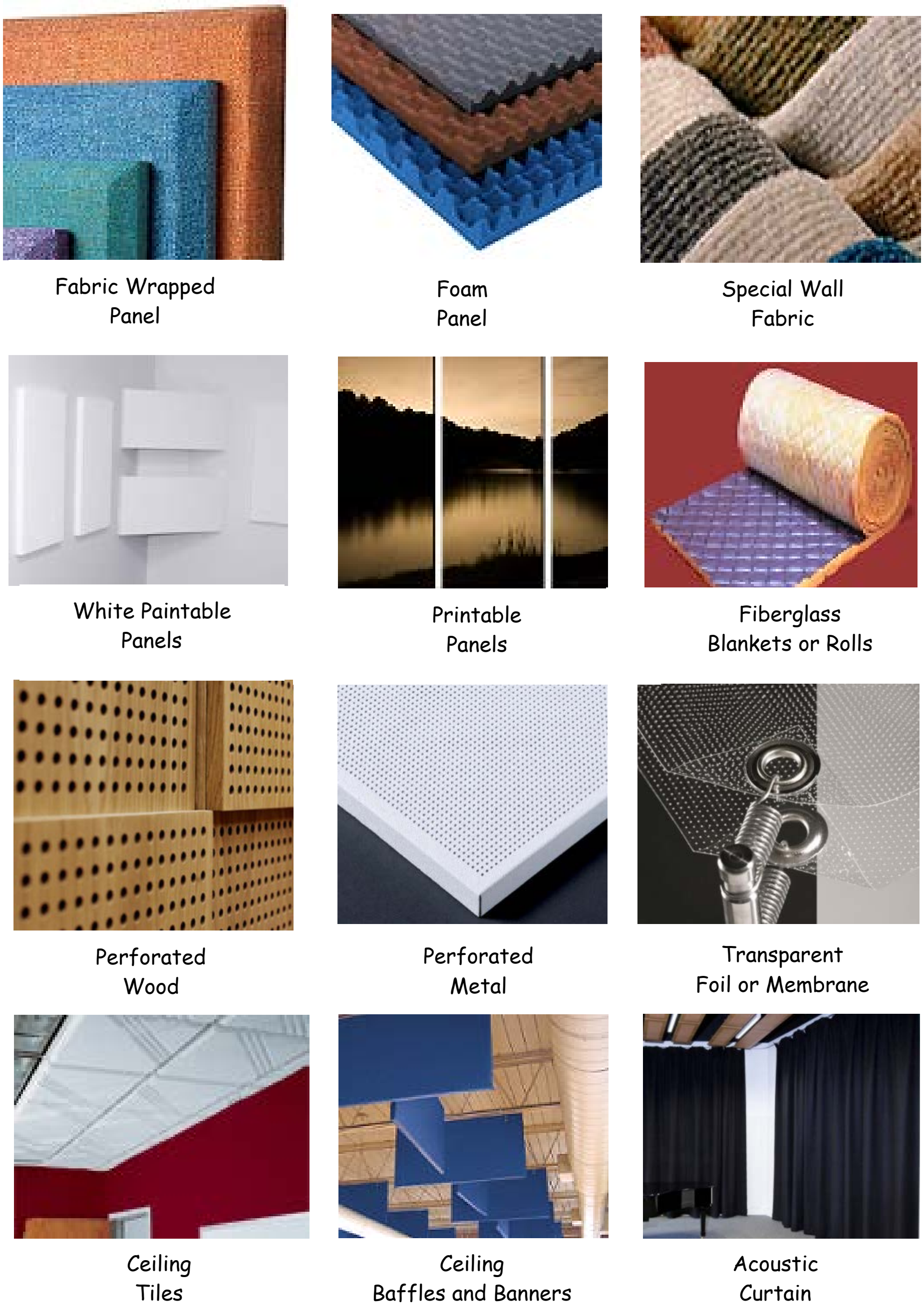


Figure 2-50 Photos taken from the web which illustrate the various types of acoustic products that exist today in the market.

2.6 Assessment of Product Opportunity

2.6.1 Filling the Assessment Form

Assessment Form for the Evaluation of the Product Opportunity, "Glass Sound Absorber"		
	Yes	No
A. Cost		
A1. Can it be produced at low cost?		✓
A2. Is the product feasible? Can it be produced?	✓	
A3. Is the cost going to be reduced in future?	✓	
Answer	**2**	**1**
B. Quality		
B1. Is there an appropriate market?	✓	
B2. Is there a clear competitive advantage?	✓	
B3. Does it have a good acoustical performance?	✓	
B4. Is it safe?	✓	
B5. Can it be customized adding other characteristics?	✓	
B6. Is it easily maintainable?	✓	
Answer	**6**	**0**
Total	**8**	**1**

The explanation for choosing the Yes/No answer is found in Section 2.4.12 and Section 2.8.

The assessment form works as a **guide** for the author and the whole development team in real case situations. It summarizes the results of the preliminary development process and gives a positive or negative overview of the product's potentials. In the current situation, getting a total number of 8 **positive** answers against 1 negative, shows that the new product opportunity can be **successful in the market**. The next step is to look closer on the results and assess the effect of the negative answer in the whole process.

2.6.2 Reflect on the Results

Question A1 of the assessment form indicates that the **cost** is expected to be **high**. According to the results of the preliminary market survey (see Figure 2-8, pg. 36), cost is the most important parameter for product success. In Section 2.4.2 it is explained that the cost of fabricating a microperforated glass plate is very high today due to the complexity of the micromashining technology. It is expected though, that the cost will drop in the future as the technology progresses.

Cost Analysis of Glass Fabrication based on Data provided from 4JET microtech Company

To get a clear overview on how the **cost** of fabricating holes is being **modeled in numbers**, the results of questions[6] addressed to an expert in micromashining glass technology are presented below:

The **cost** of fabricating a microperforated glass panel is shared between **fix and variable cost**:

Cost	
Fix	Variable
Initial setup cost is distributed among the number of glass pieces that need to be processed.	Depends on the following parameters of the project: - Tact time cost o Number of holes o Diameter o Glass thickness o Glass type o Handling o Glass size - Specification o Diameter accuracy o Quality of the hole o Allowed chipping size

The quantity of units has a big effect on the final cost/unit:

For example if we have one plate and the set up cost is let's say 390€ and the cost of processing glass is 50€ the final **Cost=390€+50€=440€ for one piece**.

[6] The questionnaire with the answers is included at the Appendix A "Questionnaire to 4JET microtech Company/ Thomas Melle"

If for example, we have 50 plates, the initial set up cost is distributed in the 50 plates, which means that the Cost of the 50 units is **Cost=390€+(50€x50units)=2.890€ (57,80€/unit).**

Focusing now on the cost of processing glass, this cost depends on **how many hours needs the machine to process the glass**.

The cost/hour is defined by the machine cost. A machine costs **500T€ which leads to 15€/hour.**

If a hole needs10secs of processing, then for 2000holes we need 5,5hours of processing 5,5h x 15€/h = 83€

If a hole needs 1sec of processing then the cost drops to
0,5h x15€/h=7,5€

But when the time of processing a hole increases the quality of the hole also increases but the cost goes higher. So at the end

So, the price really depends on the time we need for drilling the hole. When we seek for less chipping around the hole then he process becomes slower and the cost goes up.

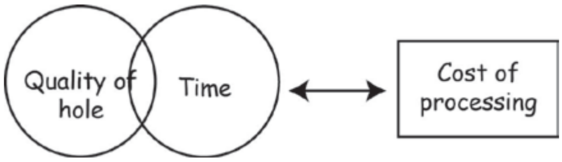


Figure 2-51 Scheme which shows what parameters define the cost of processing holes to glass according to the data given by 4Jet Company (By the author)

2.7 Product Planning

A list of propositions is formulated in order to describe the generalized characteristics of the future glass sound absorber. These will be used as input information for the actual product development phase which follows in Chapter 3. The propositions are the following:

1. Microperforated glass can be successful in the market of acoustic solutions as **façade-front application**. The competitive acrylic products like PC or PMMA are much cheaper and safer than glass and thus are satisfactory for the most interior applications. However, in façade-front applications, plastics present low quality due to their degradation and discoloration when exposed in UV-light and temperature differences. Glass can be an excellent solution for façades because it combines robustness, longevity and resistance in scratches.

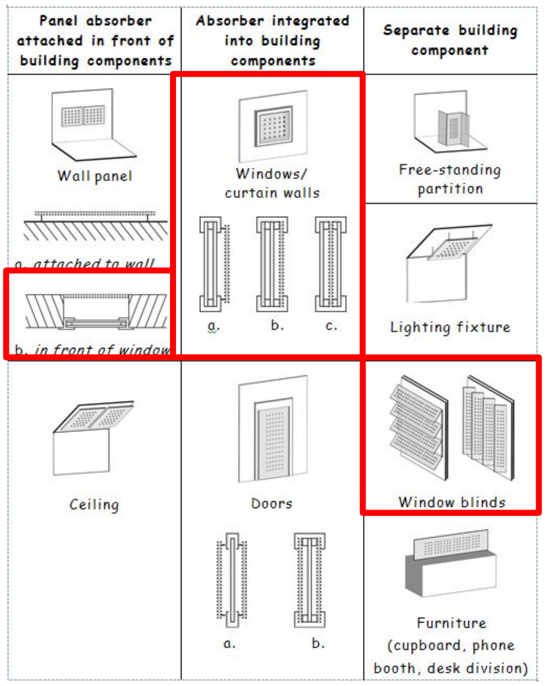


Figure 2-52 Table 2-18 of Section 2.4.8 which shows all possible room applications of the glass sound absorber. According to the planning, façade-front applications are selected for further product development. These are indicated with red color (By the author)

2. A **strictly market-oriented methodology** is required throughout the whole process of product development. In Section 2.2, microperforated glass is characterized as a “technology-push” type of innovation, which means that the appropriate must be defined. Satisfying the needs of the market ensures the product success.

3. In Section 2.3 we learned that **customizability and flexibility** are two important parameters for product success according to the market research. Section 2.4.3 presents the options for customizability that microperforated glass has and section 2.4.9 speaks about the flexibility which can be found in during product use. These qualities have to be integrated in the design of the glass sound absorber.

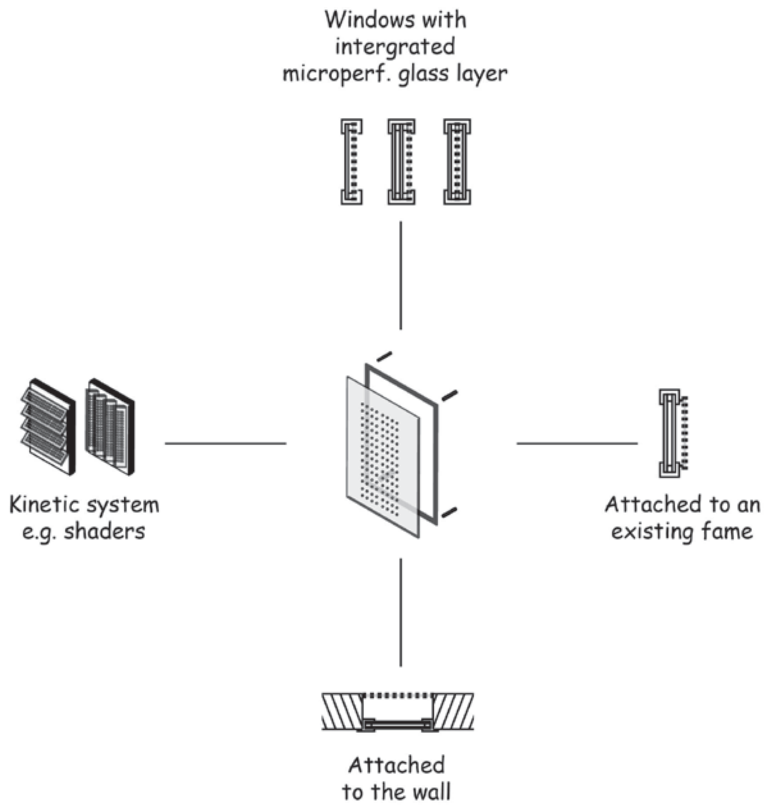


Figure 2-53 Platform of facade-front applications which share the common technology of microperforated glass (By the author)

Product Definition Statement

Product Definition: The Glass Sound Absorber	
Concept Description	A transparent façade-front sound absorber for room acoustics
Benefit Proposition	Durability in temp. differences & UV Robustness & Longevity Scratch resistance Low maintenance
Performance	Aver. Absorption coef. at peaks > 0.70 Adjustable & accurately designed
Attributes & Features	Capability to adjust acoustic performance Variety in hole pattern, safety concept, shape, color, texture, application concepts Customizability
Market Description	For window applications Very large spaces with glass boundaries e.g. atria, hotel lobbies, museums Historic buildings under preservation
Constraints	Glass is the plate material Microperforation is the acoustic principal
Stakeholders	Investor/Developer User Architect/ Façade Eng. Production Glass & system supplier Maintenance company Sales
Cost	Very high Cost compared to other microperforated acoustic materials. Varies according to the design Expected to drop in the future due to technology progress in manufacturing

Table 2-21 Product Definition Statement, which describes the key points of the new product Opportunity (By the author)

2.8 Answers to the Research Sub-questions

What type of product opportunity there is and what guidelines are implied for the next phase?

It is a "technology-push" type of opportunity because the development of the new product is pushed by the innovative technology of microperforated glass. The opportunity exists for a new acoustic solution that integrates the microperforated glass technology to absorb sound. In this type of market opportunities, the appropriate market has to be found. Hence, intense market research on customer's needs and expectations is required. The market input is necessary, amongst others, in the design phase, in order to set a list of market-oriented product requirements. Market success is ensured if the product satisfies the product requirements as set by the market.

What are the criteria to assess product success in the marketplace?

1. Cost of production: If the cost is high, a prediction on how cost will be in the future is useful.
2. Quality of the product: The criteria for good quality are defined by the market and are related to acoustic performance, safety, aesthetics, customization and low maintenance.
3. Manufacturing: The product has to be feasible with the available technology today.
4. Market size: Appropriate market and a clear competitive advantage have to be defined.

How can the microperforated glass be compared against its competitive materials?

Competitive materials are other transparent microperforated plates made out of polymers such as PC, PETG and PMMA. The advantages of glass are found in robustness, UV and scratch resistance and longevity. Glass doesn't creep, degrade or become yellow as most plastics do due to temperature differences or UV radiation.

What capabilities and what limitations exist in the design and production of microperforated glass?

Capabilities

<u>In the production:</u>

The glass can be processed with various available technologies. The demand for good surface quality around the hole or fast production define the cost of the process.

Possibility to fabricate holes of different diameters

Computer-controlled arm which allows for freedom in the design

<u>In the design:</u>

Customization of glass in color, texture, digital printing

Forming /curving glass

Laminating with plastics for safety and customizing the hole's pattern

The acoustic performance can be measured in detail. A more broadband acoustic performance can be achieved by varying the cavity depth, combining different hole patterns or designing a multi layered system.

Limitations

<u>In the production:</u>

High cost of production

<u>In the design:</u>

Brittleness of glass requires safety measures

What is the cost and what are the expectations in the future?

The cost of processing the holes in glass is high. The technology is still new but it is continuously progressing, which means that in the future will definitely become cheaper. One method to reduce the cost is the production in series of the same element. The cost drops significantly because the initial setup cost is distributed in many pieces. It is worth to mention here that 4Jet Microtech Company, is expanding by adding a

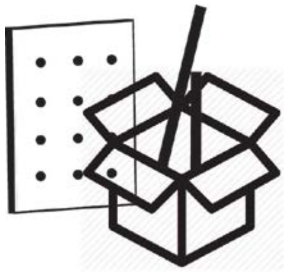
machine for mass production in the Jobshop. This means that the possibility of fabricating glass faster and cheaper is a demand in the market.
The cost of the process is ultimately defined by the time needed to fabricate one hole. By increasing the speed, the cost is reduced but the quality of the machined surface around the hole drops due to microchipping. Bad surface quality leads to lower bending strength around the hole and thus the strength of the glass is reduced. Roughly we can say that the cost of $1m^2$ sound absorbing glass is 1000€.

Looking into the whole process of product's lifecycle, what actions can be taken in order to increase product value?

Firstly, designing for low maintenance has to be considered. Transparency needs to be preserved, and thus a method for cleaning the inner glass surfaces has to be planned. Secondly, flexibility can be achieved not only in the product itself by customizing its characteristics, but also during the usage phase. By adjusting the acoustic performance of the absorber to the varied acoustic requirements of the space, the value of the product is increased.

