Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

Graduation Plan: All tracks

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

Personal information	
Name	Ludwika Buczyńska
Student number	6068804

Studio		
Name / Theme	Building Technology Graduation Studio	
Main mentor	Faidra Oikonomopoulou	Structures & Materials
Second mentor	Martin Tenpierik	Environmental & Climate Design
Third mentor	Gabriele Mirra	Digital Technologies
Argumentation of choice of the studio	n/a	

Graduation project	
Title of the graduation project	The sound of recycling. Transfoaming glass waste into acoustic panels.
Goal	
Location:	Delft, The Netherlands
The posed problem,	According to the European Commission, construction and demolition waste is one of the largest waste streams in the European Union, accounting for approximately 30% of total waste (Vermeulen, 2016). Among other materials, glass has a significant potential for recycling due to its unique properties, such as complete recyclability and resistance to quality loss through remelting (Bristogianni et al., 2018); DeBrincat & Babic, n.d.). Despite this, only container glass is recycled in a closed loop in Europe, while other types, including architectural, automotive, household and electronic glass waste are mostly downcycled (usually added as glass powder to other construction materials) or landfilled (Bristogianni et al., 2018; Bristogianni & Oikonomopoulou, 2023). This presents a critical environmental challenge. One of the primary barriers to recycling glass other than container is contamination, which makes remelting difficult or unsafe. Adhesives, coatings, and lamination are often impossible or uneconomical to remove. For cullet to be remelted into float glass, its origin must be known, and the

purity standards are strict. Contaminated glass cannot be recycled into container glass either, as it could affect the taste of products. Additionally, large amounts of uncontaminated glass end up in landfills due to recipe mismatch - differences in melting temperatures between types of glass further complicate recycling process (Bristogianni et al., 2018). Therefore, alternative methods for recycling glass waste, particularly those tolerant of higher levels of contamination, are urgently needed (Bristogianni & Oikonomopoulou, 2023).

Recycling glass offers numerous benefits, including reducing landfill waste and preserving raw materials such as sand and sodium carbonate (Hestin et al., 2016.; Surgenor et al., 2018). This research explores the potential of glass waste as a raw material to produce acoustic panels, offering a solution that meets both environmental and functional demands in architecture.

Sound absorption technologies, though widely used, are often limited by traditional production methods that fail to meet customization needs or rely on synthetic materials with high environmental impact, like rockwool, glass wool or polyester (Buratti et al., 2016; Setaki et al., 2023). Research has shown that foam glass, made from recycled materials, holds promise for acoustic applications due to its porous structure (Cai et al., 2023; Cho et al., 2005; Yan et al., 2019). What is more, research by (Hesky et al., 2015) indicates that waste glass can replace up to 70% of the raw materials required for foam glass production. Foaming techniques have shown great potential for incorporating glass waste into the production of porous glass, as proven by the work of (Da Silva et al., 2021) and (Giassia, 2022). These findings, discussed in more detail later in this paper, emphasize the potential of foam glass as a sustainable material with promising acoustic properties.

Research conducted at TU Delft has shown that contaminated glass waste can be successfully recycled through casting. This solution addresses challenges like contamination or recipe mismatch that are often the main reasons for downcycling or landfilling of glass (Oikonomopoulou, 2019). Casting not only enables mixing of different glass recipes in the same furnace but also allows for creating objects with higher tolerance for imperfections in their meso-structure, compared to thin glass standards (Bristogianni et al., 2021). Furthermore, the use of moulds in casting provides freedom in shaping the final product, allowing for the creation of customized geometries

