Designing with Scarcity

Algorithmic Workflows for Structural Optimization
Using Reclaimed Timber

Thanks to

We want to dedicate this page to the people who have helped us make this thesis.
Thanks to:
Woodstock Robotics for their inspiration and for welcoming us into their workshop.
Our supervisors Mads Brath Jensen and
Thomas Vang Lindberg for continuous support.

Info

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Using Reclaimed Timber

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Motivation

The construction industry stands at a critical crossroads. With the built environment contributing nearly 40% of global carbon emissions, the urgency to rethink how we design and build has never been greater. Timber, long celebrated for its carbon-storing potential and renewability, has emerged as a leading candidate for low-carbon construction.

Yet, as with every resource it can't keep up with the growing demand of the twenty first-century.
This thesis emerges from that tension. It recognizes that simply replacing steel and concrete with virgin timber will not be enough. Instead, it argues for a deeper transformation in legislative and architectural thinking, one that views the world through material scarcity, not as a constraint to be overcome, but as a driver of design innovation, for a new paradigm to emerge, one where form can follow the availability of reclaimed timber.

Use of AI

Large Language Models (LLMs), such as ChatGPT, were used to assist with proofreading throughout the thesis. The AI helped identify and correct grammatical errors, improve sentence clarity, and ensure overall consistency in tone and structure. All edits were reviewed manually to maintain authorial intent and academic integrity.

During the development of the algorithm, the large language models (LLMs) ChatGPT and Clause 3.7 Sonnet were used to help generate the code.

The LLMs were used to improve the algorithms, help identify errors, provide explanations and optimize the computational time. Due to the algorithms being applied in the Rhino Grasshopper environment, the LLMs could not test the scripts within its domain, therefore testing and debugging the received code from the LLMs was important, as to check for any errors.

This thesis follows the guidelines established at Aalborg University, regarding the use of generative AI in the development and publishing of source code (AAU, 2025). These guidelines mention the use of licensed open source code, which the LLMs may use, therefore double checking the code and imported libraries were the main concern. All libraries used in the code of the algorithms were related to the RhinoCommon, Grasshopper and Karamba3D APIs.

Glossary

Reuse - Using something for the prior purpose again.

Reclaimed - A used product recovered to a usable state.

Algorithmic Workflows - A structured sequence of computational steps used to automate design and optimization processes.

Discrete – Meaning individually separate and distinct, is used in the thesis in context of timber structures, where engineered timber such as GLT and CLT are assembled of multiple pieces of timber, a discrete timber structure is of timber elements that are not processed.

Structural Optimization – The process of refining the design of a structure to achieve maximum performance with minimal material use by modifying the geometry.

Volumetric optimization – The process of optimizing the use of reclaimed materials for roles that result in the least amount of waste across length, width and height.

Material Utilization - Determines how well a structure uses material, either in terms of length cut-off, weight and the volumetric optimization.

Structural Utilization - Describes the used structural capacity of a structure.

Abstract

This thesis addresses the pressing need to consider timber as a scarce resource and mitigate its overconsumption in the built environment and by exploring algorithmic workflows for the structural optimization of buildings using reclaimed timber. Grounded in principles of circularity, metabolism and tectonics, the research claims that reclaimed materials are often seen as a constraint, but can be leveraged as a driver for architectural design. The core of the methodology is centered around a parallel approach of the development and application of a computational tool on design cases, informing each iteration of the tool through evaluation of the design. This tool, operating within the Rhino Grasshopper environment and utilizing Karamba3D for structural analysis and Wallacei for multi-objective optimization, integrates heuristic and meta-heuristic algorithms for stock matching and geometric refinement.

The efficacy and implications of this approach were investigated through two distinct design studies, with use of reclaimed timber from the mink farm industry: the renovation of a residential structure and the conceptual redesign of a large-scale architectural project. The residential renovation demonstrated the tool's capacity to inform the design process by suggesting incremental changes in the geometry in order to achieve full reclaimed timber utilization, effectively translating the "form follows availability" paradigm into a tangible design outcome. The second experiment tested the tool on a larger structure of increased complexity, this concluded in the lengthening of computation time, to the detriment of the amount of design iterations.