What type of product planning can lead to market success?

1. Design for façade-front applications
2. Strictly market-oriented product requirements.
3. Customizable product
4. Design a flexible system that can be adjusted in various acoustic situations or perform more than one functions together e.g. acoustics and solar control



Product Development

CHAPTER THREE

3.1 Introduction

In this chapter the **actual product development** phase of the glass sound absorber is presented. The aim here is to generate concepts and select one based on market-oriented design criteria. The “Co-Creation” Centre is the selected **pilot project** to demonstrate the feasibility of the product. An analysis of the acoustic requirements will be carried out and the selected concept solution will be developed in detailed level. The process of product development will continue to follow a **structured methodology** likewise to the preliminary phase of “Opportunity Assessment and Planning”. The two phases are linked together and output information of the first phase will be used as input for the one to follow.

3.1.1 What guidelines are derived from the first phase?

First, the new product will be developed for façade-front applications.

Secondly, a strictly market-oriented product development process needs to be followed. Microperforated glass is very expensive and thus the high cost must be balanced by very good quality. The quality of the product is successful if it satisfies the market needs.

Thirdly, customization of glass with various characteristics such as color, texture, printed image and form is possible. Flexibility in the process can be found during usage phase by designing a product that can be adjusted in to the acoustic requirements of the room.

3.1.2 How can a structured product design process be developed in order to ensure market success?

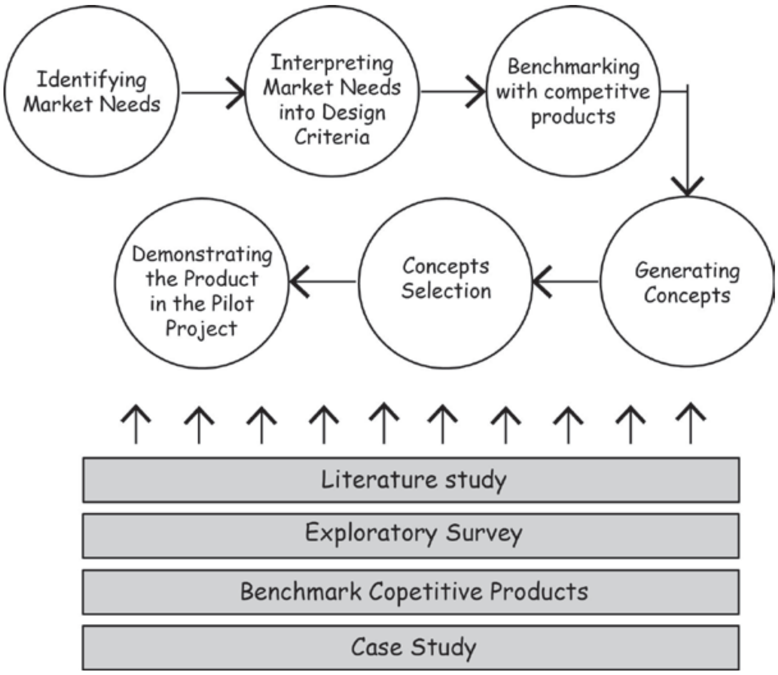


Figure 3-1 Scheme which illustrates the sequence of steps and the applied methods in the “Product Development” phase. (By the author)

3.2 Identifying Market Needs

3.2.1 Designing the Interview

In this activity, i**n-depth market research** in customers' needs will be conducted. The purpose is to collect valuable information from people who are the **decision-makers** for buying the microperforated glass absorber. This requires a carefully designed interview methodology having clear goals. Then, the collected information will be processed, resulting in a **final list of product requirements** which describe market needs. These product specifications will be used in a following step as a guideline for a strong market oriented design development process (see Fig. 2-x).

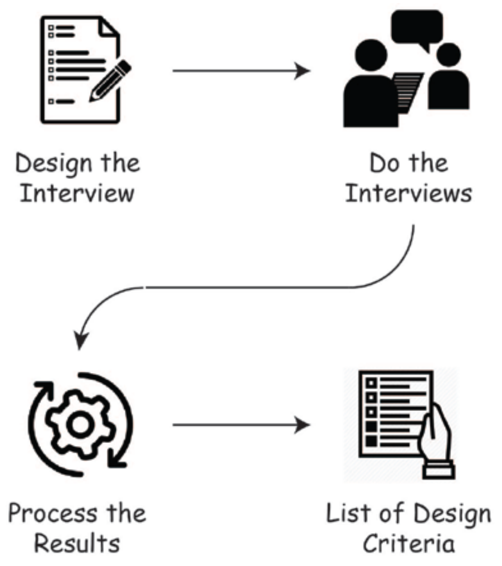


Figure 3-2 The structure of the in-depth market research (By the author)

The market research was conducted from **February to March 2017** and had the form of depth interviews. Designing the interview and processing the results is done in a structured method. The preliminary exploratory survey of Section 2.2 preceded the depth interviews of the current phase and was helpful to clarify **the goals and the context** of the depth interviews.

The Interview

- Face to face in-depth interviews
- 6-8 Interviewees who are decision makers
- Semi-structured methodology: An interview guide will be developed which will contain a list of main topics to be covered. Spontaneous questions or discussions related to a non-planned topic may interrupt the general interview guide.
- The results of the un-structured pilot work which was conducted in Bouwbeurs in previous phase are used to form the context of the interview guide.
- Open-ended questions, spontaneous answers are wanted.
- The general frame of the thesis will be shortly presented before starting the interview (see Appendix).
- Each interview will last approx.. 30mins.

The Sample

The interviewees are professionals or academics with expertise in **architectural, acoustic or glass façade design**. These groups of experts are selected because we assume that are the ones who choose and decide for the acoustic solution in a development project.

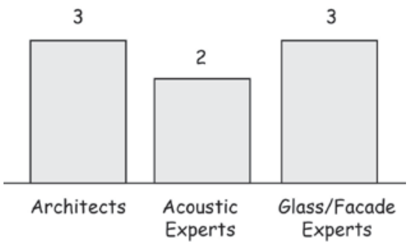


Figure 3-3 The Sample, in total 8 interviewees (By the author)

.

The Interview Structure

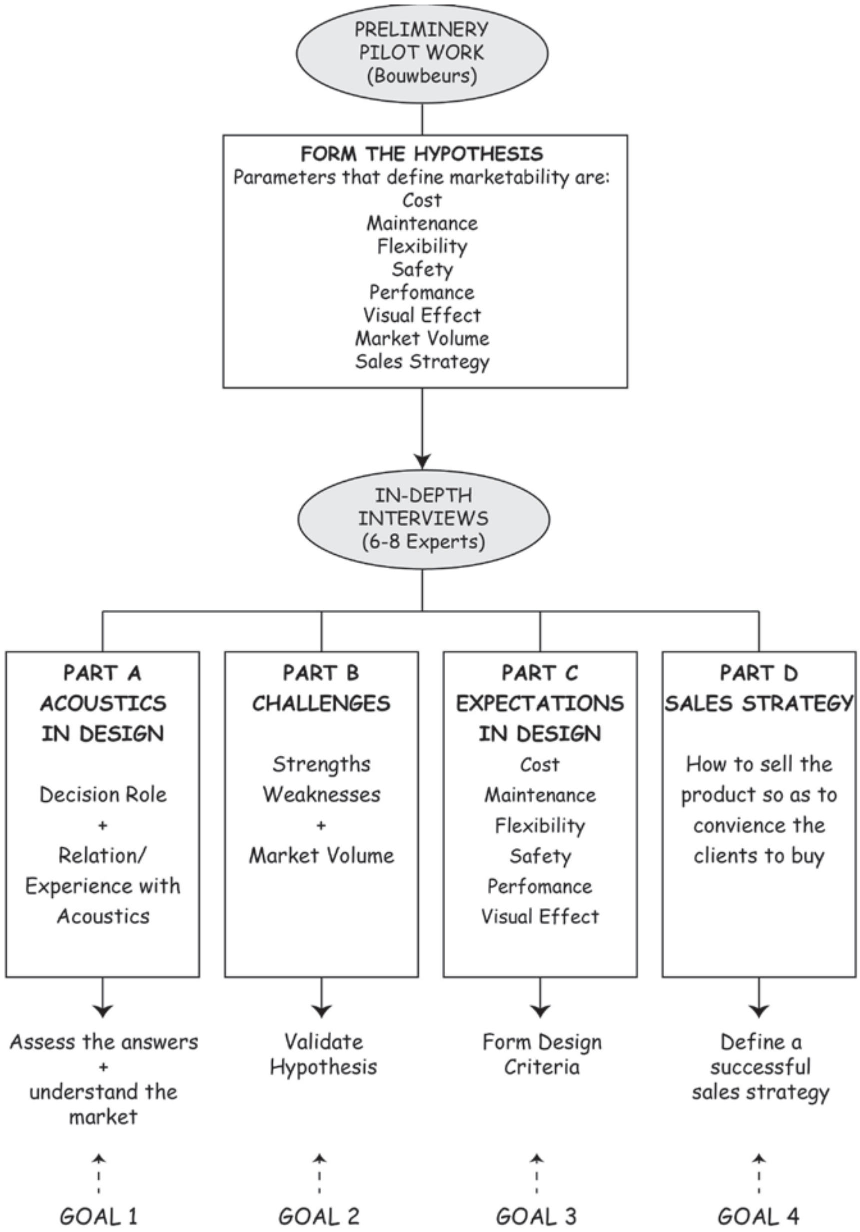


Figure 3-4 Schematic for the Interview Structure (By the author)

3.2.2 Processing the Data

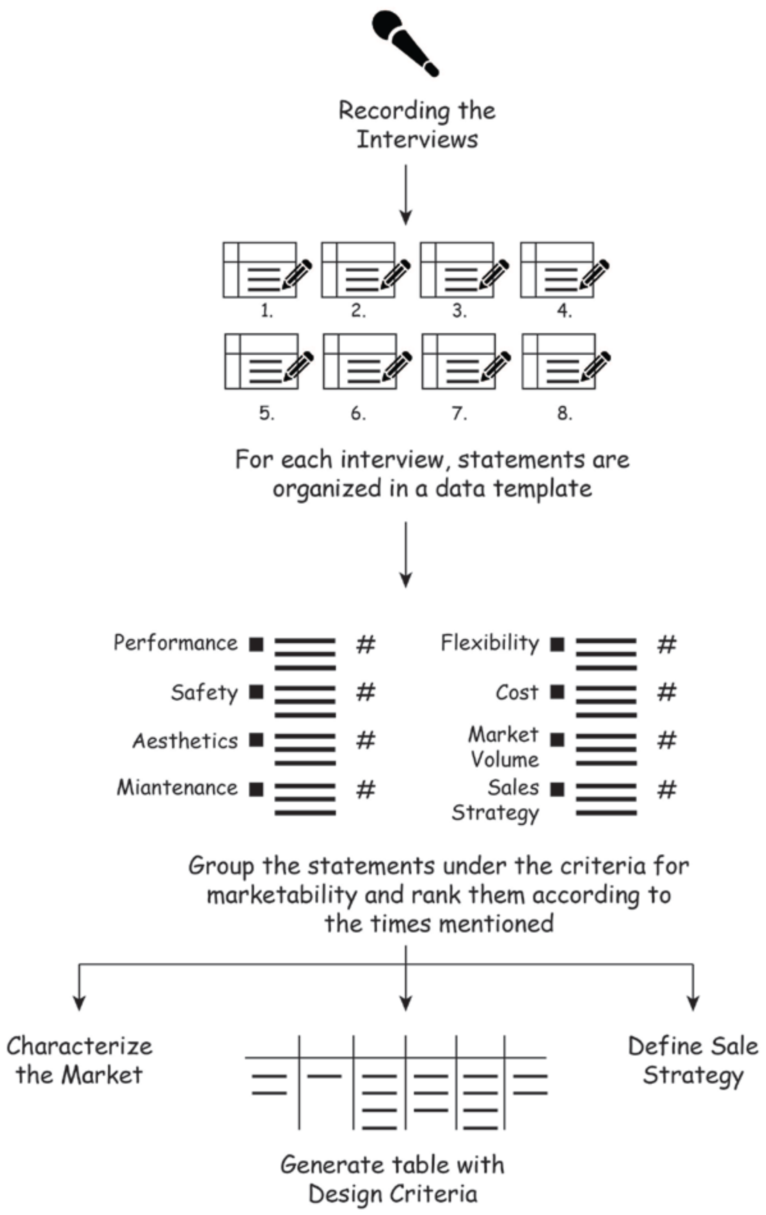


Figure 3-5 Scheme which shows how the interview results are analyzed (By the author)

NAME: JAMES O' CALAGHAN
PROFFESION: STRUCTURAL ENGINEER/ GLASS EXPERT

CATEGORY	INTERVIEWEE STATEMENT	MARKET NEED What has the product to do?
Performance	"…" other factors determined less transparency that had to do with solar gain, heat and thermal performance, having an all glass building was a problem for energy perspective so an opaque acoustic solution was chosen that solved this problem.	It has to consider thermal energy aspects.
Safety	The many perforations must weaken the glass. The laser technique introduces many flaws to glass.	It has to be safe.
	Very thin glass covering large sizes is flexible.	It has to be stiff.
Aesthetics	N/A	N/A
Maintenance	The gap will be filled with dust and you can imagine how the window will look like.	It has to be maintainable.
Flexibility/ Adaptability	Most of the products that are developed by people are focusing in one thing.	It has to be customizable in general.
	People never are happy with one product; always want to do smth different after some time.	It has to allow for upgrade of its characteristics
Cost	Cost is always a barrier but if certain amount of quality is required and there is no other alternative then will buy it.	It needs a clear competitive advantage. It has a competitive price.
Market Volume	The biggest market is in standardized solutions, e.g. A standard window that can be implemented in a lecture theater.	It has to satisfy the trends of the market.
Sales Strategy	Is difficult for people or designers to understand how they are going to use that. People are afraid of where the boundaries might be.	It needs a persuasive sales strategy.

NAME: ROB NIJSSE
PROFFESION: STRUCTURAL ENGINEER/ GLASS EXPERT

CATEGORY	INTERVIEWEE STATEMENT	MARKET NEED What has the product to do?
Performance	What does the law demands, what is in the standards, what are the comfort criteria	It has to achieve sufficient acoustical performance.
	It will be an advantage if it can regulate the solar radiation	It has to consider thermal energy aspects.
Safety	How much is the effect in the strength of this material? How much is the effect in the stiffness of this material? You make holes in smith and it gets weak.	It has to be strong. It has to be stiff.
Aesthetics	You have to design a beautiful connection as absent as possible	It has to preserve transparency with its components.
Maintenance	What happens if water goes to the other side? The housewife asks how it can be cleaned.	It has to be maintainable.
Flexibility/ Adaptability	Need to produce single glass layers that you connect in some way somewhere	It has to be adaptable in various positions within the room.
Cost	The price depends on if the product offers smth special. By making series if it proves to be successful you reduce the price.	It needs a clear competitive advantage.
Market Volume	Any type of building that an acoustical problem might be occurred, church, factory, music hall	
Sales Strategy	Present simple solution which proves the quality.	It needs a persuasive sales strategy.

NAME: MARTIN TENPIERIK
PROFFESION: ARCHITECT/ ACOUSTICS EXPERT- ACADEMIC

CATEGORY	INTERVIEWEE STATEMENT	MARKET NEED What has the product to do?
Performance	If it is part of the façade it actually improves the energy performance of the façade.	It has to consider thermal energy aspects.
	What is important for lot of applications is that the relevant frequencies are in speech frequency domain, it means that in that range you want to have constant high absorption coefficient.	It has to achieve sufficient acoustical performance.
Safety	N/A	N/A
Aesthetics	How variations in cavity depths will that affect the appearance.	It has to be appealing.
Maintenance	Glass will take longer than plastics to get dirty. Needs to be cleaned once in a while from the inside.	It has to be maintainable.
Flexibility/ Adaptability	You might think of a system that supplies fresh air "…" If it is sold with light as a fixed standard solution then might limit yourself but if it is an option then it is different	It can integrate other functions.
	The pattern and the absorption characteristics can be designed by the client	It allows customizability in acoustic performance.
Cost	If the product is very expensive like this one, then chances are very big that will be only used in buildings for large budget. The most important is that the price has to drop.	It has a competitive price.