	that might be difficult to achieve with conventional materials used for acoustic solutions (Ioannidis et al., 2024). Despite these advances, research combining glass with acoustics remains relatively tight. Similarly, studies integrating material engineering with computational acoustics – another important aspect of this project - are also limited. This study aims to address these gaps by exploring the acoustic potential of fully recycled glass panels produced through foaming and casting techniques. By integrating glass material engineering with computational methods for acoustic design, this research aims to develop sustainable acoustic material, promoting manufacturing methods for recycling glass in a closed loop.
research questions and	**Main research question** ***What are the potential and limitations of developing a porous material from glass waste to produce acoustic panels for architectural space?*** **Sub questions** *Material engineering* • What types of glass waste are suitable for acoustic panel production? • Which glass waste streams are better suited for casting, and which for foaming? • (How) do different fabrication parameters impact the porosity of the material and (how) can its porosity be controlled? • What are the optimal physical parameters in the process of fabricating a recycled glass panel? *Acoustics* • (How) do impurities in glass waste affect the material's acoustic performance? • What are the effects of porosity on the panel's sound absorption? • What are the effects of panel's geometry design on its acoustic properties? **Background questions** *Concerning case study* • What is the current acoustic performance in the Theater Hall? • What functions does this space (want to) host?

	• What are the ideal acoustic parameters for the Theater Hall and its users (both the audience and performers)? *Concerning research* • How is the acoustic performance of a material assessed? • What are the environmental benefits of upcycling glass waste into acoustic panels? • What metrics of acoustic performance of the room are important for classical music? • What new applications could the new material offer?
design assignment in which these result.	This research aims to explore the potential for upcycling glass waste into high-value acoustic panels employing casting and foaming methods. The proposed panels will have a two-layer structure: a porous layer of foamed glass for sound absorption and a rigid layer of cast glass for rigidity, fused together into a single unit. The panel's acoustic performance will be evaluated using impedance tube, and computational acoustic simulations will be employed to assess its effectiveness in a case study. The project investigates the influence of design parameters (such as porosity, geometry) and physical parameters (such as firing temperature, material composition, particle size) on sound absorption of the material. Finally, the study seeks to establish a framework for future applications of recycled glass panels in architectural acoustics, showcasing their potential as a sustainable and functional design solution.

Process

Method description

This section of the paper describes the approach adopted to finalize the project and answer the research question. The research is divided into four main parts, each corresponding to a different stage in the project. Each phase targets a specific goal and builds on the outcomes of the previous phase. Therefore, future phases may be subject to adjustments, as it is challenging to fully predict the results of the experimental aspects of the project at this stage.

Phase 1: Context definition

This serves as an introduction and the foundation for the project, providing an overview and establishing the context for the research. It outlines the key issues related to glass waste and materials used in acoustics and highlights the research opportunity in combining these fields at the intersection of material engineering, computational acoustics and design optimization. The main research question is presented, and the sub-questions are formed, helping guide the research.

Phase 2: Literature review

This part supports the methodology with insights from prior research and experiments and establishes the theoretical framework for the study. The section provides a foundation for understanding glass recycling processes to be tested in the project, explores key acoustic aspects critical to the research, and explains computational methods for acoustic design that are crucial to complete the thesis.

The section is divided into subsections, each focused on a different aspect of the research.

- The first explores glass, including its waste streams, production methods, and relevant techniques such as kiln casting, foaming, and fusing, drawing from previous experimental studies. It also presents research on the acoustic properties of porous glass and highlights relevant findings.
- The second part of the literature review addresses architectural acoustics. It begins with an overview of sound propagation, followed by an explanation of the importance of achieving optimal acoustics in various environments. Solutions for enhanced acoustic performance are then discussed, with a focus on architectural or geometry design as well as material level. They are supported with examples of existing spaces known for their excellent acoustics.
- The third subsection of the literature review focuses on computational methods for acoustic design. It highlights the significance and limitations of computer simulations in acoustics, describes various types of acoustic simulations, and examines optimization methods used to refine acoustic performance.