The thesis concludes that algorithmic workflows offer a viable pathway to integrate reclaimed timber into architectural design, transforming material limitations into opportunities for resource-efficient, spatially considered solutions. While the developed tool provides a proof-of-concept for designing with scarcity, its broader adoption necessitates further advancements in data management for reclaimed materials, refined user interface and joint adaptation to bridge the gap between innovative research and practical application in fostering a more materially intelligent built future.

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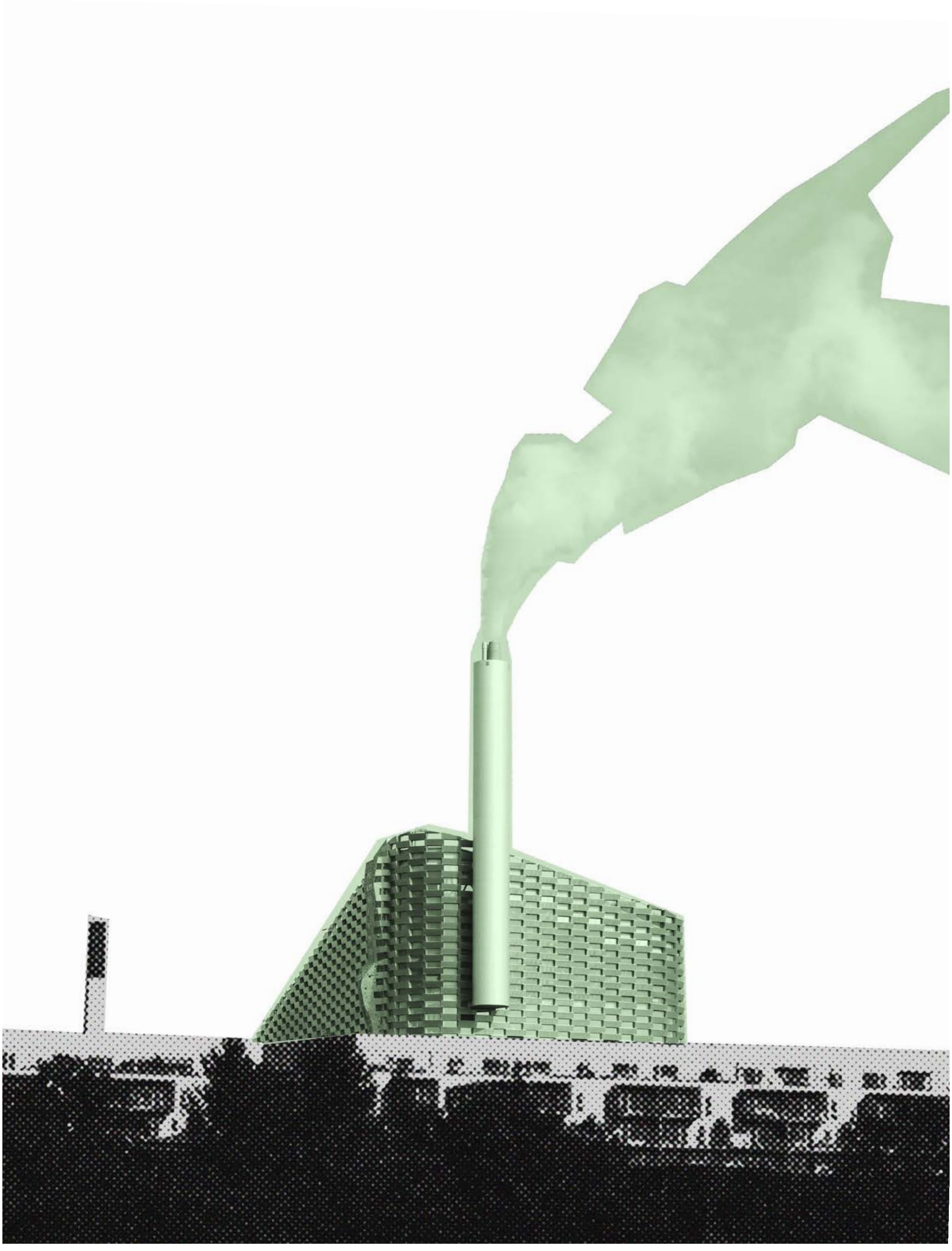


Figure 1: Carbon collage

Pre-Face

Circularity - Current Climate Challenge

The built environment accounts for 39% of global carbon emissions, with 28% coming solely from operational emissions—such as heating, cooling, and electricity—primarily due to a "dirty" energy grid.