Market Volume	Very special high quality buildings are well designed and typically are not complaints afterwards but are complaints in offices, hospitals, gyms with children.	It can be adapted in existing buildings.
	If it is a bigger market with more standardized solutions the one who sells needs to have standard connection details.	It has to be adaptable in standardized situations.
Sales Strategy	The architect, the client wants to know its acoustical properties in single number values	It needs to be tested.

NAME: MICK ECKHOUT/ BARBARA VAN GELDER
PROFFESION: GLASS FACADE ENGINEERS

CATEGORY	INTERVIEWEE STATEMENT (The interview was not recorded, so the statements are presented as noted down by the interviewer)	MARKET NEED What has the product to do?
Performance	Always need to think how to reduce the g-value, because a glass box will become very hot in the summer.	It has to consider thermal energy aspects.
Safety	N/A	N/A
Aesthetics	N/A	N/A
Maintenance	The outside face of glass usually is cleaned every half year but the inside only once every 2 years or even never.	
Flexibility/ Adaptability	N/A	N/A
Cost	Price is important for the decision.	It has a competitive price.
	The product is expensive so it has to be protected from damage during installation.	It prevents failure.
Market Volume	N/A	N/A
Sales Strategy	What is the competitive advantage of the product and quantify to see how much money it saves	It needs a clear competitive advantage.
	I need to see three solutions with different applications.	It needs a persuasive sales strategy.
	I want to see proofs of data that it works acoustically.	It has to come along with proofs of quality.

NAME: ARIE BERGSMA
PROFFESION: ARCHITECT/ FAÇADE ENGINEER

CATEGORY	INTERVIEWEE STATEMENT	MARKET NEED What the product has to do?
Performance	N/A	N/A
Safety	There are many micro cracks. There is risk for damage.	It has to be safe.
Aesthetics	Is still the same material. You have 2 layers behind that can work beautifully together. Flexibility in the design of the patterns is important for the designers I can imagine for a big print that goes together and looks nice	It has to allow customizability of its appearance.
Maintenance	Cleaning is a risk. Dust is a problem after 5-6 years.	It has to be maintainable.
Flexibility/ Adaptability	It is interesting to combine two properties together. It would be more interesting if the acoustic screen is combined with thermal comfort	It can integrate other functions.
	Flexible concept so it can be integrated later in the design. The more integrated solution, the more the need is reduced. I would go for a concept that goes for more options possible. You pay extra money for the flexibility.	It can be adapted in existing buildings.
	The architect wants to see that there are many things possible.	It has to be customizable in general.
Cost	Cost is an issue. I will always look for cheapest solution. Look at products that already existing	It has a competitive price.

Market Volume	If I want smth transparent and you don't have many options to solve acoustics then this could be an option.	It needs a clear competitive advantage.
	I would make the market bigger and look at solutions that already exist.	It has to be adaptable in standardized situations.
Sales Strategy	N/A	N/A

NAME: THEODOROS TIMAGENIS
PROFFESION: ARCHITECT/ ACOUSTICS EXPERT

CATEGORY	INTERVIEWEE STATEMENT	MARKET NEED What has the product to do?
Performance	Is it fireproof?	It has to be fire rated.
Safety	I am concerned about the safety of this glass since I believe that it can't be easily toughened or laminated.	It has to be safe.
Aesthetics	N/A	N/A
Maintenance	The glass needs to be opened in some way and be cleaned. The dust settles easily in rough surfaces so needs to be taken into consideration for rough surfaces.	It has to be maintainable.
Flexibility/ Adaptability	It is good that it can either be fully transparent or be colored or printed and used as decorative.	It has to allow customizability of its appearance.
	What are the biggest dimensions of glass panel that can be achieved?	It has to be flexible in sizing.
	Is it possible to work as sunshade like inner curtains or rollers do?	It can integrate other functions.
Cost	The cost can be reduced if less people are needed to install it	It has to allow for low cost installation.
Market Volume	In the market exist both occasions either that acoustic solutions need to be added afterwards like the under preservation buildings or designed from scratch.	It can be adapted in existing buildings.
Sales Strategy	The client or the architect has too see the product and then decide how to use it.	It needs a persuasive sales strategy.

NAME: PADDY TOMESEN
PROFFESION: ARCHITECT

CATEGORY	INTERVIEWEE STATEMENT	MARKET NEED What has the product to do?
Performance	For every product I want to have guarantees. Especially if it is expensive, I don't take the risk.	It has to come along with proofs of quality.
Safety	N/A	N/A
Aesthetics	N/A	N/A
Maintenance	My concert is how it works when I clean it.	It has to be maintainable.
	The more complete is the more safe ends up in a building.	It prevents failure.
Flexibility/ Adaptability	Maybe there is a light which has a cover which has some acoustic quality then I have a light and some acoustics.	It can integrate other functions.
	What sizes can you deliver?	It has to be flexible in sizing.
	Depends on the project needs to be smth integrated in a system or frame or smth as a half product that you can finish it yourself.	It has to be customizable.
Cost	If there is another way out because this is too expensive, then I tend to research this too. The problem is the money if the price is so high.	It needs a competitive price in the market.
Market Volume	If it really necessary for that special space because we need good view and acoustics and there is no other choice, then you do it.	It has a clear competitive advantage.
	The market is "…" in offices were transparency is needed or in a call center were daylight is needed.	It has to preserve transparency with its components.
Sales Strategy	I would like to be informed well or have pages with information that explain how it works so I can understand the product. If you have available technical information then you can convince the client to buy.	It needs a persuasive sales strategy.

List of Market Needs

The first output is a table which summarizes the market needs and the times mentioned by the interviewees (see Table 3-1).

Market Needs	#
It has to consider thermal energy aspects.	4
It has to be safe.	4
It has to be maintainable.	6
It has to be customizable in general.	2
It has to allow for upgrade of its characteristics	1
It needs a clear competitive advantage.	5
It has a competitive price.	5
It has to satisfy the trends of the market.	1
It needs a persuasive sales strategy.	5
It has to achieve a broadband acoustical performance.	2
It has to preserve transparency with its components.	2
It has to be adaptable in various positions within the room.	1
It has to be appealing.	1
It can integrate other functions.	4
It allows customizability in acoustic performance.	1
It can be adapted in existing buildings.	3
It has to be adaptable in standardized situations.	2
It has to come along with proofs of quality.	3
It prevents failure.	2
It has to allow customizability of its appearance.	3
It has to be fire rated.	1
It has to be flexible in sizing.	2

Table 3-1 List of market needs as concluded by the interviews on the left side and times mentioned each one of them on the right column (By the Author)

Interpreting Market Needs into Design Criteria

The aim of this activity is to come up with a sort of design criteria, based on market needs, which will be useful to assess the design concepts in further step.

Cost	
It has a competitive price.	5
Safety	
It has to be safe.	4
Maintainability	
It has to be maintainable.	6
Customizability (in: appearance, sizing, performance)	
It allows customizability in acoustic performance.	1
It has to allow customizability of its appearance.	3
It has to be customizable in general.	2
It has to be flexible in sizing.	2
It can integrate other functions.	4
Flexibility (in: application type, usage)	
It has to be adaptable in standardized situations.	2
It has to allow for upgrade of its characteristics	1
It can be adapted in existing buildings.	3
It is adaptable in various positions within the room.	1
It has to achieve a broadband acoustical performance.	2
Performance (acoustics, thermal energy, fire)	
It has to come along with proofs of quality.	3
It has to consider thermal energy aspects.	4
It has to be fire rated.	1
Transparency	
It has to preserve transparency with its components.	2
Competiveness	
It needs a clear competitive advantage.	5
It has to satisfy the trends of the market.	1
Other	
It has to be appealing.	1
It needs a persuasive sales strategy.	5
It prevents failure.	2

A list of **final design criteria** is presented in the following table. The right column provides a scoring of the importance of each product requirement based on the times mentioned during the market research.

The scoring is divided in three Levels:
Level 1: (***), if at least one need is mentioned max. 5-6 times
Level 2: (**), if at least one need is mentioned max 4 times
Level 3: (*), if at least one need is mentioned 1-3 times

Product Requirements	Scoring
Cost	***
Safety	**
Maintainability	***
Customizability (in: shape, size, color, performance)	**
Flexibility (in: application type, usage)	*
Performance (acoustics, thermal energy, fire)	**
Transparency	*
Competiveness	***

Table 3-2 List of design criteria and the scoring according to the times mentioned in the interview (By the author)

3.2.3 Reflect on the Results and the Process

Sufficient information was collected by the experts of the field. The final list of design criteria validated the hypothesis which was formed based on the preliminary market research. Due to the fact that the interviewees had technical expertise in glass, façade design or acoustics, the tendency was observed to provide ready technical solutions. The purpose of the interviews though, was not to find specific solutions on how to solve a technical problem. The intention was collect data about the needs and the expectations of the market for the new glass absorber. Hence, interviewing the user or client could yield useful information about the products requirements.

3.3 Benchmarking with competitive products

Understanding the characteristics of the competitive products is critical in order to identify the gaps in the market and define a clear competitive advantage for the new product. This is what will ensure the commercial success of the product.

The **competitive acoustic products are selected** based on two main functional characteristics:

a. They should perform acoustically well in mid to low frequencies. So, basically they follow the microperforation mechanism.

b. They should present some degree of transparency and are promoted in the market for this advantage.

Five products are selected and presented in Table 3-3 comparing their performance, cost and other characteristics using numerical or qualitative data.

The final goal is to construct a competitive benchmarking chart with rows corresponding to the product requirements and columns corresponding to the competitive products and the new microperforated glass product. This chart is useful to understand in what degree the competitive products satisfy the market needs and where the competitive advantage of glass can be found.

	Microsorber® film (BARRISOL)	Microsorber® acrylic glass (KAEFER)	DeAmp®Clearsorber™ (DeAmp)	AlphaW 0.5-0.6 acoustic curtain (Vescom)	Acoustic plastic glass PG (Akoustik & Raum AG)
					
MATERIAL	ETFE (UV resistant), Stretchable PVC sheet	Acrylic glass	Acrylic (PMMA), PETG, Recycled PETG(slightly cloudy)	Polyester	PETG for the surface Honeycomb for the core
COST	250-350 Euro/m^2	N/A	120 Euro/m^2	35-54 Euro/m^2	230 Euro/m^2
PATTERN DESIGN	Micro-perforated film Standard types: 0.1mm-1%(ratio), 0.15-0.8%, 0.2-0.6% 0.5-5%	Micro-perforated panel 0.7mm-0.95mm Spacing 5mm and other	Micro-slotted panel with air cavity behind Slots < 0.2mm 1% surface cover Slit pattern: linear, triangular, sinusoidal, custom	Variation in woven	Micro-perforated sheet 0.5mm hole fixed Honeycomb core type 12mm, 7mm, multi 4/7/12mm
THICKNESS	0.18mm	3-15mm	2mm- 15mm	150mm	69, 200, 400mm of core 18-25mm of facing
NRC	0.30-0.62	N/A	0.45-0.55	0.50-0.60	0.55-0.70
SIZE	No standard sizes Customization	No standard sizes Customization	Standard sizes: -1200x600mm -600x600mm Customization	No standard sizes Customization	No standard sizes Customization
MAXIMUM SIZE	1250mm width 1500mm width(ETFE)	2000x3000mm	2000X3000mm	1500, 2950,3000mm (width)	2500x1220mm
COLOUR/ SURFACE	Colorless, clear Translucent/ Transparent Printable 110 colors 7 finishes	Translucent/ Transparent	Translucent/ Transparent Colored (RAL)-variation Printed Engraved	Translucent Available colors	Transparent, Anti reflex, Translucent light matted Colored
AVAILABLE STANDARD PRODUCTS	A15 nanoperf, A20 acoperf, A30 microacoustic,	Artificial glass B1, Artificial glass B2, MICROSORBER® micro	Panel Absorber, Box absorber, Framed Wall absorber (MDF	Carmen, Marmara, Formoza	N/A

	A40 miniperf, ACOUSTIC LIGHT®, MICROSORBER® Screen, blind slats, baffle system, blinds,	perforated artificial glass screen	frame)		
BUILDING PARTS	Walls, Glass facades, Ceilings,	Walls, Glass facades Ceilings, Stand-alone/ Partition	Walls, Ceiling, Windows, Ceiling tile, Separation in office furniture, Standalone partition	N/A	Walls, Ceilings, Partition Wall
INSTALLATION SYSTEM	Double layer of films, Combined with lighting behind, Stretched from wall to wall, Under thermos active ceilings/ cold ceilings, Blinds in front of windows	Hanged or fastened in front of a rigid surface	Hanged or fastened in front of a rigid surface, Mounted in front of light sources or windows, Hanged in free space display mounts, standoff mounts and free standing screens	Suspended in front of walls or glass surfaces	Framed sandwich component used as building element
FIXATION SYSTEM	MICROSORBER® spacing supports Hanging rail/perimeter harpoon Stretched at the corners type 4-way attachment	MICROSORBER® spacing supports 52 /90/140mm Stand alone in a frame with wheels or fixed steel legs	Fixed or removable attachments: - standoff pins - wire systems	N/A	3D-Silberkante (aluminum frame)
OTHER CHARACT.	Lightweight Light transmitting UV resistant Fire rated Easy to install/ re-install Clean Recyclable Resistant to mechanical stress due to elasticity	UV resistant Malleable if hot Not easily flammable	Easily cleaned Variety in fire rating options Light-transmitting Fiber- free	Fire safe Thin, lightweight strong Resistance to daylight Washable	Fire classification of cores Light transmitting

Table 3-3 Table which presents the competitive products and their characteristics

3.3.2 Competitive Benchmarking Chart

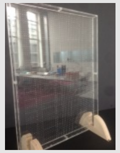
	Microsorber® film (BARRISOL) 	Microsorber® acrylic glass (KAEFER) 	DeAmp®Clearsorber™ (DeAmp) 	AlphaW 0.5-0.6 acoustic curtain (Vescom) 	Acoustic plastic glass | PG (Akoustik & Raum AG)	Microperforated Glass 
COST	-	-	+	++	-	--
SAFETY	++	++	++	++	++	+
MAINTAINABILITY	--	-	-	++	--	+
CUSTOMIZABILITY (in: appearance, sizing, performance)	+	+	++	+	+	++
FLEXIBILITY (in: application types, usage)	+	++	++	-	+	++
PERFORMANCE (acoustics, thermal energy, fire)	+	+	-	+	+	+
TRANSPARENCY	-	++	++	--	-	++
COMPETIVENESS	++	+	+	--	++	++

Table 3-4 Competitive benchmarking chart based on the market-based product requirements
From scale 1 to 4, the above symbols indicate: Level 1 (--), Level 2 (-), Level 3 (+), Level 4 (++). Level 1 (--) represents the lowest performance and Level 4 (++) the highest

3.4 Generating Concepts

3.4.1 The Method

At this step an array of concepts will be generated based on the market needs as concluded from the interviewing method. Even though it is a creative process, a structure method will be followed which contains the steps of the diagram:

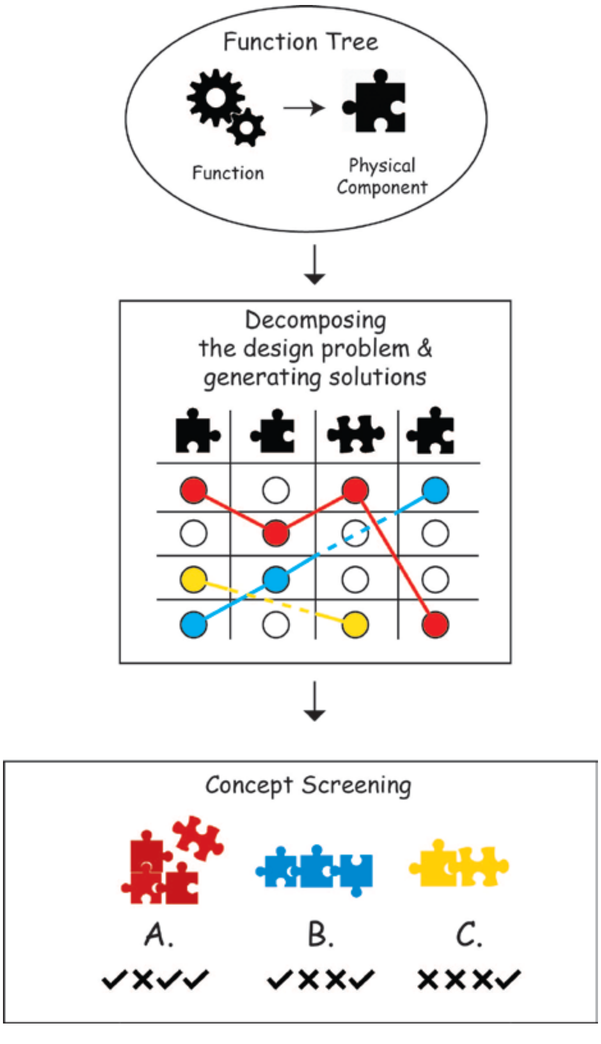
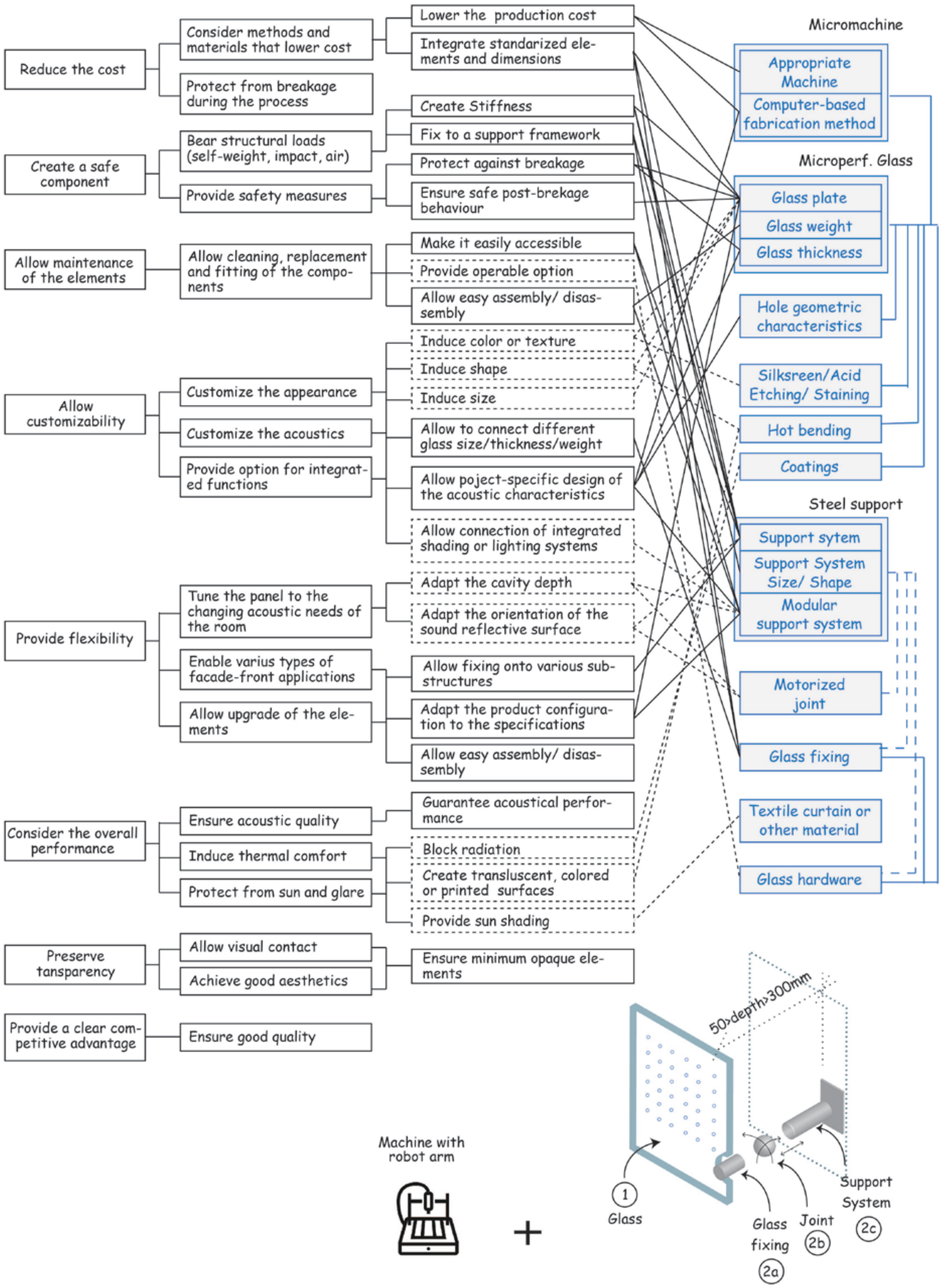
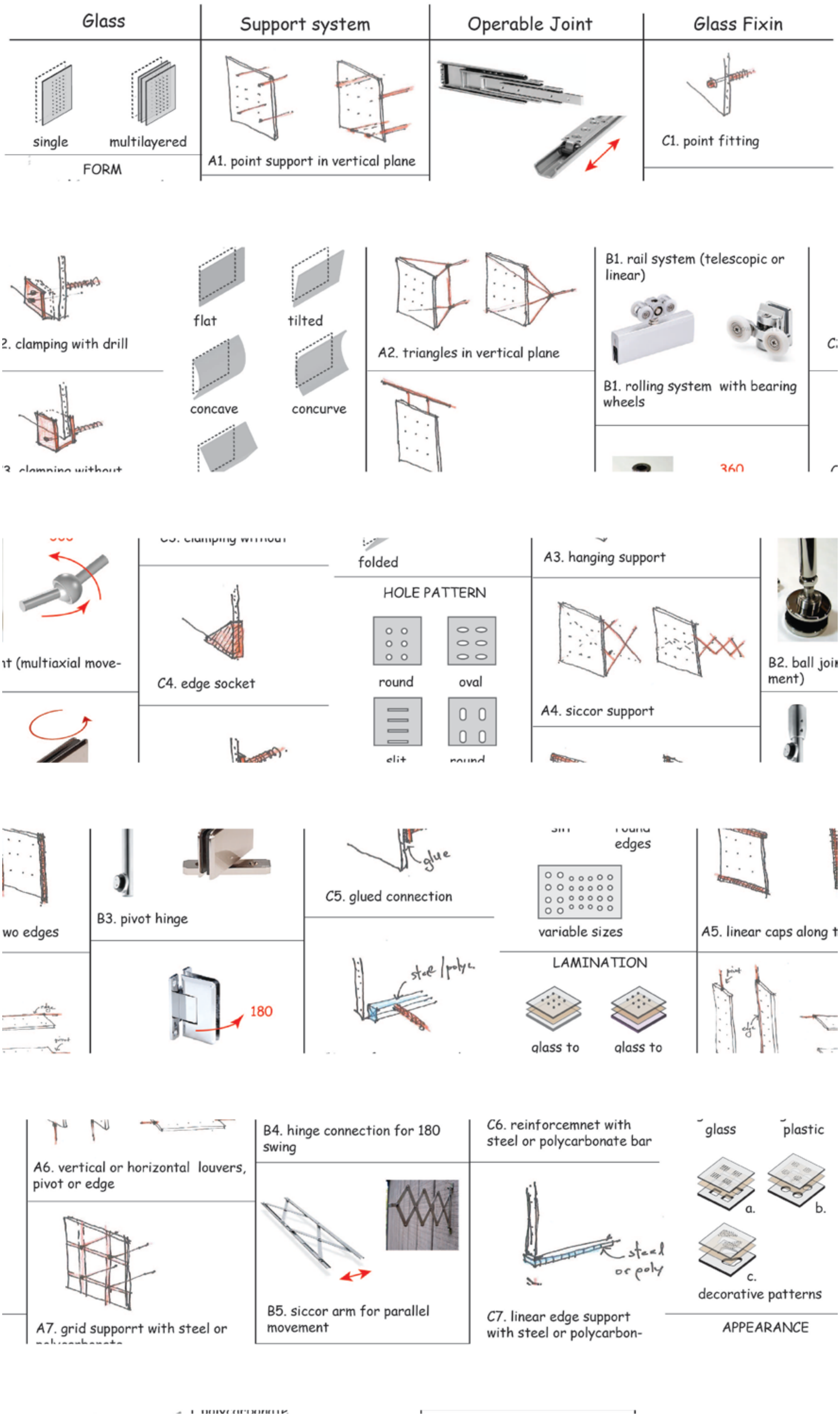


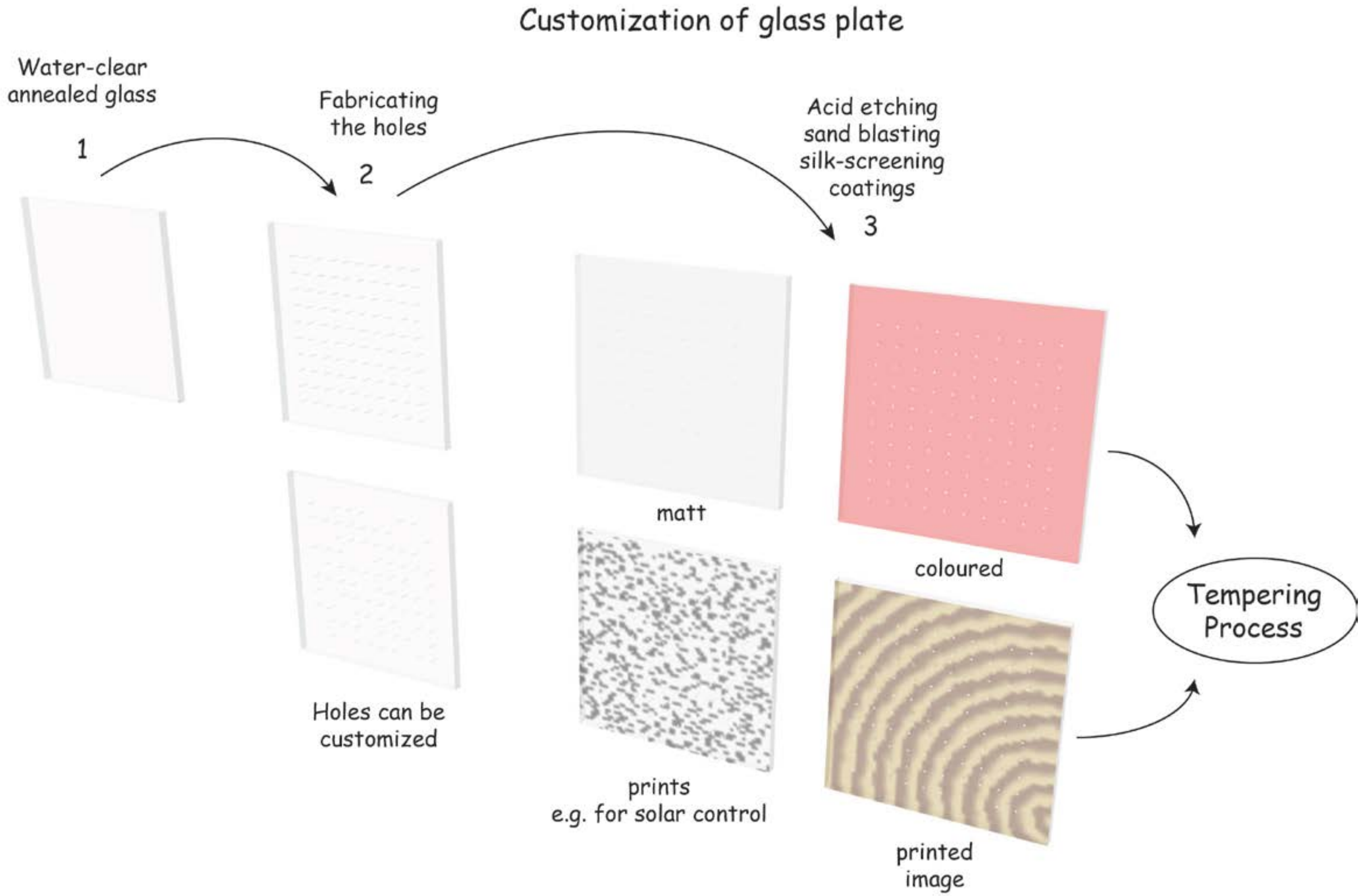
Figure 3-6 Scheme which illustrates the steps of Generating and Screening Concepts (By the author)

Function Tree

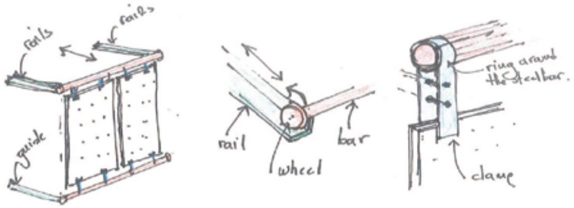
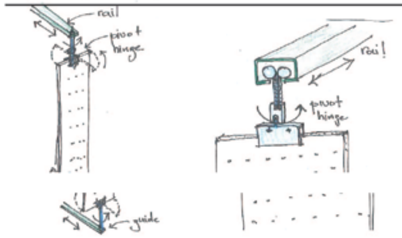
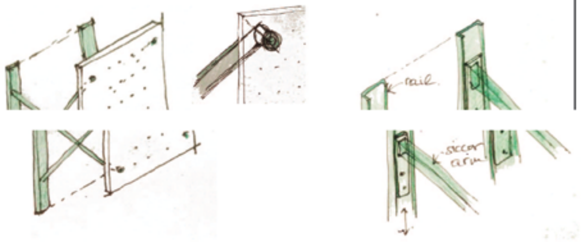
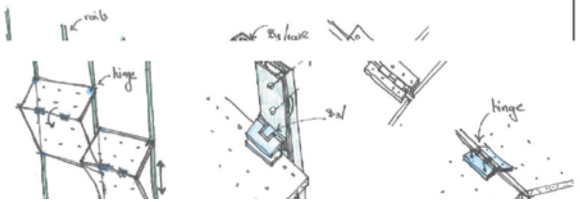


Morphological Chart for glass acoustic product



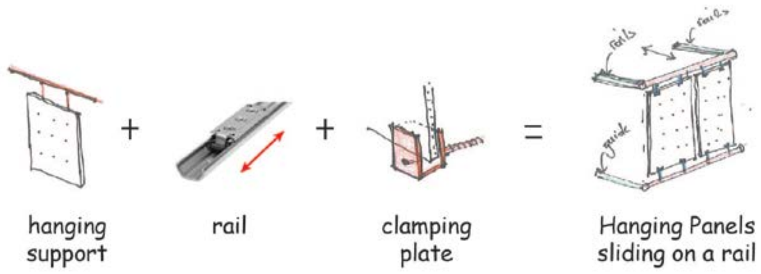

Customization of glass plate
Water-clear
annealed glass
1
Fabricating
the holes
2
Acid etching
sand blasting
silk-screening
coatings
3
Holes can be
customized
matt
prints
e.g. for solar control
coloured
printed
image
Tempering
Process

Screening Concepts Matrix

Generating Concepts \ Design Criteria	Cost	Safety	Maintenance	Customizability	Flexibility	Performance	Transparency	Competiveness
 Hanging Panels sliding on a rail: A3-B1-C3	N/A	●●●	●●	●●●	●●	●●	●●	●
 SELECTED Rotatable louvers sliding on a rail: A6-B1/B3-C3	N/A	●●●	●●●	●●●	●●●	●●●	●●●	●●
 Parallel projection on a siccor arm: A4-B5-C1	N/A	●●	●●	●●●	●●	●●	●●●	●●●
	N/A	●	●	●●●	●●	●●●	●●	●●●

3.4.2 Reflect on the Concepts

1. Hanging Panels sliding on a rail



The panels are supported with clamping plates at individual points along the horizontal edges of the glass pan. The forces are transferred by friction and the clamping connection can be with or without drilled holes. The self-weight of the panel is carried by the top two brackets. The out of plane actions like a light wind that can occur by an open door is taken by the clamping plates at the four edges. The structure has very good stiffness and stability. Cleaning the glass surfaces which face the cavity is difficult unless the cavity is minimum 30cm and accessible from one side. This will allow people to place tools to clean the surfaces.

