Final P5 Reflection

Modular Float Glass Systems Designed for Reuse

Minoo Motedayen

Student number: 6020631

This graduation project is positioned primarily within the **structural domain** of the **Building Technology track**, with a strong focus on the performance and detailing of **structural glass** and **demountable connections**. The research dives into material behaviour, load transfer, and component interaction, placing it firmly within the engineering side of the track. At the same time, the project touches on **product design**, particularly in the development of a connector system with precise geometry, assembly logic, and fabrication constraints. **Computational tools** such as Rhino, Grasshopper, ANSYS, and Karamba were integrated throughout the process to support both the design development and the structural validation of the system.

The **research-through-design** approach was used to explore and develop the concept. Starting with a research question and a clear problem statement, I investigated structural glass, its mechanical limitations, and the possibilities for dry, reusable connections. This led to the design of modular systems and connector variations inspired by woodworking and cabinet joints. Rather than being a linear process, the design and research evolved in loops: **module shape influenced connection**, and **connection limitations** led to adjustments in the modules and reciprocal system shaped by modules.

To validate the concept, I built prototypes and performed full-scale tests, starting with Plexi glass and wooden (Meranti) mock-ups and later testing with the final material: laminated, heat-strengthened glass and hard wood(oak) connectors. These tests revealed useful insights—such as bolt bending, wood cracking, and misalignment—which led to changes in bolt type, connector shape, and preload strategy. Structural analysis ran in parallel using **Karamba** (for system-level behaviour) and **ANSYS** (for detailed simulation of connections and modules). The final physical tests (two times) confirmed that the system could safely carry the design load and helped determine its **ultimate load capacity**. Notably, ANSYS results aligned well with physical testing, confirming the simulation's reliability for further development.

While the **studio methodology** follows a structured, step-by-step approach, my process followed the same logic in a **loop-based way**. Instead of moving strictly from theory to validation, I moved back and forth between testing, prototyping, and redesign. This allowed the research and design to continuously inform one another while remaining within the framework of the studio's methodological goals.

Research and design were tightly linked throughout the project. Insights from material studies and joinery systems guided early design decisions, while physical tests and simulations repeatedly raised new design questions. In this way, the development of the system was not based on abstract research alone but grounded in direct material feedback and assembly behaviour.

One ethical consideration in this project was the conscious selection of **locally available hardwood** and **glass panels sourced from within Europe** to reduce the **embodied carbon associated with long-distance transportation**. Among various candidate materials for the connector, **wood was chosen** not only for its dimensional performance but also for being a **natural, renewable, and sustainable** option. Although stronger but high embodied carbon alternatives could have been used for higher loading conditions, the decision to work with hardwood was made to prioritize **environmental responsibility** and align the project with **low-impact, sustainable design principles**.

Additionally, considering a broader context, making the connector system **affordable** and widely **available** could **increase its acceptance within the industry**. Since glass panels are inherently luxurious and **costly** components, both contractors and clients **would prefer failure to occur predictably in less expensive, easily replaceable parts**. This **makes wooden connectors particularly advantageous**. Wood's lower stiffness relative to glass **allows minor misalignments or inaccuracies** during assembly to be accommodated **without** causing **critical stress concentrations or breakages** in the glass itself. This also significantly **reduces the need for costly precision** and permits simple **on-site adjustments** by workers. Consequently, this approach enhances safety, reduces overall project costs, and maintains the structural integrity of the critical glass components.

Societal Impact and Broader Relevance

This project was developed with the aim of making **glass use more sustainable** by addressing a major limitation in current construction: the lack of reusable glass connections. While glass is technically recyclable, its **practical reuse is limited** due to permanent fixing or bounding methods. The design proposed here reimagines glass as a **modular element**, capable of being **assembled, disassembled, and reshaped**—similar to LEGO pieces. This design-for-reuse logic has the potential to **extend the lifespan of glass**, **reduce energy consumption** associated with recycling, and **minimize construction waste**.

The **intermediate material**, oak, was selected for its **dimensional stability**, **local availability**, and relatively low environmental impact. As a result, the system demonstrates how **three different materials—glass, wood, and steel bolts—can work together** in a structurally and environmentally responsible way.

The broader societal impact of the project lies in its potential to **influence the culture of building with glass**. If adopted, modular glass systems could **reduce material waste**, extend the lifelong span of glass components for more than only one time use, and support **circular**

construction strategies. The project also introduces a **new architectural language** that embraces reversibility and assembly as design features—not just technical constraints.

Not only does the project aim to extend the lifespan of glass components, but it also thoughtfully considers **end-of-life scenarios for repurposing glass units**, further prolonging their usability before recycling becomes necessary. Beyond their original modular design purpose, these glass modules are **structural elements in their nature** and could serve structural roles such as fins and beams in facade systems or even find new life in permanent small-scale structures like greenhouses or furniture, such as bookshelves. Thus, this approach significantly broadens the **sustainability potential of the materials used, reduces embodied carbon emissions, and ensures the project's environmental impact remains positive across multiple life cycles**.

Limitations and Future Work

Overall, this project has **successfully demonstrated a viable solution to the initial research problem**, achieving strong results in line with the established design goals and assessment criteria. Therefore, I believe the project has effectively **accomplished its intended objectives**, while simultaneously **opening new avenues for future exploration and development**.

The practicality and simplicity of the modular system and its connections, combined with the realistic approach in their assessment and testing, enhance **the likelihood of industry adoption and practical implementation**.

While the system proved successful in the tested configurations, several limitations need to be acknowledged. The scope of the project is inherently broad; modular systems allow for countless geometric variations, and it is **unrealistic to guarantee the performance of every potential configuration**. In this study, four specific variations were structurally analysed and found to perform safely. Consequently, future users must individually verify the structural performance of their specific configurations, which is a **common consideration** rather than a limitation inherent to modular systems.