As a result, climate action has largely focused on reducing these operational emissions by increasing thermal capacity, improving insulation, and implementing active strategies like heat pumps and photovoltaics. However, as operational emissions decrease, the carbon burden shifts toward embodied energy, which can account for up to 70% of the total energy over the 50-year life cycle of low-energy and passive buildings (Amiri et al., 2020).

The most effective way to halt carbon emissions from the building industry is, quite simply, to stop building altogether. But that's an unrealistic solution within the current global paradigm—economically unfeasible and politically unpopular due to its lack of opportunity for profit and its disruptive implications for growth-oriented models (Usto 2023).

"It is my assumption that there is an unspoken understanding of the building industry.. i.e, we have to design a circular building industry where more and more building activity will be more and more sustainable than a slow (and considerate) building industry (and its subsequent material consumption)."
p - 6 (Usto 2023)

The problem, simply put, is the overconsumption of resources. Switching from concrete or steel to more sustainable materials like timber, while continuing the same rate of building, misinterprets the core issue. Even so, timber has become the focal point in architecture, engineering, and construction (AEC).

The industrial streamlining of timber production may give the illusion of progress—but often, greater efficiency leads to greater consumption, not less, which is a common observation known as Jevons Paradox, referring to the discrepancy between an intended outcome and the actual result of an idea's implementation. Increased demand will encourage large-scale forestry (Usto 2023).

While planting more trees is commonly labeled "sustainable," it often prioritizes profit, potentially leading to harmful outcomes of large-scale forestry, such as soil degradation and reduced biodiversity (Osman, 2014).

The Parallax View, as described by Žižek (2006), is where the same facts take on different meanings depending on the scale or lens through which they're viewed. So, more forestry isn't inherently bad—but the intent and context matter. From one perspective, it's climate action; from another, it's "greenwashing" and "bad circularity"—whether done knowingly or not.(Usto 2023)

"... the economic dynamics of the building industry are poorly designed buildings are built and will followingly require either extensive renovation or demolition. This then loops back to more demand for new buildings - this maintains the economic circular model of supply and demand by design (Cairns, Jacob 2014). Jeremy Till describes this phenomenon as architecture being dependent on demolition"
p - 15 (Usto 2023)

The AEC industry, as it stands, is deeply invested in preserving an economic model that thrives on continuous construction and material turnover. That model, however, is inherently unsustainable.

Amid this reality, there is a growing wave of circular thinking, particularly among young architects and experimental studios. A notable example is Resource Rows by Lendager Group, which uses upcycled bricks reclaimed from demolished buildings for its facade. That approach resulted in 10% of the building's materials being upcycled, reducing CO_2 emissions by up to 29% (Lendager Group, n.d.).

Other contemporary projects—like the Tate Modern in London and the Meatpacking District in Copenhagen—have preserved existing building facades while repurposing their interiors for new functions. These cases minimize waste, reduce demand for virgin materials, and retain cultural and architectural history, transforming the old into new community landmarks (Jones, 2013; Strömberg, 2018).

This wave needs more momentum. In this thesis, the focus will be on narrowing and slowing material consumption—not by stopping building entirely, but by designing with scarcity. The aim is a design practice that respects material limits, embraces reuse, and prioritizes longevity over novelty.

Metabolism

While circular strategies are gaining traction, they often operate at the level of individual projects or components. To scale this thinking systemically, a broader conceptual framework is needed, one that accounts for the dynamic flows of materials. This is where the concept of metabolism becomes useful.