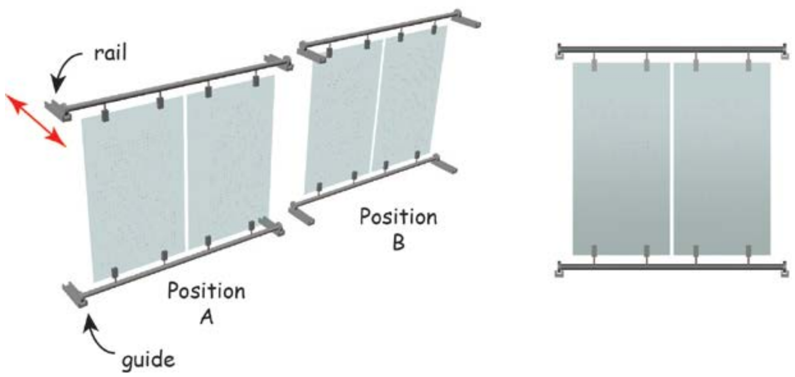
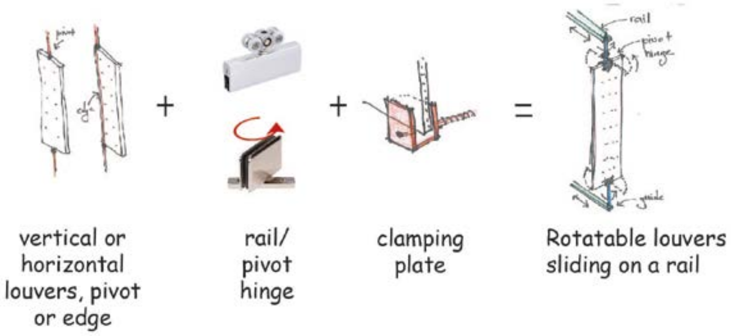


Figure 3-7 3d- model of the concept “Hanging panels sliding on a rail” (By the author)

2. Rotatable louvers sliding on a rail (Selected Concept for further Development)



This concept is similar to the commonly used rotatable louvers which are placed for sun protection to the outside of the glass facades. However, in this case, the acoustic glass louvers are placed to the inside and they rotate pivotally in order to adjust the reflections. The pivotal movement allows for easy cleaning of the all surfaces. When the glass is placed in 90^{o} from the backwall, then all glass surfaces are easily accessible for cleaning. Apart from acoustic blinds, these can also function as solar blinds, if printed, placed to the interior improving not only the acoustic quality but also the thermal comfort of the room.

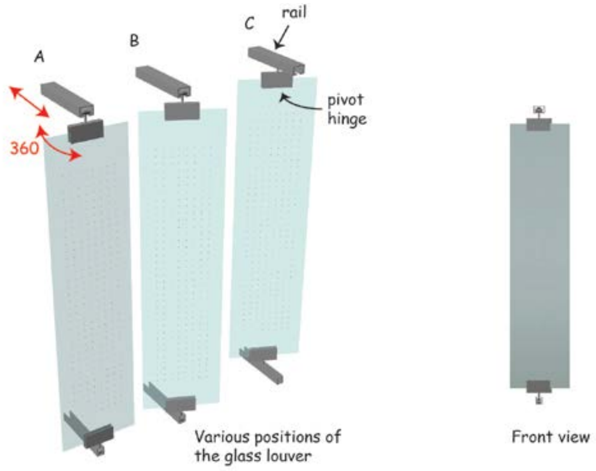
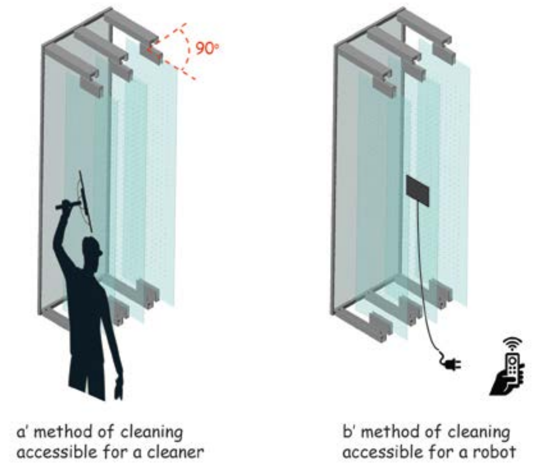
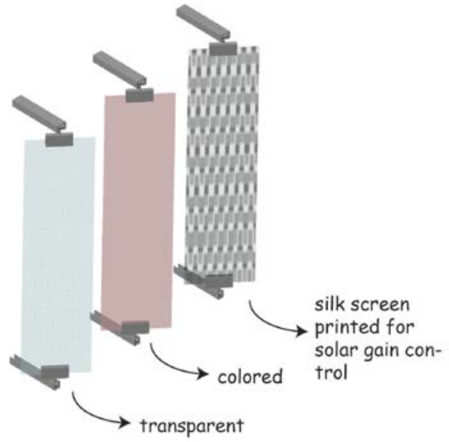


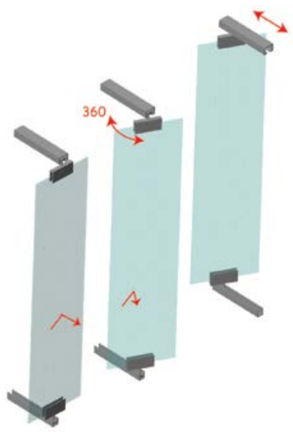
Figure 3-8 3d-model of the concept “Rotatable louvers sliding on a rail”.

Maintenance Strategies

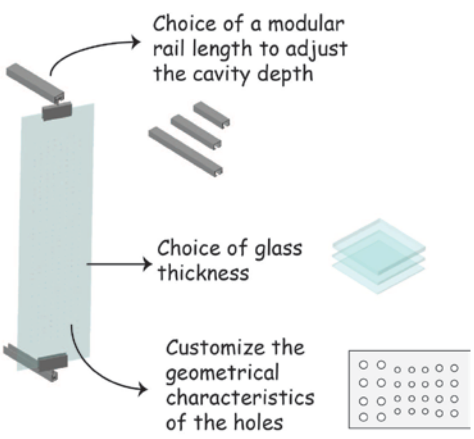




Customization of glass

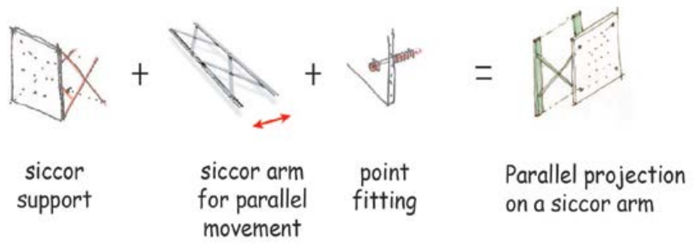


Flexibility in performance:
By rotating the louver, mid to high frequency sound is redirected
By adjusting the cavity depth, the bandwidth performance changes



Customization of the acoustic performance

3. Parallel projection on a siccor arm



The adjustment of the cavity depth is achieved with the siccor arm. The idea is taken from the ventilating windows which open with a parallel projection to the outside in order to allow minimum air circulation. Similarly to the first concept, this product configuration is difficult to maintain unless the projection is more than 30cm and accessible from the sides.

The point fittings to the glass create high stress concentrations which is less desirable since we design for a single glass pane without frame.

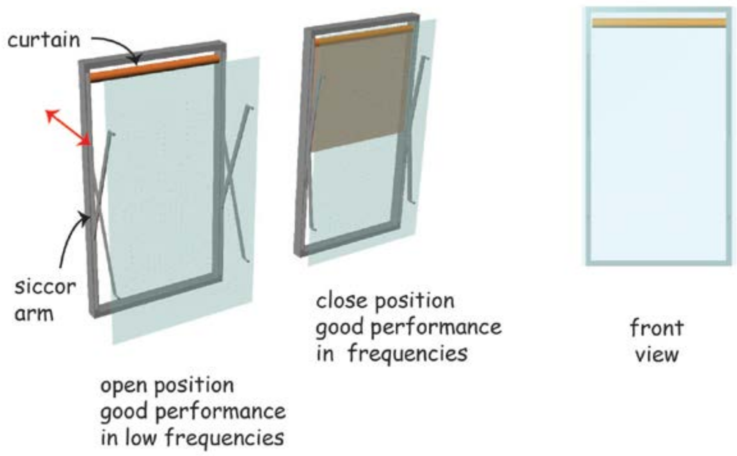
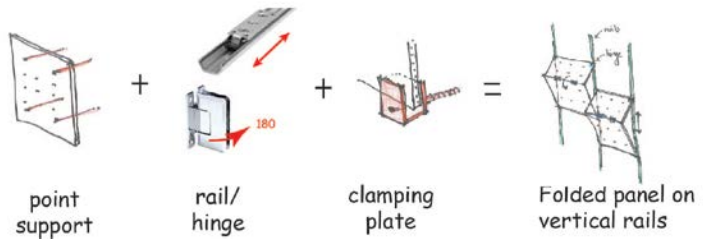


Figure 3-9 3d- model of the concept “Parallel projection on a siccor arm”.

4. Folded panel on vertical rails



In this solution the glass panes slide on rails. The hinge connection between the panes enables the folded position. The system is quite complex and requires careful engineering solutions that allow rotation at the connections without creating peak stress concentrations. From the aspect of cleaning, the operation is quite difficult unless there is distance from the backwall and accessibility from the sides.

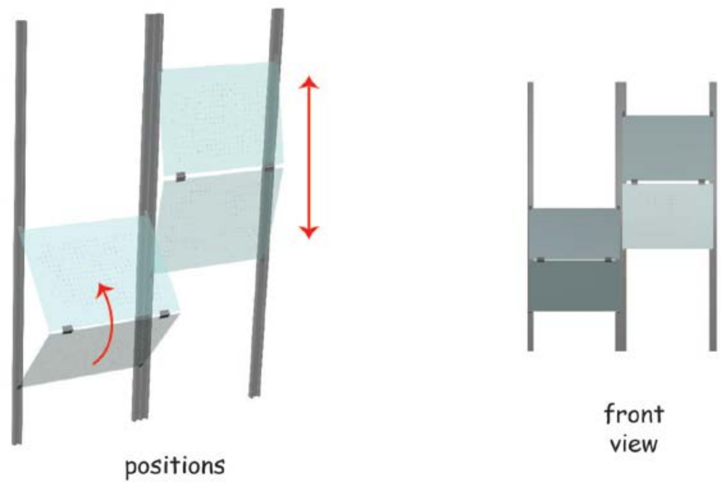


Figure 3-10 3d- model of the concept “Folded panel on vertical rails”.

3.5 Testing the Case Study: The"Co-creation Centre"

The aim of this section is to **demonstrate the selected design** concept at the pilot project. The acoustical problem will be analyzed and quantified in order to decide how much of the sound absorbing glass is required and what should be its design (hole diameter, perf. ratio, glass thickness, aircavity depth).

The "Co-Creation Center" is one of the future buildings of **"The Green Village" project** which will be located in TU Delft campus (see Fig. 3-11). The "Green Village" project will function as a platform where innovative technical ideas and prototypes can be developed, tested and demonstrated.

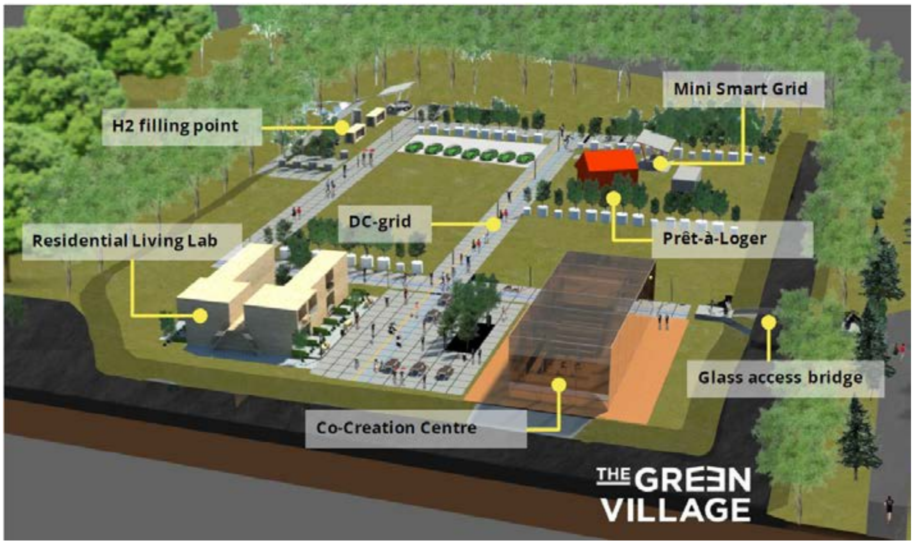


Figure 3-11 View of the 'Green Village" project showing which building are included in the master plan, source: https://www.thegreenvillage.org

The **"Co-Creation" Centre** (see Fig. 3-12) is an all glass cubic building and the innovation will exist in the first realization of 12m long loadbearing glass beams. The building will be a **multifunctional space,** mainly functioning as **Auditorium** for lectures, presentation and other speech events.

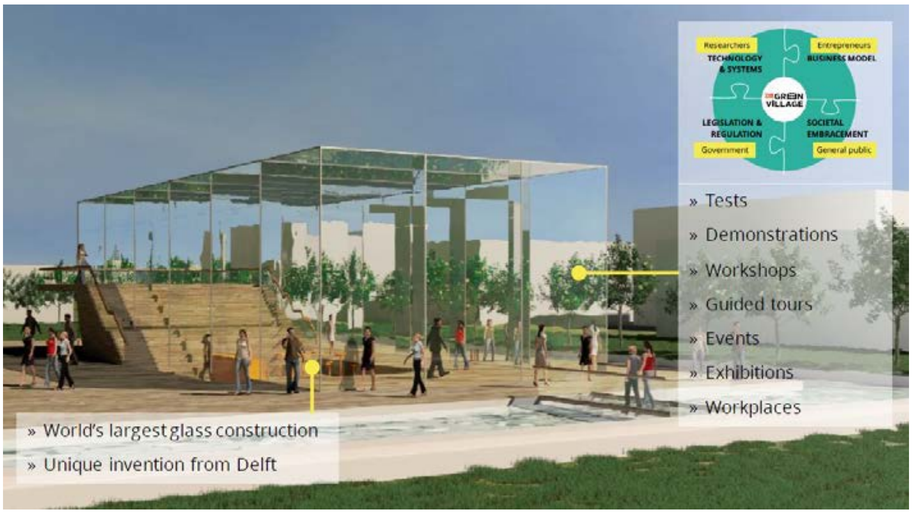
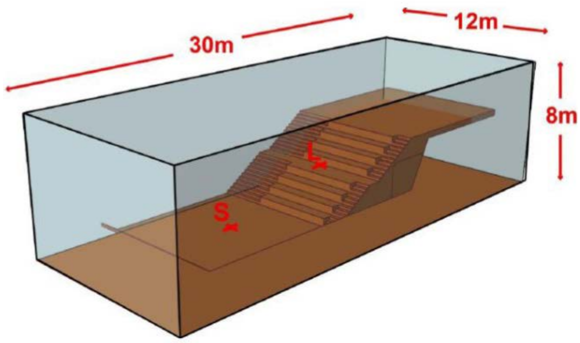


Figure 3-12 View of the 'Green Village" project showing which building are included in the master plan, source: https://www.thegreenvillage.org

3.5.1 Room Acoustic Design

a) Building Parameters

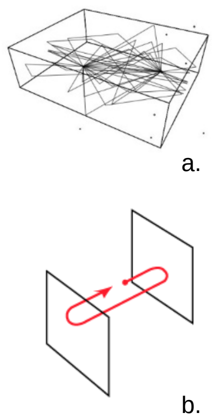
Volume = 30m x 12m x 8m = 2.880 m^3



b) The acoustical problem

When designing an auditorium, achieving good **speech intelligibility** is a demand. The acoustic problem of the "Co-Creation Centre" is caused by the **extensive glass surfaces and parallel walls**.

Late-arriving reflections reduce the speech intelligibility of a lecture hall



a.

b.

Figure 3-13 a. Multiple Reflections within a room with hard and parallel wall surfaces, b. Standing waves and flutter echo caused by parallel surfaces

due to the resulted ambient noise. These reflections are generated by the sound which is bouncing around the room for long time and finally arrives lately to the ears of the receiver. In the case of the “Co-Creation Centre” the problem of late-arriving reflections exists because the room is surrounded only by glass which is a high reflective material. A method to quantify the problem is to calculate the **Reverberation Time (T)** which shows how much time is needed to drop the sound 60dB below the original level.
Secondly, the geometrical form of the “Co-Creation Centre” is characterized by parallel, flat and high reflective surfaces. The parallel wall configuration causes **standing waves and flutter echo.**
Late-arriving reflections and flutter echo are the main problems which affect the sound intelligibility of the “Co-Creation Centre”

c) Design a room for Speech

An effective acoustic design for the “Co-Creation Centre” is achieved by the following actions:

- The direct sound and the **early-reflections** are enhanced using appropriate combination of reflective and diffusive surfaces.
- The **late-reflections** caused at the frequency range of speech (250-2000Hz) are reduced by using the correct amount and type of the glass absorber.

