Reflection

This chapter reflects on the overall trajectory of the thesis project, from its initial conception to the final outcomes. It assesses the graduation process, addresses ethical considerations, and explores the potential societal impact of the work. The aim is to highlight the strengths and limitations of the chosen approach, examine how challenges were navigated throughout the development, and evaluate the project's broader significance within both architectural and scientific contexts.

Graduation process

The chapter is divided into three parts: the first reflects on the graduation journey and the relationship between the project and the broader context of the Building Technology track; the second examines the research strategy, tools, and methods employed; and the third evaluates the outcomes in relation to the initial goals and research question, with a focus on the interplay between research and design. Together, these reflections offer insights into the effectiveness of the project and the methodology applied.

Relationship between the thesis topic and the Building Technology track

This thesis is situated within the Building Technology Graduation Studio at TU Delft, where it contributes to the broader discussion on sustainable materials and circular design strategies in architecture. The focus on transforming waste glass into functional acoustic panels aligns with the track's emphasis on environmental responsibility and material innovation.

The Building Technology master track at TU Delft integrates architectural and engineering disciplines, with a strong emphasis on sustainability and innovative design thinking. Within this context, glass stands out as a material of both everyday presence and architectural significance.

Glass has long been recognized for its unique properties - its ability to visually connect interior and exterior spaces through transparency, its structural strength, and its excellent performance in compression when cast, all of which have been extensively researched within the AE+T department at TU Delft. I am glad to contribute to this body of work by adding acoustic performance to the list. This material's versatility, combined with its potential for infinite recyclability without degradation, makes it a strong candidate for advancing a circular built environment. Aligned with ongoing research into innovative glass recycling strategies, this graduation project demonstrates that glass can serve as both a smart and sustainable material in the future of architecture.

Research approach and outcomes

The research approach combined material experimentation, acoustic measurements, computational simulation and design-optimization techniques. This interdisciplinary strategy turned out to be a major strength.

- **Strengths:** This approach enabled a holistic investigation of the problem. The iterative experimental process allowed for continuous material refinement based on real measurements and extensive hands-on experience, truly a case of learning by doing. It was especially rewarding to implement the panels I had personally manufactured (even if only in a virtual model), using absorption coefficients I had measured myself, and to see the acoustic performance improve. Furthermore, by focusing on the reuse of glass waste, this project addresses a key technical challenge in glass recycling: contamination. It demonstrates that even low-quality, severely contaminated cullet can be effectively repurposed for sound-absorbing applications, turning a problematic waste stream into a valuable resource.

- **Weaknesses:** Time constraints limited the scope of real-world validation, such as testing in a reverberation chamber, which could account for oblique sound incidence, unlike the impedance tube that measures only normal incidence. Although the lab process was time-consuming, I managed to produce more samples than initially expected and gained valuable insight into how manufacturing parameters influence both material structure and acoustic performance. However, further testing is needed, particularly for fused samples. So far, only those fused simultaneously with the foaming process have been measured. While this project shows that technical barriers in glass recycling, especially contamination, can potentially be overcome, it does not address supply chain challenges, such as the separation and collection of different types of glass waste.

- **Opportunities:** There is significant potential to expand this research by investigating the structural and thermal performance of the material and by developing panel designs suitable for industry application. Further opportunities lie in the integration of machine learning within the design and simulation workflow. Strengthening the connection between parametric modeling environments such as Rhino/Grasshopper and acoustic simulation tools like CATT-Acoustic could greatly enhance both this project and future studies, given the widespread use of these platforms in architectural and acoustic design contexts.