Metabolism, in biological terms, refers to the chemical processes that occur within a living organism to maintain life (Cambridge Dictionary). In this context, the term functions as a metaphor within industrial ecology—a branch of chemical engineering that employs methodologies like material flow analysis to map the movement and transformation of materials through systems. For architects, Life Cycle Assessment (LCA) is the tool that corresponds most directly with this methodology (Usto 2023).

The metaphor of "metabolism" (or Stoffwechsel, in German) has been used historically by figures such as Gottfried Semper to describe the evolution and transformation of architecture, culture, technologies, and stylistic movements. Earlier still, Karl Marx introduced the term metamorphism to reflect on the problematic interface between nature and human activity—particularly the consequences of technological intervention. Both metaphors engage with the notion of resource limitations in the face of capitalist dynamics.

Material flow can function as both a design strategy and an analytical tool (see figure 2), wherein the narrative of a project emerges from an understanding of how materials move through the world and the built environment (Usto, 2023). This duality—bottom-up (design) and top-down (analysis)—shouldn't stand alone, but instead be employed alongside other methods. Nevertheless, it provides a valuable orientation, especially when attempting to reconcile the disparity between intention and outcome, as seen in Jevons' Paradox. This "material-flow-first" principle is a major influence on the direction and methodology of this thesis—both in the selection of tools and in the design process itself.

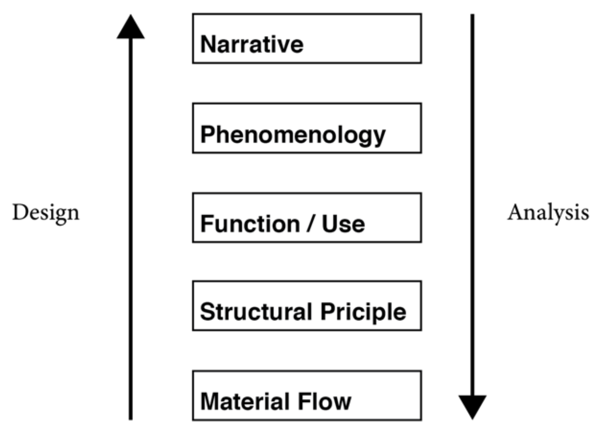


Figure 2: Diagram of material flow as design. Adapted from Usto (2023, p. 282).

Metabolism, by nature, is circular meaning a continuous intake of energy followed by output, maintaining life through continuous dynamic exchange. However, when juxtaposed with the way material circularity is often discussed—via "re-" words like reuse, recycle, refurbish, etc.—it becomes clear that the reality of material use is not truly circular. It's no ouroboros. Instead, it's linear, as seen in figure 3; the 'cycle' ends once further downgrading becomes unfeasible or economically unattractive.

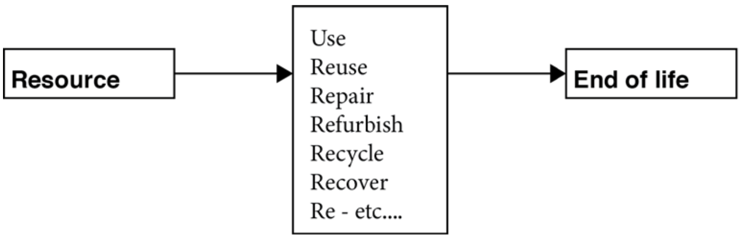


Figure 3: Diagram of the linear flow of materials. Adapted from Usto (2023)

Currently, in the material flow of timber, waste wood is frequently reused for chipboards, regardless of its actual quality. That's because construction timber is often seen as too inconsistent to reuse directly (Sørensen et al., 2019). However, many of these factories already have an adequate supply of low-grade wood, resulting in a surplus that is exported—often to Germany—for the same purpose. This leads to a misallocation of resources. High-quality timber is being diverted into low-value production streams or energy recovery rather than being reused structurally.