Phase 3: Material development and testing (experimental research)

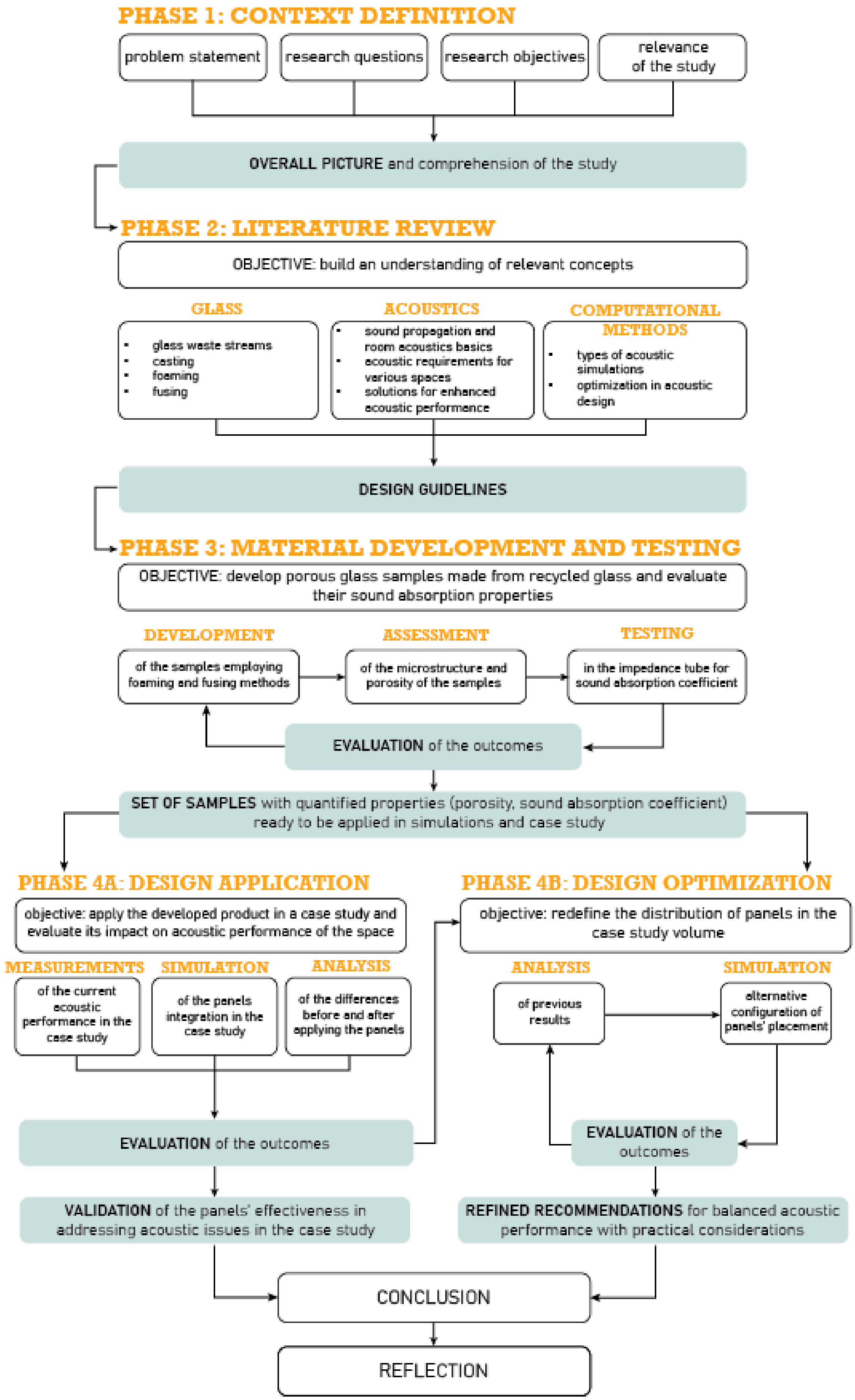
This phase builds upon the key takeaways and knowledge gained from the literature review. The material development process focuses on two primary techniques: foaming and fusing. The resulting panel has a dual-layer structure: a porous layer, created through foaming, for sound absorption, and a solid glass layer for structural rigidity. Once both layers are prepared, they are fused together into a single unit. The panels are then cut into smaller samples using a waterjet cutter at the Glass Lab, Faculty of Architecture, TU Delft to fit into the impedance tube, where their sound absorption coefficient is measured. The experimental process described is iterative, with adjustments made to different manufacturing parameters based on the results of each test. Guided by the literature review, special attention is given to factors such as the glass recipe (type and additives), particle size, and foaming and fusing temperatures. Data on the samples' density, porosity, and sound absorption is systematically collected and analyzed to guide the next stages of the research.