To achieve these goals, an acoustic concept is required, as described and illustrated below (see Fig. 3-15):

- The **glass boundaries** need to be covered with a kind of **absorbing material.** Microperforated glass is adequate solution because it combines these properties and its geometric parameters can also be designed exactly for the specific acoustic requirements. To redirect or diffuse the high frequency noise glass sound absorbing panels have to be tilted or curved.
- **Above the audience reflective panels** in lower height are required, in order to direct the sound from the speaker straight to the audience.
- The **rear top and back wall** ideally require high absorptive material in order to diminish completely the reflective noise arriving to the audience from behind.

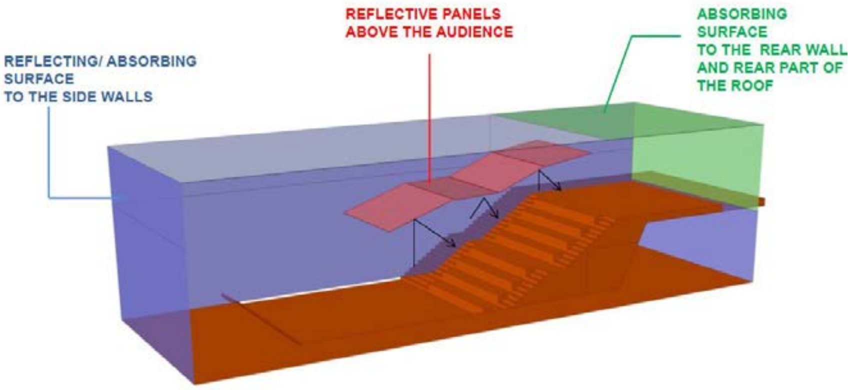


Figure 3-15 Conceptual sketch of the acoustic design of the “Co-Creation Centre”, (By the author)

d) Calculations in acoustics

The **reverberation time (T)** is the most significant acoustic property which measures the acoustic quality of a room. It depends on the absorption and the volume of the room. What we expect regarding the “Co-Creation Centre” is that since it is surrounded by high reflective glass surfaces the reverberation time will be **very long**. Absorption is achieved only by **people** who exist in the space. The analysis starts with calculating the existing (T) and continuous with the optimized situations.

The reverberation Time (T) is calculated using the Sabine's formula:

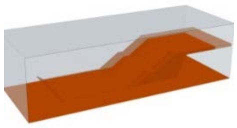
$$T = \frac{1}{6} \times \frac{V}{A} [s]$$

T in [s]

V in [m^3]

A in [m^2sabin], $A = a_1 S_1 + a_2 S_2 + a_3 S_3 + ..$

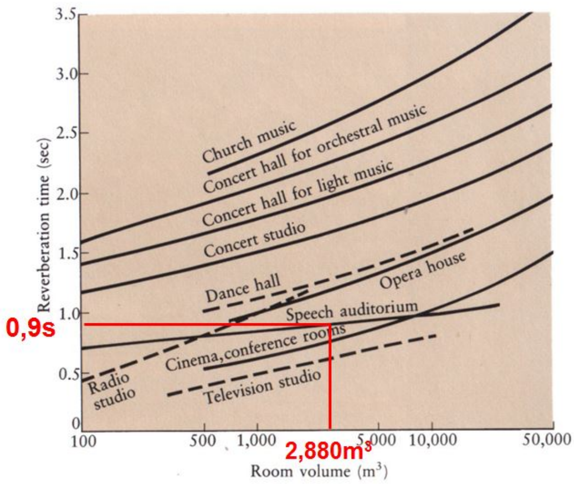
1. Calculating the **Reverberation Time (T)** of the "Co-Creation Centre" **with no absorbing material, while occupied by 250 people.** The absorption coefficient of the materials depends on the frequency, so the reverberation time is frequency dependent according to the following table:

EXISTING SITUATION WITH AUDIENCE						
	**Absorption coefficients (a) at center frequencies**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Glass Envelope S_g=1,032m^2	0.1	0.04	0.03	0.02	0.02	0.02
(a x S_g)	**103.2**	**41.28**	**30.96**	**20.64**	**20.64**	**20.64**
Vinyl Floor S_v=360m^2	0.02	0.03	0.03	0.03	0.03	0.02
(a x S_v)	**7.2**	**10.8**	**10.8**	**10.8**	**10.8**	**7.2**
Audience 250# S_a=250x0.5m^2	0.52	0.68	0.85	0.97	0.93	0.85
(a x S_a)	**65**	**85**	**106.25**	**121.25**	**116.25**	**106.25**
A[m^2sabin]	**175.4**	**137.1**	**148**	**152.7**	**147.7**	**134.1**
$T = \frac{1}{6} \times \frac{2,880}{A} [s]$	**2.74**	**3.5**	**3.24**	**3.14**	**3.24**	**3.58**

From the above table we see that the reverberation time in the "Co-Creation Centre" for the targeted frequency range of **250Hz to 2000Hz** lies between:

3.5s < T[s] < 3.24s (a)

2. Using the following table, we define **the required Reverberation Time (T) of a lecture theater** against the volume (V) of the "Co-Creation Centre".



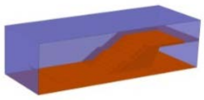
Required (T) = 0,9s (b)

Comparing (a) and (b) we see that the existing T is at least **3.5 times higher** than what is required to be. It means that absorbing material must be added so as to improve the acoustic quality of the room.

3. According to the acoustic design concept, the absorbing glass has to be placed in front of the glass boundaries in order to avoid unwanted reflections. Based on this decision together with the demand for **T=0.9s**, two simplified concepts are presented:

Plan A: Absorbing material covers all glass boundaries (walls and roof)

Plan B: Absorbing material is placed at ¾ of glass walls

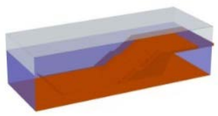
(Plan A) IMPROVED SITUATION WITH AUDIENCE (100% of walls and roof covered with absorbing material)						
	Absorption coefficients (a) at center frequencies					
	125	250	500	1000	2000	4000
Microperforated glass $S_{mpg}=1{,}032m^2$	0.43	0.4	0.38	0.37	0.37	0.39
$(a \times S_g)$	442.8	419.2	398	382.7	388	402
Vinyl Floor $S_v=360m^2$	0.02	0.03	0.03	0.03	0.03	0.02
$(a \times S_v)$	7.2	10.8	10.8	10.8	10.8	7.2
Audience 250# $S_a=250x0.5m^2$	0.52	0.68	0.85	0.97	0.93	0.85
$(a \times S_a)$	65	85	106.25	121.25	116.25	106.25
$A[m^2 sabin]$ $A = 0.161 \times \frac{2{,}880}{0.9}$	515	515	515	515	515	515
$T = \frac{1}{6} \times \frac{2{,}880}{A} [s]$	0.9	0.9	0.9	0.9	0.9	0.9

According to the calculations, if sound absorbing glass is placed in front of all glass surfaces of the room, walls and roof then the absorption coefficient between the targeted frequencies of 250Hz and 2000Hz has to be 0.4.

Plan A: Requires a=0.4, for 250Hz<f<2000Hz

Sound absorbing glass can achieve higher absorption coefficient and thus the total surface of glass surface can be reduced.

Plan B calculated the alternative to add absorbing material only at the ¾ of the wall surface.

(Plan B) IMPROVED SITUATION WITH AUDIENCE (only 75% of walls covered with absorbing material)						
	Absorption coefficients (a) at center frequencies					
	125	250	500	1000	2000	4000
Glass Envelope S_g=528m^2	0.1	0.04	0.03	0.02	0.02	0.02
(a x S_g)	52.8	21.12	15.84	10.56	10.56	10.56
Microperforated glass S_{mpg}=504m^2	0.77	0.79	0.75	0.74	0.75	0.77
(a x S_g)	390	398.1	382.11	372.4	377.4	391
Vinyl Floor S_v=360m^2	0.02	0.03	0.03	0.03	0.03	0.02
(a x S_v)	7.2	10.8	10.8	10.8	10.8	7.2
Audience 250# S_a=250x0.5m^2	0.52	0.68	0.85	0.97	0.93	0.85
(a x S_a)	65	85	106.25	121.25	116.25	106.25
A[m^{2}sabin] $A = 0.161 \times \frac{2,880}{0.9}$	515	515	515	515	515	515
$T = \frac{1}{6} \times \frac{2,880}{A}$ [s]	0.9	0.9	0.9	0.9	0.9	0.9

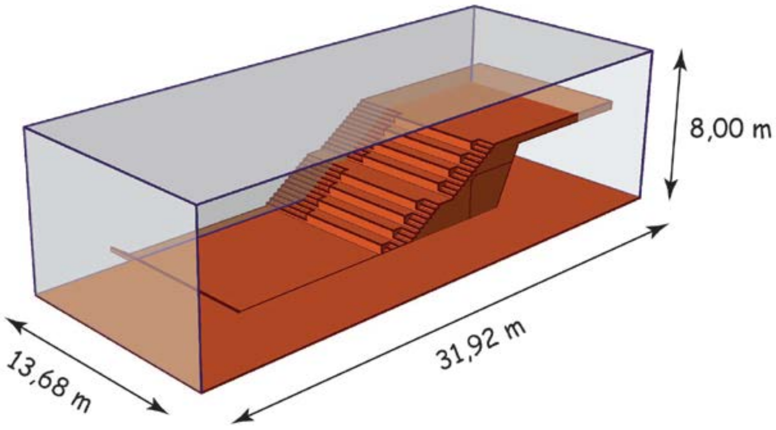
According to the alternative Plan B, if the surface of sound absorbing glass is reduced to half then the acoustic efficiency needs to reach the value of a= 0.75

Plan B: Requires a=0.75, for 250Hz<f<2000Hz

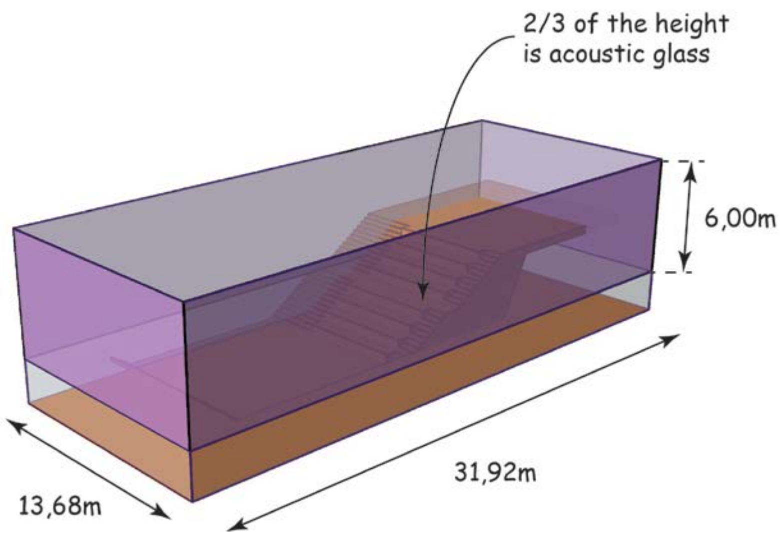
Based on the results of Plan B, the sound absorbing glass for the Co-Creation Centre will be designed.

3.5.2 Acoustic Design of the Sound Absorbing Glass Panel

a) Room without absorbing material:



b) Room with absorbing material:



Total glass surface without absorbing material	1,032m^2
Required sound absorbing glass of a=0.75 for targeted freq. from 250Hz to 2000Hz	504m^2

Results from Matlab:

The calculations are done in order to define what the margin of the variable cavity depth has to be in order to achieve a broadband performance of 0.75 from 250Hz up to 2000Hz. Various combination of geometrical characteristics were tried; the optimal cases are presented below:

Red line

```
fvector=0:5000;                                     %Frequency range [Hz]
dpanel=3.0*10^-3;                                   %Panel thickness [m]
repd=10*10^-3;                                      %Repeat distance (D) [m]
holedia=0.7*10^-3;                                  %Hole diameter [m]
holerad=holedia/2;                                  %Hole radius [m]
cavity=25*10^-3;                                    %Cavity depth [m]
perfrate=5.1/100;                                   %Perforation rate [%]
angle=0.0;                                          %angleofincidence
```

Blue line

```
f2vector=0:5000;                                    %Frequency range [Hz]
dpanel=3.0*10^-3;                                   %Panel thickness [m]
repd=10*10^-3;                                      %Repeat distance (D) [m]
holedia=0.7*10^-3;                                  %Hole diameter [m]
holerad=holedia/2;                                  %Hole radius [m]
cavity=50*10^-3;                                    %Cavity depth [m]
perfrate=5.1/100;                                   %Perforation rate [%]
angle=0.0;                                          %angleofincidence
```

Magenta line

```
f3vector=0:5000;                                    %Frequency range [Hz]
dpanel=3.0*10^-3;                                   %Panel thickness [m]
repd=10*10^-3;                                      %Repeat distance (D) [m]
holedia=0.7*10^-3;                                  %Hole diameter [m]
holerad=holedia/2;                                  %Hole radius [m]
cavity=110*10^-3;                                   %Cavity depth [m]
perfrate=5.1/100;                                   %Perforation rate [%]
angle=0.0;                                          %angleofincidence
```

Yellow line

```
f4vector=0:5000;                                    %Frequency range [Hz]
dpanel=3.0*10^-3;                                   %Panel thickness [m]
repd=10*10^-3;                                      %Repeat distance (D) [m]
holedia=0.7*10^-3;                                  %Hole diameter [m]
holerad=holedia/2;                                  %Hole radius [m]
cavity=200*10^-3;                                   %Cavity depth [m]
perfrate=5.1/100;                                   %Perforation rate [%]
angle=0.0;                                          %angleofincidence
```

Final Acoustic Design

The absorption coefficient of the panel having a variable cavity depth from 20mm to 2000mm is presented below:

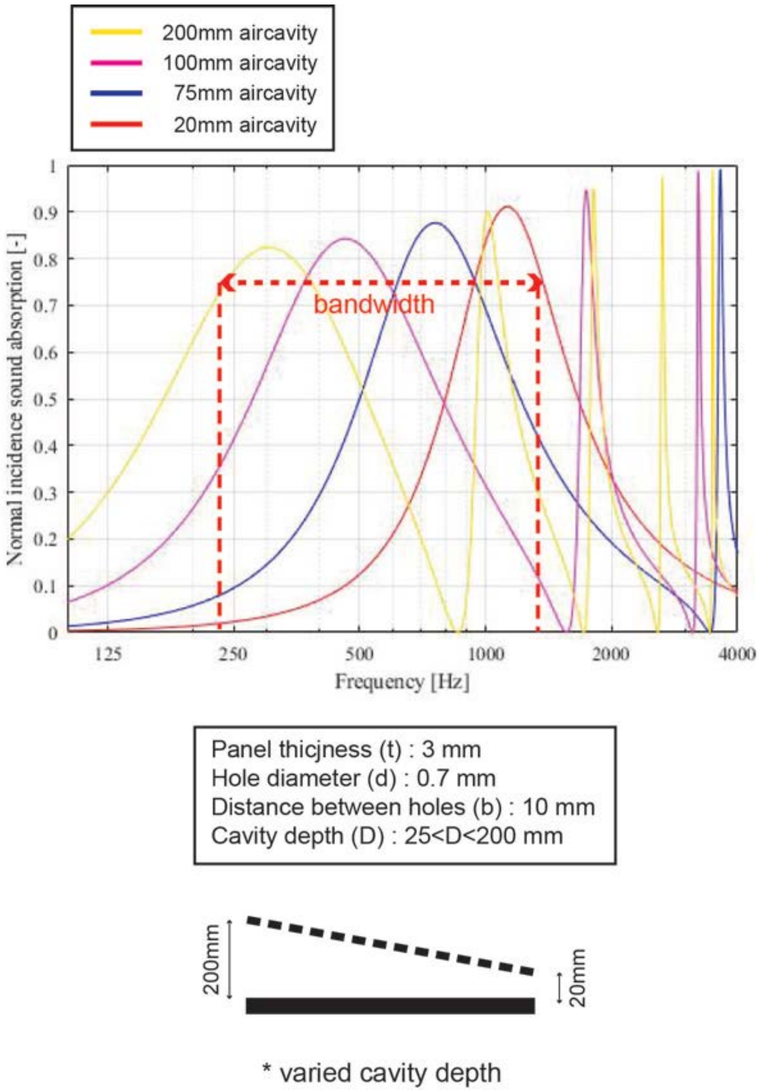
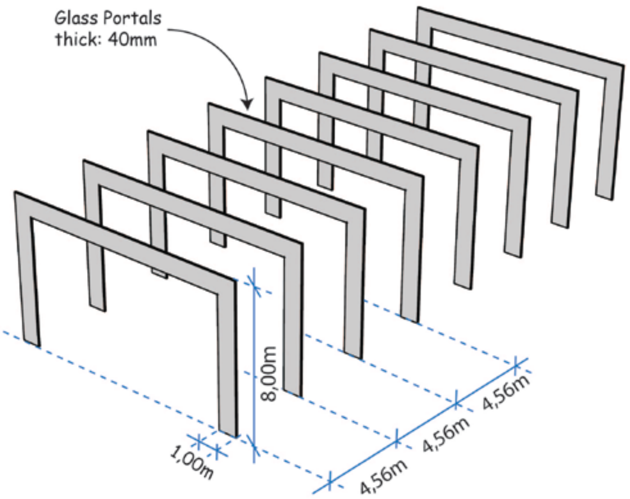