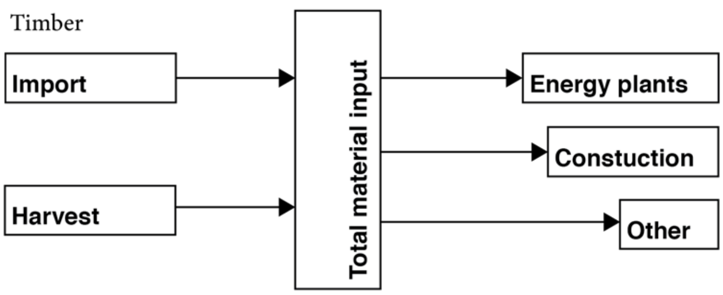


Figure 4: Simplified material flow of timber.

Companies like KronoSpan hold large volumes of waste wood in storage, highlighting a market saturation for chipboard feedstock. Unfortunately, because the industry isn't designed to support the direct reuse of timber, a great deal of this high-potential material remains unused.

At the same time, the demand for biobased construction is growing rapidly, outpacing the availability of virgin timber from sustainable sources, particularly in countries like Germany (Szichta et al., 2022). This raises a critical question: Where will future wood come from? Especially given that large-scale, sustainable forestry is not widely practiced in many timber-rich regions such as parts of Asia and South America.

Although the market increasingly favors biobased materials, timber resources are depleting, and long-term planning to address this shortage is lacking. In Denmark, for instance, approximately 800,000 m^3 of waste wood is processed annually. Of that, only 40,000 m^3 is classified as structural timber suitable for reuse (Andersen et al., 2023).

In total, Denmark uses about 2.275 million m³ of wood for material applications out of a national consumption of 17.5 million m³ per year. Of this, 600.000 m³ is used in construction, meaning reclaimed structural timber could potentially meet up to 6.7% of construction wood demand, considering the 40,000 m3 of structural timber waste (Brownell et al., 2023). That may sound small, but it's not insignificant and it represents an untapped opportunity.

However, current demolition practices rarely prioritize the recovery of individual elements. The focus remains on speed and efficiency, leading to timber waste being incinerated for district heating instead of being salvaged.

Another issue is that only 44% of timber can be traced back to its origin and species, which is essential for assessing quality and determining structural viability (Brownell et al., 2023). This lack of information further limits timber's reuse potential. Without proper classification, even good wood is treated as waste.

Therefore, the issue isn't just a matter of choosing reuse over energy recovery, it's about reorganizing the entire flow of materials as seen in figure 5. If neither virgin nor reclaimed timber is readily available, construction will default to concrete and steel, ultimately undermining sustainable efforts.

To avoid this fallback, the loop must shift toward a system that prioritizes circular reuse, not just in theory but in logistics, policy, and design thinking. That means embracing a model where the flow of materials is slowed, not through restriction, but through intelligent, value-preserving design.

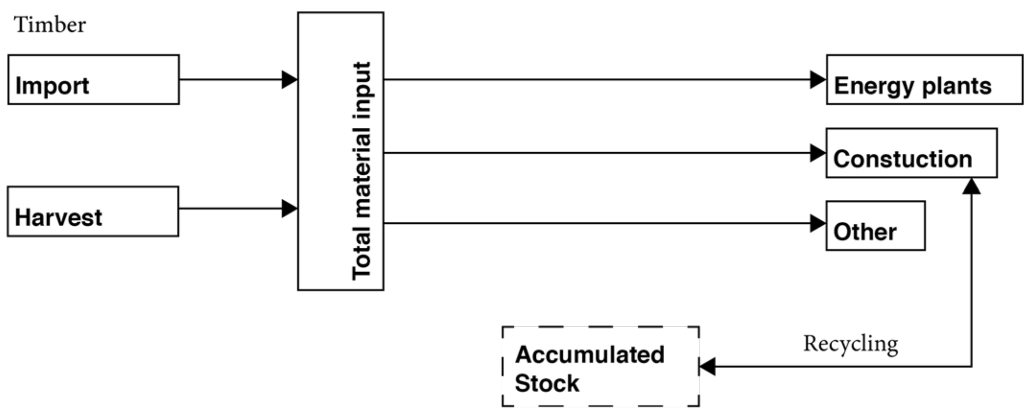


Figure 5: Ideal material flow of timber.

Safe Sink

If metabolism helps frame the movement and transformation of materials over time, then the concept of the safe sink begins to define their eventual resting place.