Phase 4a: Design application in the case study

It this phase, the acoustic potential of the glass panels is demonstrated through their virtual application in the case study, Theatre Hall at TU Delft X. Simulations in relevant software are used to predict the acoustic performance of the room after implementing the panels. The results are compared with the room's acoustic performance before applying the panels. The aim of this phase is to validate the panels' effectiveness in addressing acoustic issues in the case study which is crucial for drawing the final conclusion. To be able to perform this part, acoustic measurements have been taken in the space to gather the data needed about its current acoustic performance. The methodology and results of these measurements are described in the next chapter.

Phase 4b: Design optimization

In this phase the distribution of the panels is optimized by simulating alternative configurations for their placement. Genetic optimization algorithms are used to find the best design solution that fulfills the predefined set of objectives. The goal of this phase is to provide design recommendations for using the panels, and a workflow that can be re-purposed for other performance spaces with minimal adaptation.


PHASE 1: CONTEXT DEFINITION
problem statement
research questions
research objectives
relevance of the study
OVERALL PICTURE and comprehension of the study
PHASE 2: LITERATURE REVIEW
OBJECTIVE: build an understanding of relevant concepts
GLASS
glass waste streams
casting
foaming
fusing
ACOUSTICS
sound propagation and room acoustics basics
acoustic requirements for various spaces
solutions for enhanced acoustic performance
COMPUTATIONAL METHODS
types of acoustic simulations
optimization in acoustic design
DESIGN GUIDELINES
PHASE 3: MATERIAL DEVELOPMENT AND TESTING
OBJECTIVE: develop porous glass samples made from recycled glass and evaluate their sound absorption properties
DEVELOPMENT
of the samples employing foaming and fusing methods
ASSESSMENT
of the microstructure and porosity of the samples
TESTING
in the impedance tube for sound absorption coefficient
EVALUATION of the outcomes
SET OF SAMPLES with quantified properties (porosity, sound absorption coefficient) ready to be applied in simulations and case study
PHASE 4A: DESIGN APPLICATION
objective: apply the developed product in a case study and evaluate its impact on acoustic performance of the space
MEASUREMENTS
of the current acoustic performance in the case study
SIMULATION
of the panels integration in the case study
ANALYSIS
of the differences before and after applying the panels
EVALUATION of the outcomes
VALIDATION of the panels' effectiveness in addressing acoustic issues in the case study
PHASE 4B: DESIGN OPTIMIZATION
objective: redefine the distribution of panels in the case study volume
ANALYSIS
of previous results
SIMULATION
alternative configuration of panels' placement
EVALUATION of the outcomes
REFINED RECOMMENDATIONS for balanced acoustic performance with practical considerations
CONCLUSION
REFLECTION