Due **to testing constraints and available facilities** at TU Delft, only the smallest module size and one of three connection categories could be tested. Full-scale testing for longer spans or other module types exceeded the scope of this master's thesis. However**, structural simulations** conducted with ANSYS covered all proposed connection types and span variations, effectively **compensating for the limitations** in physical testing and **reinforcing the overall validity** of the project's findings.

Furthermore, **lateral loads** were addressed in only one iteration at an average of 0.5 kN/m^2. Although the system **successfully resisted** these loads, considerations for outdoor use, such as moisture resistance and thermal performance, remain important for future development. These factors should be addressed through additional number of connectors, modified bolt types, and slight geometric refinements.

Initially designed as a **pure shear connection**, testing revealed that the system behaves more like a **moment-resisting joint**, significantly impacting structural behaviour and detailing logic. Typically, moment connections are known for their complexity and higher implementation costs compared to shear connections. However, in this case, the developed joint remains **relatively straightforward** in terms of **assembly and analysis** but **limited to bolt moment resistance** after exceeding the clamp and friction force which could be **less favourable**.

The **hardwood connectors** performed **adequately** under moderate loading conditions; however**, alternative materials** may need consideration for applications involving **larger spans or heavier loads**. Several suitable alternatives were proposed within the report. Nevertheless, within the designed loading conditions, hardwood (specifically oak) remains the **optimal choice** due to its **predictable failure behaviour and cost-effectiveness** (wood crushes and glass is safe). Furthermore, the overall cost for materials and CNC milling with the required precision in wood is **significantly lower—approximately 50 times** less expensive—compared to aluminium. for each set of 4 connectors and one cylindrical component wood stands about 5 to 6 euros and aluminium is 350euros.

Bolt access and **preload control** posed practical challenges. More **specialized tools** could address these issues by enabling **easier tightening** without inducing **extra stress** in wooden components or glass, also, **enable higher accuracy** in applying deigned torque. Although such equipment was beyond the student's budget, practical recommendations have been provided in report.

Manufacturing challenges included maintaining tight tolerances and **friction-based performance**, which could be disrupted by changes in moisture, temperature, or glass alignment. This study emphasized that **wooden components** should be **stored in controlled conditions** (e.g., vacuum-sealed with silica packs) and standardized tolerances established through testing. However, the precision required for wooden connections remains lower than alternatives such as aluminium, making the design practical and cost-effective.

Despite these limitations, the system exhibited robust behaviour. Even after partial failures, such as connector cracking, the **overall structure remained stable**, **functional**, and **replaceable** This robustness indicates a reassuring level of redundancy and safety within a delicate material system. This condition was also tested in Karmba, **assuming failure in one glass panel**, but the structure was able **to keep stability until replacement** could occur.

Outlook and Next Steps

Moving forward, this project offers several promising avenues for further research and practical application, suitable for additional master's theses or PhD research within TU Delft or internationally. Proposed next steps include:

- Conducting **further testing** on the existing design:

   - Exploring additional **connection types and varying module sizes**, potentially in collaboration with other faculties, such as civil engineering, to extend beyond current testing limitations.
   - Evaluating **alternative materials** like aluminium for enhanced structural capacity. Preliminary investigations, including material preparation and CNC milling consultations was done by this author but it was not financially affordable to be done within this project (350 Euros)
- Investigating a **wider variety of module shapes** to broaden design possibilities. For instance, developing curved modules suitable for arch formations or modules designed specifically as connectors could significantly expand the system's versatility.

- **Refining the design** to accommodate **longer spans, increased loading conditions**, or more **challenging outdoor environments** by:
   - Introducing **additional connection points** (holes and connectors number) to improve the system's structural capacity.
   - **Enlarging holes in glass modules**, while carefully maintaining aesthetic standards, to help reduce local stress concentrations by increasing contact surface area.
   - **Adopting stiffer connector materials** such as aluminium or titanium, which better match the mechanical properties of glass and can support heavier loads than wood.
   - Implementing **Minor refinements in wooden connectors** to boost joint performance, such as:
      - Adding an extra wooden **capping layer** secured by screws to **reduce bolt slippage.**
      - Utilizing **larger bolts** to enhance **preloading capability**, significantly increasing the joint's resistance (**Higher Cr and Ct of joint**).
      - Increasing the number of **support points** and fully utilizing available fin-to-beam joint positions to improve overall stability.
      - Replacing **wooden strips** used as intermediate **spacers** between glass panels with materials exhibiting **higher friction coefficient**, thereby enhancing the connection's load-bearing capacity.
- **Adapting and developing** the design for **applications and use cases** beyond modular structural glass systems, such as facade systems or furniture, to demonstrate the practical flexibility and potential broader appeal of the modular concept.

- Utilizing this project as a **foundational case study** to stimulate **further exploration** of modular systems or alternative connection types, such as pure shear joints. The novel nature of this research positions it as a potential cornerstone for future innovations in structural glass.
- Advancing **parametric modelling** using Grasshopper scripts integrated with Karamba for automated assessment of structural performance. By defining module lengths, connection types, and span limitations, the proposed system could automatically generate viable modular arrangements. This step has been taken partially by this author and proper reference paper in exact this scope has been provided supporting the feasibility of this ambitious goal.

Conclusion

This project successfully demonstrated the **feasibility of a modular, dry-assembled glass-timber system** designed for reuse. While simplifications were made—especially regarding testing scale and environmental conditions—the system was developed, tested, and validated to the extent possible within the timeframe. The concept opens new possibilities for **adaptable, structurally expressive glass architecture**, and lays the foundation for continued development toward practical application in circular building systems.