In chemical engineering, a safe sink refers to a system or entity capable of continuously absorbing and containing materials or elements without adverse side effects. Traditionally, this role has been played by landfills, which are static, singular-use spaces designed purely for containment. They serve no functional or aesthetic purpose beyond material storage. (Usto 2023)

In his PhD dissertation Safe Sink Tectonics, Kemo Usto (2023) proposes a radical reinterpretation: that the urban built environment itself could become a kind of "beautiful landfill." In other words, rather than treating buildings as short-lived emissions machines, they could become active agents of long-term carbon sequestration by absorbing and holding material in use for decades, even centuries, while still performing essential urban and architectural functions.

Through the concept of safe sinks, can buildings function as carbon sinks, delaying the release of stored carbon, in the context of timber released through incineration. In this sense, the built environment transforms from being a net emitter to a medium-term carbon reservoir.

Usto further suggests that in order to fully realize this potential, the practice of designing for disassembly must become standard. Unfortunately, this design philosophy has long been neglected, especially in post-war and late-20th-century construction.

Figure 6: Upcycle studios by Lendager. Author's own photograph.

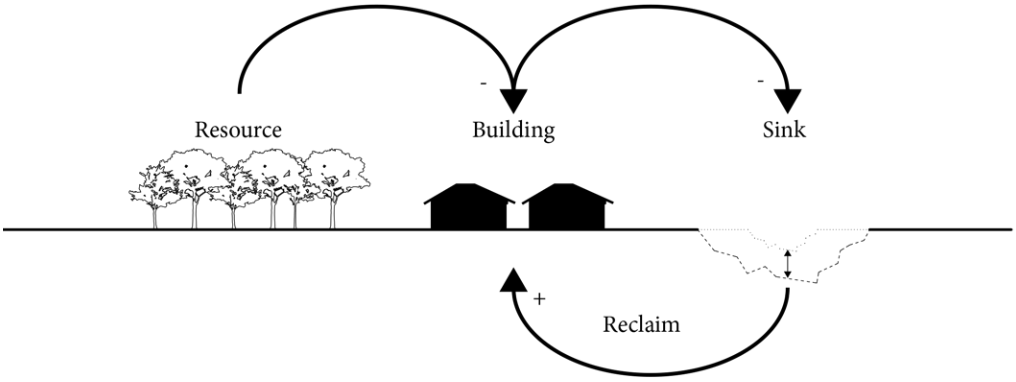


Figure 7: Buildings as repositories for materials and energy. Adapted from Usto (2023)

Today, many demolitions are executed with brute force—wrecking balls, excavators, total site clearance—making selective salvage resource-intensive and inefficient. Reusable elements are often damaged or discarded due to lack of foresight in the original assembly (Usto 2023).

One tool for addressing this problem is the material passport (Materialpass, 2025), a digital record of the composition, provenance, and performance characteristics of specific building elements. However, for this to be effective, the passport must be embedded within 3D building models and maintained over time. Future disassembly should be made appealing, both practically and economically, through accurate modeling and easily accessible data.

But this technical infrastructure must be matched by a cultural and regulatory shift. Economically and legally, buildings are still too often seen as eventual waste rather than carbon banks. For this to change, policymakers and financial stakeholders must embrace long-term material value as a core principle of urban development. As part of the European Union "Green Deal" to reach carbon neutrality by 2050, two core points were to prioritize a circular economy and increase building renovation from a rate of 1% to 2-3%. This is a small fraction suggesting most buildings are made from entirely new materials, highlighting the need for stricter policies and embracing the concepts of metabolism and safe sink in every aspect, not just renovation, in order to reach the 2050 goal (Simon, 2019).

Looking forward, architectural design must evolve to become a tool for carbon and resource management. The buildings we design are not just objects or spatial solutions, they are repositories of material and energy, holding the potential to extend the life of resources that would otherwise be discarded see figure 7. This means embracing a stock-based design approach, where the materials already in circulation, entirely or mostly, define what can be built.

The built environment must evolve into a repository of material value, not just a vessel of temporary utility. This shift requires new tools that track, sort, and preserve material identity across time.