Figure 3-16 The absorption coefficient and the geometrical characteristics of the microperforated glass panel calculated in Matlab (By the author)

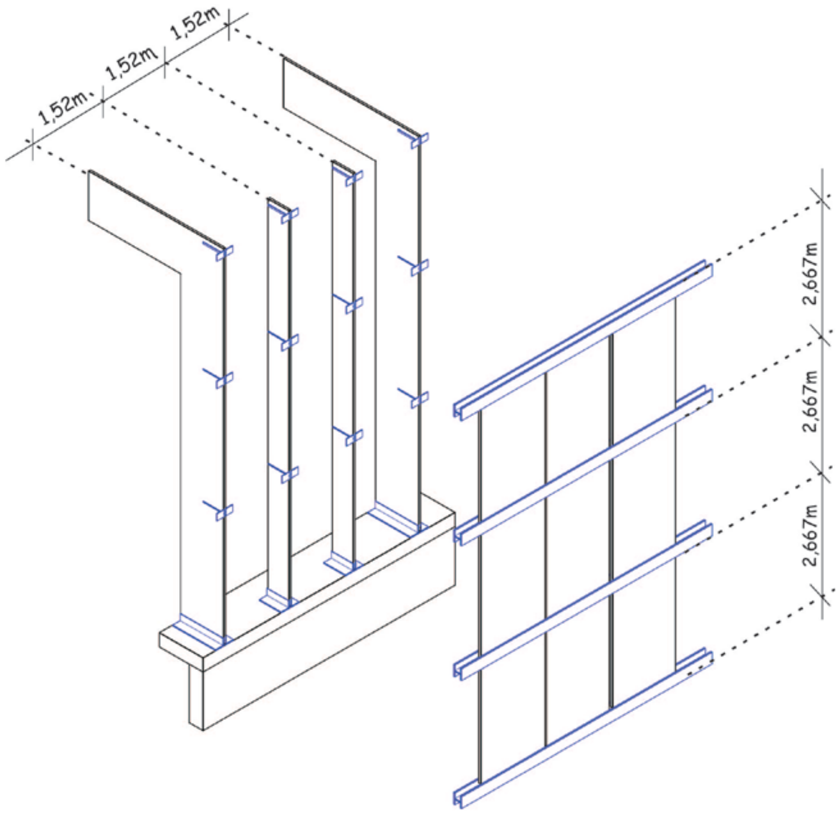
3.5.3 Detailed Design

The Building

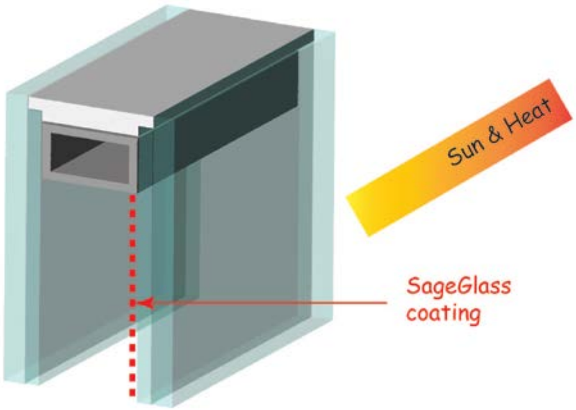
a. The main loadbearing structure: glass portals



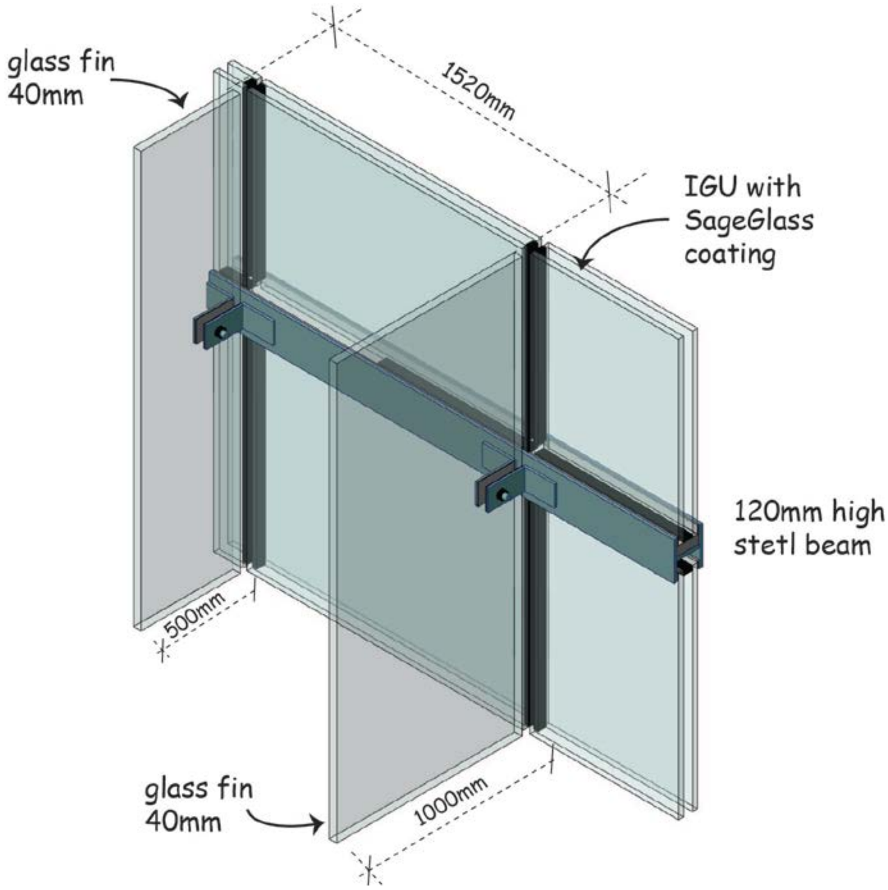
b. Façade Structure: Axonometric View



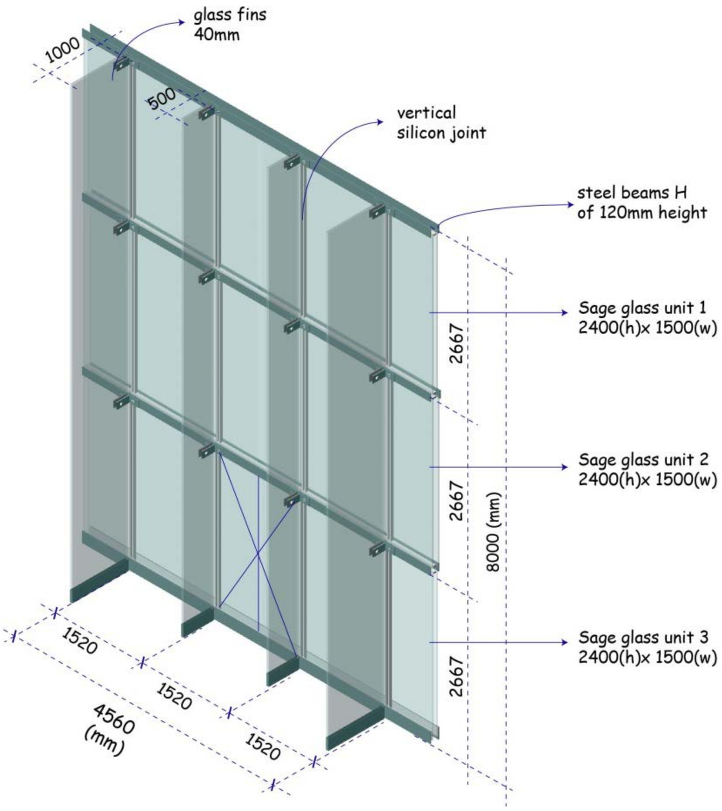
c. Façade: Sage Glass Insulated Unit



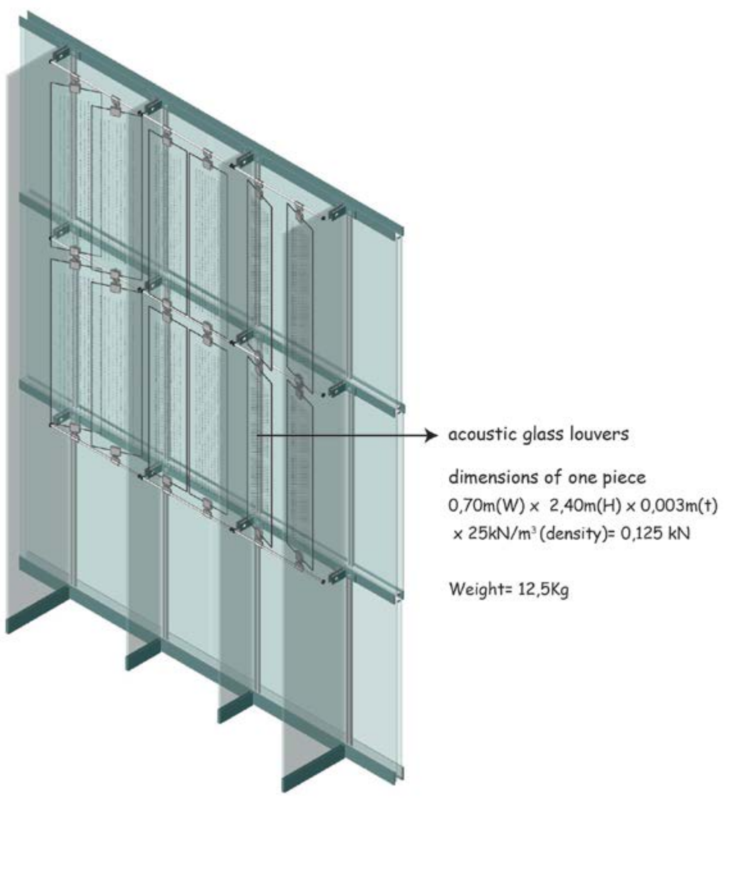
d. Connection of glass fins with the facade



e. View of the façade from the inside without the sound absorbing louvers

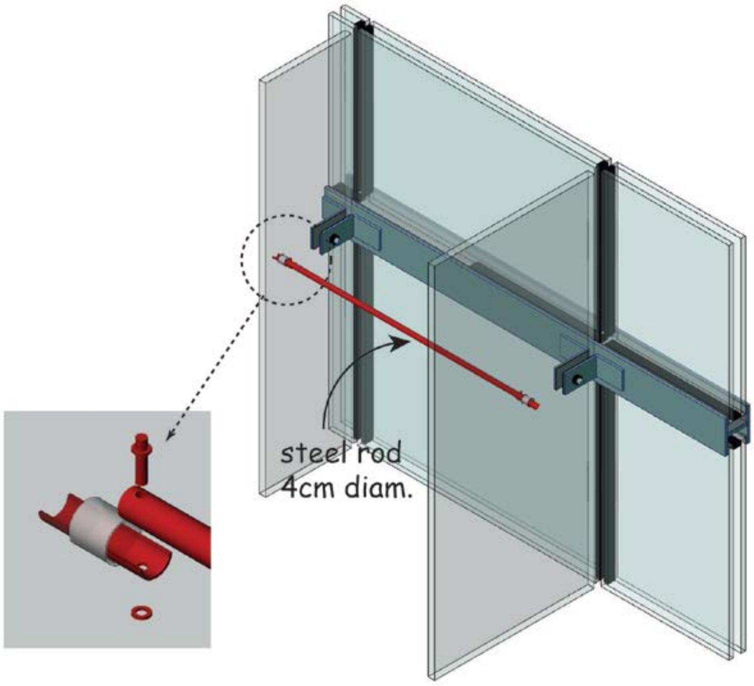


f. View of the façade from the inside with the sound absorbing louvers



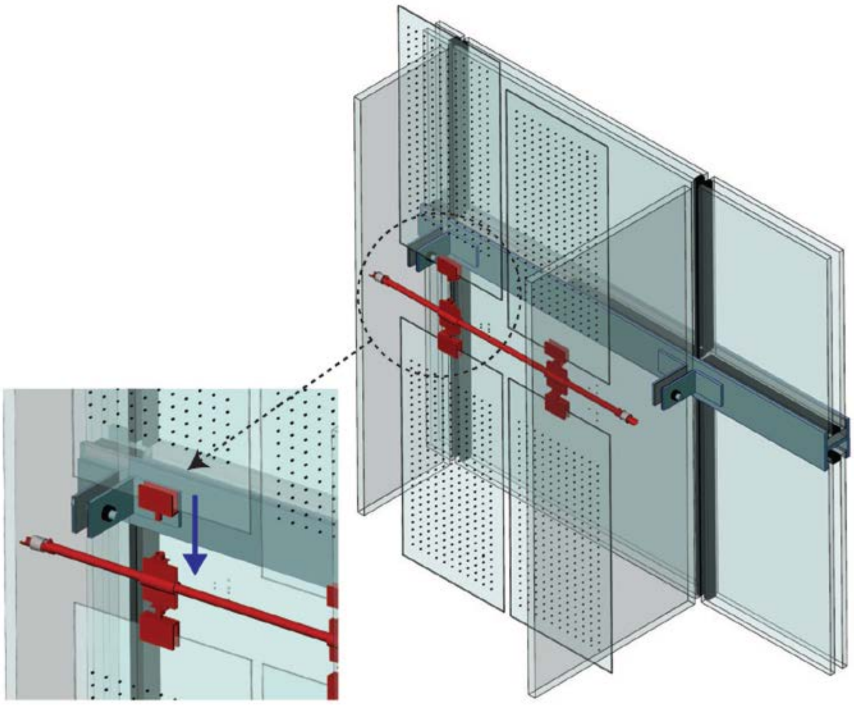
The Product Solution

1. Connection of the steel rod with the glass fins



2. Connection of the pivotal hinge to the steel bar

3. Connection of the glass louvers to the steel bar with the pivot hinge



4. Final Impression-3dmodel

3.6 Summary of the Results

In **Section 3.2**, an **in-depth market research** was conducted, aiming to collect data regarding the desirable product requirements. The targeted group of interviewees was selected to be those experts who have decision-role in selecting the acoustic solution of a project; these are architects, acousticians and glass/ facade experts. After processing the results in a strict structured method, a list of design criteria is presented in **Section 3.2.2**. Based on these criteria, the final concept solution will be selected.

The aforementioned design criteria are used to **benchmark** microperforate glass with **competitive product** solutions from the market. In Section 3.3.2, a chart is been developed which asses the various transparent acoustic solutions based on these criteria. From there we conclude that glass has great potentials to succeed in the market due to its great quality but its cost is significantly higher than the existing solutions.

In **Section 3.4,** four product concepts are generated for the glass sound absorber. Already from the early stage of creating a morphological table, the design was driven by the ideas of customizability and flexibility in the performance. **Section 3.4.2** chooses for the concept of **"sound absorbing glass louvers".** It is the one among the others, which satisfied the most the design criteria set by the market.

The "sound absorbing glass louvers" are demonstrated in detail, for the occasion of the **pilot project**, the "Co-Creation Centre". The feasibility and the acoustic efficiency of the concept are proved based on acoustic calculations and matlab simulations. The strongest **advantage** of the concept though, is its ability to **rotate pivotally** and thus, **adjusting its acoustical performance** to the demands of the specific project. The absorption bandwidth of the microperforated glass depends on the cavity width. By simply using a simulation program the louvers can be adjusted to the specific acoustic requirements.