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Reflection

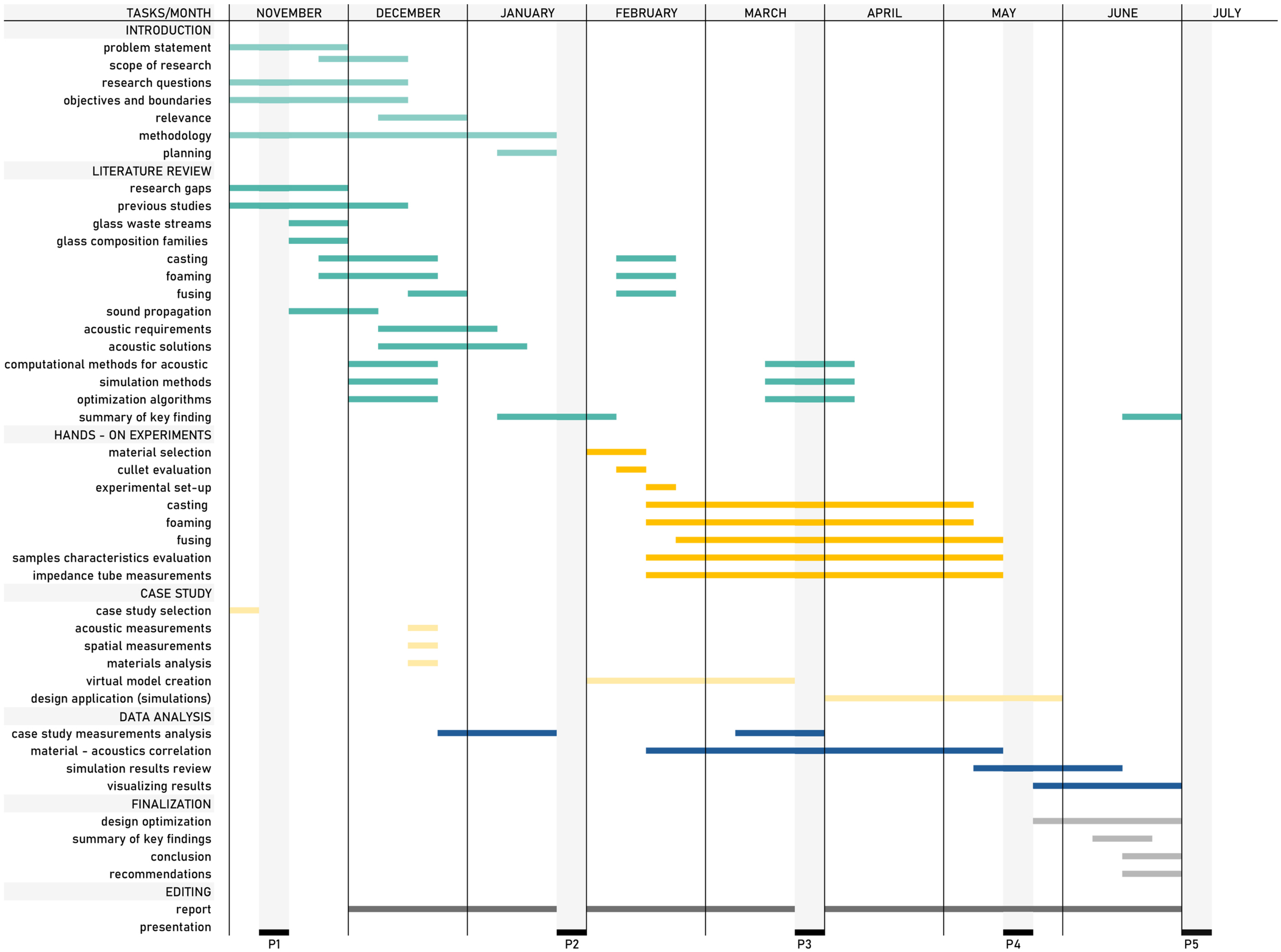
The thesis, combining engineering with design, closely aligns with the objectives of the Building Technology Track that is centred around technological design and innovations valuable for construction industry and the built environment. It builds on the research being carried out at the Architecture Engineering and Technology department within the Architecture Faculty, particularly in the area of glass recycling through casting and novel acoustics applications.

Environmental relevance

This research contributes to environmental sustainability by addressing the issue of glass waste that is due to multiple reasons is not recycled back to glass. By upcycling this waste into fully recycled high-value architectural products, the study promotes circular economy principles, reducing landfill waste and resources extraction, and supports energy-efficient building design and global goals for reducing carbon footprint.

Scientific relevance

This thesis contributes to scientific knowledge by addressing a research gap at the intersection of glass engineering and acoustics, an area with considerable but underexplored potential. Additionally, it integrates materials science with computational acoustic methods, both of which are important parts of this study's scope.



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