- **Threats:** Even though understanding was gained on how different manufacturing parameter affect the sample, controlling foam properties proved to be complex, with occasional unexpected results that couldn't always be expected or explained. The variability of recycled glass waste and the unpredictability of the foaming process pose challenges for standardizing production. Whenever unusual results occurred, experiments were repeated to verify outcomes. For instance, the first SL5CCT2 sample turned out denser and less foamed than expected, despite using the same material and conditions that had worked in smaller moulds. A second attempt produced much better foaming and ultimately the best sound absorption result. This experience highlights the inherent randomness in foaming, despite careful control, results were not always repeatable. Factors such as uneven foaming agent distribution, possibly local temperature fluctuations, or unpredictable chemical reactions during firing likely contributed to these inconsistencies. While the panels show potential for indoor use, their porous structure makes them prone to dust accumulation and difficult to clean – an important consideration before launching them as a product. This also raises the question of whether such panels could be adapted for outdoor use. Additionally, even the rigid, solid samples showed some surface crumbling, which would need to be addressed to ensure durability and long-term performance in a commercial application.

Research-design relationship

In this project, research directly informed design. The relationship between research and design was iterative and mutually reinforcing. Rather than treating research and design as separate phases, they informed and evolved next to each other throughout the project.

Material testing provided performance data that guided design decisions for the panel system. In turn, the architectural case study allowed the simulated testing of these materials in a realistic context. This interplay between material research and spatial design exemplifies the iterative relationship between experimentation and application.

The design of the glass panels was driven by insights gained from material research. Early-stage literature review and experiments on foaming provided a scientific foundation for understanding how different glass types and fabrication parameters influenced the physical and acoustic properties of the material. These findings informed critical design decisions - such as the two-layer composition of the panel (porous foamed layer for absorption and solid cast layer for structure), the choice of tack fusing to bond layers without adhesives, and the focus on open porosity to optimize sound absorption.

At the same time, the design goals - creating an acoustic panel suitable for a dual-use performance hall - set clear functional requirements for the material: sound absorption in specific frequency ranges and structural integrity. These goals guided the research process by narrowing down which acoustic properties to measure, what fabrication parameters to test, and how to define success.

Moreover, the use of computational acoustic simulations created a bridge between material-level findings and spatial performance. Laboratory measurements of the prototype were translated into absorption coefficients, which were then implemented in digital models of the Theatre Hall at TU Delft. This allowed the panel's real-world effectiveness to be evaluated in context, and further informed adjustments to design and panels' placement in the case study volume.

Ultimately, the project demonstrates that research is not just a foundation for design - it is an active part of the design process itself.

Ethical and moral considerations

One ethical consideration I had throughout this project was the feeling that, at times, my results might not be enough to draw broad conclusions, because truly proving a pattern would likely require hundreds of experiments like the ones I conducted. Still, I'm confident that the work I've done contributes to the core problem I defined to address. That's why I chose to present my findings honestly and confidently, always making sure to explain exactly what was done, even if some outcomes didn't fully support the expected or "positive" result. A key part of that was not overstating the environmental benefits of the panels. While the project promotes the reuse of waste glass, I did not conduct a Life Cycle Assessment which would be essential to formally support sustainability claims. Instead, I based these claims on literature and clearly positioned an LCA as a necessary step in future research. I also deliberately avoided using binders or chemical additives that could hinder recyclability, in line with circularity principles.

Another concern relates to the impedance tube measurements. Some of the samples were slightly too small for the tube, which needs a tight fit to ensure accurate readings. To address this, I sealed the gaps with tape or a rubber strap, which may have introduced minor inaccuracies. That said, the resulting SAC curves didn't show any unusual artifacts, so I remain optimistic (but cautious) about their reliability. Still, I would repeat those specific tests if the time allowed, manufacturing new samples, cutting them precisely to size, and re-measuring, to ensure the validity of the data.

Lastly, over the course of the project, I intentionally narrowed down the number of variables I tested. Early on, I made decisions about which samples and parameter combinations to continue with, focusing on those that showed promising results and would eventually need to be tested for sound absorption. As the study progressed, I concentrated on materials and settings that performed better. This is why, for example, low iron soda lime glass appears in far more experiments than automotive or aluminosilicate glass. Similarly, calcium carbonate proved effective with most glass types and was eventually replaced with eggshell as a more sustainable alternative.

That said, the samples or combinations I set aside at the early phase of the project may still have potential, perhaps under different firing conditions or with alternative foaming agents. It wasn't easy to let go of these possibilities, but it allowed me to develop a deeper understanding of what was working and why.