Conclusions

CHAPTER FOUR

4.1 Introduction

The technology of glass is continuously progressing and the potentials of the material are investigated. With this thesis a new function for glass is presented, the sound absorption and thus, new opportunities for innovative products are challenged. The objective of this thesis is to develop an acoustic solution for the market of building materials, made out of the innovative microperforated glass. The conclusions that follow, provide answers, initially to the two research questions, which correspond to the phases of “Opportunity Assessment and Planning” and “Product Development” respectively. Then the main research question is answered summarizing all conclusions once again. Recommendations for further research are provided at the end.

4.2 Answers to the Research Questions

4.2.1 What are the potentials of the innovative microperforated glass to succeed in the market of sound absorbing materials?

Microperforated glass has potentials to succeed in the market, as a sound absorbing solution for **façade-front applications**. The reason for this is, that the competitive transparent plastic materials such as PC, PETG or PMMA, present high degradation and discoloration under UV exposure and high temperatures. Besides these, **plastics** have lower surface quality than glass due to vulnerability in scratches and finger prints. This fact is inhibitor for applications like windows which require high optical quality. Hence, there is a gap in the market where the sound absorbing glass can gain success. The rest type of applications such as overhead panels, partition walls or furniture can be satisfied by the existing acrylic solutions which are by far cheaper than glass.

Speaking now about the **cost** of microperforated glass, it is necessary to mention that it is approximately 4 times higher than the competitive plastics. We can roughly say that the cost of 1m^2 of sound absorbing glass, which has a relatively broadband absorption around 0.7, is 1000€. The cost can definitely drop, if series of the same product are fabricated. Expectations that the cost will drop in the future exist, because, on the one hand the technology of micromashining continuously progresses and on the other hand, the industry is challenged to become more cost efficient by achieving quicker turnaround.

Due to its high cost, the sound absorbing glass addresses to high quality projects with special architectural requirements. Launching the product in the market as a façade-front solution, allows for **customization and flexibility** in its characteristics. With this kind of application, the sound absorbing glass reclaims its maximum value. Demonstrating such a solution in the market will inspire the customer further to think on its own customized design.

4.2.2 How can a glass sound absorber be designed for the "Co-Creation Centre" so as to meet the acoustic requirements and preserve transparency?

The "sound absorbing glass louvers" will be placed in vertical position at the upper 2/3 part of the surrounding glass walls in order to **prevent accidental loading from people**. The acoustic product is supported on the loadbearing glass fins of the building.

In the case of "Co-Creation center", there was no requirement for extra **solar control** by the glass louvers, because the façade panels integrate Sage coating. It would be interesting to see though that by adding coatings or prints on the surface of the glass louver, **a combination of acoustic and solar control function can be achieved.**

The geometrical characteristics of the panel are designed according to a Matlab model which **simulates the performance**. The challenge was **how to achieve broad bandwidth performance, without using various diameters of holes which increase the cost.** The solution was given by designing a panel in **slanted position,** so as to achieve incremental aircavity depth and thus broader bandwidth performance.

The **pivotal hinge** allows for **tuning the glass sound absorbers to specific acoustic requirements** that may be either for speech or music. By turning the glass in various positions, the cavity depth changes and affects the efficiency of the absorber. Moreover, pivoting glass in a vertical position against the wall allows for cleaning of both glass surfaces.

4.2.3 How can an innovative glass sound absorber be developed using the microperforated glass technology, in order to be successful in the marketplace?

The product is feasible with the available technology today, but it is very expensive compared to competitive acoustic solutions, as it is described in Section 2.6.2 and 4.2.1. To reduce the production cost, a mass production of the same component would be efficient. By producing a **series of the same panels,** the initial setup cost of the machine which is relatively high is distributed in more products and thus, the cost per glass panel is reduced. Another parameter which affects the production cost is the speed of fabricating per hole. Our knowledge though in this thesis is not enough for optimization since the time is dependable to the resulted glass strength.

The **market size** for the sound absorbing glass is small today due to its high cost. However, launching as a product for façade-front applications is interesting. Buildings, such as the “Co-Creation Centre” where the transparency of the architectural concept needs to be preserved, are possible customers. Still the high cost is an inhibitor for product’s wide application.

A **small company** or a company that cares about adding new **innovative product**s in their catalogue should be the producer. This type of company cares more about the quality and less about efficiency.

Customizability in its characteristics and flexibility in its performance have to be the main attributes of the sound absorbing glass, in order to achieve highest quality. The “sound absorbing glass louvers” satisfy these needs. In this way, value is created that can balance the high cost and attract at first place high quality projects.

4.3 Recommendations

In this section recommendation for further research in the topic of microperforated glass will be proposed in bullets:

- Define the design strength of a microperforated glass plate based on a chosen production method e.g. ns-laser from 4Jet Company.
- Research on the thermal performance of a façade/ window system that integrates the microperforated glass.
- Effect of the holes in the transparency from various angles
- Laminates either with glass with glass or glass with plastics

AI Appendix A

List of interviewed experts

The following experts have been interviewed. They contributed to the market research methodology which is presented in Section 3.1:

Architects

Arie Bergsma, *TU Delft/gAAgA*, NL

Paddy Tomasen, *TU Delft/ &TOMESEN architects*, NL

Thijs Asselbergs,*TU Delf/ aTA architectuurcentrale Thijs Asselbergs,* NL

Acoustician

Martin Tenpierik, *TU Delft*, NL

Theodoros Timagenis, *Timagenis Architects Acoustics Design Consultants*,GR

Glass Expert

Rob Nijsse, TU Delft/ABT bv, NL

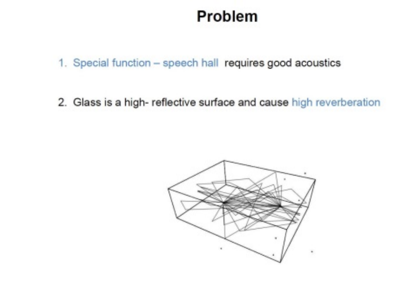
James o' Callagan, *Eckersley O'Callaghan*, UK

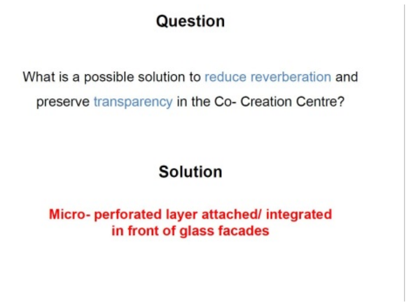
Barbara van Gelden, *Octatube*,NL

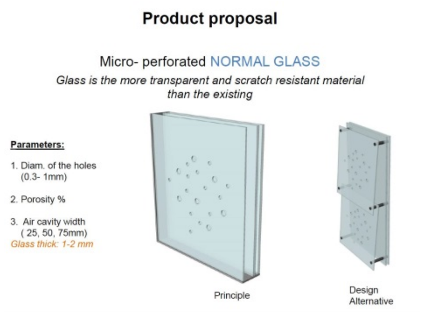
Expert in Microtechnology

Thomas Melle, *Head of MicroFab,4JET microtech*, D

Slides presented to the interviewees







Interviewees

Sample of 6-8
architects/ engineers/acousticians

WHY: These experts are involved in the design decision.

Questions/ Structure of the interview

PART A
Acoustics and design

Decision role

Relation with acoustics

Experience in acoustical solutions

Role of acoustics in design

Questions/ Structure of the interview

PART B
Challenges

Strengths

Weaknesses

Market volume

Questions/ Structure of the interview

PART C
Expectations

regarding main topics:

- Physical integration/ connection
- Durability- maintenance
- Performance
- Aesthetics
- Variation/ Flexibility
- Cost
- Structural safety

Questions/ Structure of the interview

PART D
Sales Strategy

Provide ideas how to launch the product so as to attract buyers

Questionnaire to 4JET microtech Company/ Thomas Melle

The questionnaire was sent by email on 23th of October 2017 and the answers received on 2nd of November 2017.

Von: Olga Tourlomousi [mailto:olga_arc@hotmail.com]
Gesendet: Montag, 23. Oktober 2017 17:42
An: Thomas Melle
Betreff: Microperforated glass-Questions for TU Delft/master thesis

Dear Mr Thomas Melle,

I am doing my master thesis in TU Delft on the potentials that **microperforated glass has in the market as acoustic solution for buildings**.
I met you last year when I visited 4jet with Ate Snijder and Anne Struiksma (researchers from TU Delft) and we had a tour.
Hereby would like to ask you few questions regarding the technology and cost of microperforated glass whereas **your answers will only be used for the purposes of my master thesis.**
If you would like to collaborate in this interview please **answer shortly some or all** of the following questions:
Questions:
The glass piece that you manufactured for TU Delft was 300mmx400mm and contained 1804 holes of 0.3,0.5,0.8,1.0 diameters and the cost was approx. 1500 Euro.

Cost
1a. What parameters defined the cost of the above mentioned microperforated glass plate?(Number of holes? Diameter? Other?)
Answer: A lot of parameters defined the cost of the plate. The question is if you want a estimation for a subcontract deal or for a mass production. For the subcontract the following parameters/specification are cost driven:

- Tact time cost
    - Number of holes
    - Diameter
    - Glass thickness
    - Glass type
    - Handling
    - Glass size
- Specification
    - Diameter accuracy
    - Quality of the hole
    - Allowed chipping size

1b. Can the cost per glass piece be reduced when a large amount of microperforated glass pieces is requested by the client instead of a single microperforated glass piece? For example, if the glass piece that TU Delft requested, was asked 50 times instead of 1 time, how much would the price per glass piece drop approximately or would it remain the same?
Answer: Indeed the quantity of plates have a huge effect on the price. For 1 plate you have the initial setup cost who are distributed on 1 pcs. instead of 50. Means if the setup cost are let say 390€ and the processing per part is 50€, you will pay for one part 440€ and for 50 2890€ (57,80€/pcs.). For every order you have fix cost and variable cost.
1c. Can you propose other parameters that affect cost and could possibly reduce the cost of a microperforated glass piece?
Answer: Already mention in question Nr. 1
Technology
2a. What type of laser machine did you use to manufacture the glass piece for TU Delft? Was it a CO_2 laser or other? What are the advantages and disadvantages of this type of laser for the specific project of TU Delft?

Answer: For the processing of your parts we used our own development machine. This machine is able to run small production. At the moment in time we are building up a machine for mass production in our Jobshop. In general we are a machine manufactured with Jobshop capability which is growing. Next year we will have a own location for the Jobshop activitys.

Regaring the laser, we used a ns-green laser to drill the glass. This laser is regarding drilling time and quality the best choice. With a Co2 laser you will be not able to do such holes.
2b. Is there another more recently developed micromachining technology with better potentials (e.g. cheaper or faster or creates less micro-chipping) than the laser machine you used ?
Answer: If you want to get less chipping the cost will go up and the process will be slower. At the end of the day the question is which amount of perforated glass have to be produced a year. Maybe then a combination of laser and etching becomes attractive.
2c. Do you think that the cost of microperforation in glass will be dropped in the future? If yes when do you estimate this to happen? (This answered should be based on your personal view and experience as expert in this technology)
Answer: The price will drop continually to the further development of lasers and machine components who will lead to cheaper prices. Like cell phones 10 year ago and today.

Prototype- Design

Please see the attached image. This is our design for acoustic glass louvers. Each glass piece is 700x2400mm and 3mm thickness. We need 268.800 holes of 0.3mm diameter equally distributed. How much would cost this approximately and what method would you use? Is it possible to manufacture such a big glass piece?
(I expect that the cost would be very high but please provide me your personal view on this design)
Answer: The size of the glass of 700x2400mm is challenging. At the moment in time our Jobshop machine for drilling can go up to 600mmx600mm. Some concept are in the development for industrial production with 1200x2500mm working area.

Just to get a idea for the price: If one hole need 10sec of processing, we get 746h of processing(268800holes). With 1 sec. it is still 74,6h. A machine cost 500T€, leads to 15€/h machine cost in 24d/7h production. Means that only the machine time for drilling will be something about 11190€ for 746h and 1190€ for the case if we calculate with 74,6h.

As you can see the price realy depends on the time for drilling the hole. And here the time depend on the need quality.

Thank you very much in advance and your contribution in this research will be very much appreciated.

Kind Regards

Olga Tourlomousi

AII Appendix B

Bibliography

Acoustics

1. Linden, A. C. v. d., & Zeegers, A. (2006). Acoustics. In I. E. Claassen (Ed.), Building Physics. Utrecht: Thieme-meulenhoff
2. Salter, C. M., Associates. (1998). Acoustics: architecture, engineering, the environment: William K Stout Pub
3. Everest, F. A., (2001). The Master Handbook of Acoustics, McGraw- Hill, United States
4. Hornbstel, C.(1991). Construction Materials, Types, Uses, Applications, John Wiley & Sons, United States
5. Struiksma, A. F., (2016). Transparent Acoustic Solutions: TU Delft, Delft
6. Fuchs, H. V. and Zha, X., Acrylic-glass Sound Absorbers in the Plenum of the Deutscher Bundestag. Applied Acoustics, Vol. 51, No. 2, 1997, 211-217.
7. Fuchs, H. V. and Zha, X., Sound-Absorbing Glass Building Component Or Transparent Synthetic Glass Building Component, U.S. Patent 5,700,527 issued in Dec. 23, 1997

Glass

1. Ashby, M. F., Shercliff, H., & Cebon, D. (2013). Materials: engineering, science, processing and design: Butterworth-Heinemann
2. Veer, d. i. F. A. (2014). Glass structure and strength: Technical University of Delft
3. Schittich, Staib, Balkow, Schuler, Sobek. (2007). Glass Construction Manual, Detail Edition, Munich
4. Khatib, J, (2009). Sustainability of construction Materials. Woodhead Publishing Limited, Cambridge
5. Schittich, C., Staib, G., Balkow, D., (2007), “Glass construction manual-2nd revised & expanded edition”, Birkhäuser, Basel(CH)

Facades/ Connections

1. Ching F. D. K. (2014). Building Construction Illustrated. Wiley, Canada
2. Meijs, Knaack, (2009). Components and Connections. Birkhauser, Munich
3. Herzog, Krippner, Lang (2004). Facade Construction Manual. Birkhauser, Munich

Product Development/ Market

1. Klein, T (2013). Integral Façade Construction.
2. Eekhout, M, (2008). Methodology for product development in architecture. Delft University Press, Delft
3. Ulrich, K.,(1993). The role of product architecture in the manufacturing firm. Elsevier, Cambridge
4. Cross, N. (2008). Engineering Design Methods: Strategies for Product Design. Wiley, Canada
5. Ulrich, K. and Eppinger, S.(2015). Product Design and Development. McGraw-Hill Education, United States
6. Tooley, M., (2010). Design Engineering Manual, Elsevier Ltd., United States

Research Methods/Interviewing

1. Brinkman, W.-P.(2009). Design of a Questionnaire Instrument, Handbook of Mobile Technology Research Methods, ISBN 978-1-60692-767-0, pp. 31-57, Nova Publisher

2 Fellows, R. and A. Liu (2008), Research methods for construction, 3rd edition, Blackwell Publishing (online access)

3. Groat, L.N. and D. Wang (2013), Architectural Research Methods, 2nd edition, John Wiley & sons, Hoboken; (online access)

4. Oppenheim, A. N. (1992), Questionnaire Design, Interviewing and Attitude Measurement, Pinter Publishers, London and New York

Presentations

1. Msc 1, Research Methodology Presentation, T. Klein
2. Msc 1, Research Methodology Presentation, F. Veer
3. Msc 1, Research Methodology Presentation, M. Tenpierik
4. Msc 2, Technoledge Structural Design Presentation, C. Louter

Acknowledgments

I would like to thank my mentors Tillmann Klein, Martin Tenpierik and Ate Snijder for inspiring me, motivating me and sharing their knowledge. Besides them, I received valuable help from Anne Struiksma, who as a former graduate on the topic of microperforated glass, she provided me lot of useful information to start working with.

I would like also to express my gratitude, to all the experts who participated as interviewees to the survey. Great part of this research is based on their input and knowledge.

Thank you to my friends in Holland; Antigoni, Kallia, Themos and Charles for sharing our everyday life during the last 2,5 years and always supporting each other.

Last but not least, thank you to my family who although being far, they managed to emotionally support me the most, by spending hours of discussions in front of the camera. Special thanks to my father, for everything.