Societal Impact

Practical Applicability

While still in the prototype stage, the panels developed in this research show strong practical potential. The methods explored: foaming and fusing (potentially also casting) are scalable and adaptable to architectural production. Their simulated application in the Theatre Hall demonstrated their ability to enhance acoustic performance in real-world scenarios. I believe that acoustic glass panels like these could eventually become a viable product, and not only for boutique spaces such as concert halls, where both aesthetics and acoustic quality are critical. Similar concepts have already been applied in outdoor settings for traffic noise control, suggesting broader applicability.

However, there are still challenges to overcome before these panels could be considered commercially viable. One of my major concerns is dust accumulation. The porous structure, while essential for acoustic absorption, easily traps dust, particularly problematic if panels are mounted overhead with the porous side facing upward. Cleaning would be difficult, and this issue needs to be addressed in future development. Additionally, although the panels may be water-resistant, some samples absorb significant moisture, especially after being cut in wet conditions. From experience, I found that drying takes quite a long time, and wiping the surface is not enough.

Another issue is material degradation. Even the rigid, solid samples tend to release fine dust and decompose slowly, which would be unacceptable in a commercial product. Improving crystallization, (possibly through the use of $CaHPO_4$), could enhance durability and reduce dust formation.

From a manufacturing standpoint, I see strong potential for optimization. Combining fusing and foaming in a single kiln run is particularly promising, as it saves both energy and time. This method works well when the solid glass layer (for example float glass) remains flat or needs to be curved: it can be placed at the bottom of the mould, with the foaming mixture added on top. After firing, only the top surface needs to be trimmed to expose the porous layer.

However, more complex designs, such as shaped or diffusive back layers, may introduce complications. In those cases, a deeper mould would be required to fit both layers, with the casting cullet placed below and the foaming mixture above. A challenge here is that the foaming temperature may not be sufficient to cast the bottom layer. One possible solution is a two-stage firing: first heating to a higher temperature to cast the base, then lowering the temperature, opening the kiln to add the foaming mixture, and reheating for the foaming process. While more complex and potentially riskier, this method could allow for more customized designs.

That said, if both fusing and foaming can be successfully combined in a single, well-controlled firing, this remains the most energy- and time-efficient approach.

I am also aware that the proposed panel application is somewhat specialized, focused more on comfort than safety (however I do believe that these should be equally important in a built environment) and intended for very special, acoustically sensitive environment like performance space. Still, I believe that proving the panels' effectiveness in such a demanding context shows even greater potential for their use in more common acoustically problematic spaces, such as sports halls, swimming pools, train stations, or museums, where issues like excessive reverberation are often present.

Innovation achieved

The project successfully innovated by combining two contrasting forms of glass (rigid and porous) into a single, recyclable panel system. The use of waste streams not traditionally recycled, and the development of acoustic panels from them, presents a novel contribution to both material science and architectural acoustics. This research aligns with sustainable goals also, addressing the need to reduce construction waste, reuse materials, and minimize dependence on synthetic, non-recyclable acoustic materials.

Socio-cultural and ethical impact

By proposing a sustainable material made from locally sourced glass waste, this project helps shift how we think about materials, challenging the idea that waste has no value. It also raises awareness (hopefully both among the manufacturers and architecture enthusiasts) about the challenges of glass recycling and promotes a more circular approach to design. The methodology employed in the project is clearly explained, so that the research can be built upon in the future in a responsible way. The work connects with growing concerns about waste, climate change, and sustainable construction, and offers a practical, creative solution for reusing difficult waste materials. This supports wider goals in Europe to move toward more circular and sustainable building practices.

Impact on architecture and the built environment

This thesis proposes a new material strategy that integrates acoustic performance, sustainability, and aesthetic flexibility. Its potential impact on architectural practice lies in encouraging designers and manufacturers to think outside-the-box, move beyond conventional materials and to embed environmental responsibility from the early stages of material and system design. At the same time, it allows for a high degree of customization and aesthetic experimentation – aspects that are equally important in architecture.