Tectonics

While metabolism frames our understanding of resource flows, it doesn't address how materials should be assembled into meaningful architecture. Tectonic thinking bridges this gap, transforming material reuse into an opportunity for architectural expression. If buildings are to function as "beautiful landfills" that sequester carbon while serving human needs, we must understand the framework of which we think about the material in the context of architecture.

The term tectonics originates from the Greek word tekton, meaning artisan or craftsman, much like architect derives from arkhitekton, meaning chief artisan. In architectural discourse, tectonics describes the interplay between architecture and engineering, highlighting the relationship between the architectural design and the structural and constructional considerations (Foged & Hvejsel, 2018).

Foundational Theory

The foundational theory of tectonics dates back to ancient Rome and Vitruvius, who articulated architectural design through the Vitruvian triad: Firmitas, Venustatis, and Utilitas, meaning firmness, beauty, and utility (Morgan, 1960). These principles relate architecture to the human experience, suggesting that buildings must provide safety, functionality, and aesthetic delight. However, while Vitruvius highlighted essential considerations for architects, he did not prescribe specific methodologies for their realization.

These ideas were expanded upon by architectural theorist Gottfried Semper, who instead of seeing the structure and beauty of architecture as equal concerns, argued that above everything else, the structure is a means of materializing the spatial and cultural purpose of a design. By his own definition, Semper divided these concerns into the "wand" and "gewand", meaning wall and dressing, where dressing is defined as a soft interior focused on the human body and mind, and the wall is the structure providing support for the dressing (Semper, 1989). Semper's definition thus provides clearer insight into an architect's roles and responsibilities compared to Vitruvius's more generalized triad.

Architectural historian Eduard Sekler further developed these ideas in his essay "Structure, Construction and Tectonics." Sekler divided Semper's concepts of wand and gewand into structure and construction. He defined structure as an abstract response to the forces acting upon a building, while construction refers to the tangible materials and fastening methods used to realize this structure (Sekler, 1965). Sekler emphasized the necessity of aligning structure and construction with the architect's spatial intentions to avoid purely functional or generic outcomes. He introduced the concept of tectonics as the methodological mindset to translate the architect's conceptual ideas into the lived experience of the inhabitants.

This idea, also present in the essay "Tell The Tale Detail" by Marco Frascari, sees the architect express the whole of their concept through the deliberate joining of parts, thus resulting in an abstract relationship between the spatial intention and technical means (Frascari, 1981).

The theory of tectonics offers contemporary architects a lens through which to analyze and comprehend the spatial qualities of buildings. This approach goes beyond conceptual frameworks by revealing how technical execution directly influences spatial experience. Through tectonic analysis, architects recognize that each decision in the construction process—from the harvesting of local materials to the precise detailing of a door handle—contributes to the building's experiential narrative.

Such cohesion between local materials and spatial expression can be seen in The Therme Vals by Peter Zumthor. The construction material, Valser Quartzite, is layered in a manner resembling the stone's natural geological formation. The water and steam transform the stone's texture while simultaneously shaping the acoustic environment. The stone's minimal sound absorption creates reverberations similar to those found in natural caves, hushing conversations and incentivising guests to hum and sing against the stone (Hawkes, 2020). In this example, Zumthor demonstrates the tectonic mindset of transforming construction materials into powerful mediators of the spatial experience, creating a sensory journey that connects visitors to the material's origins and the landscape.

Figure 8: Photograph of Therme Vals. (Gunnar Klack/Wikimedia Commons, CC BY-SA 4.0).

Digital Tectonics

As contemporary practice evolves, tectonics also adapts to new tools and technologies. While traditional tectonics emphasizes the poetics of construction through physical craft and material expression, the introduction of computational tools has fundamentally reshaped how architects conceive, simulate, and materialize buildings extending tectonic thinking.

The term digital tectonics may seem like an oxymoron, for how can something immaterial be associated with a theory rooted in materiality. The reality of contemporary architectural work is that computers and digital tools have been a permanent implementation since their first introduction in the 20th century. CAD and BIM have allowed architects and engineers to produce highly accurate digital copies of buildings. 3D printing and CNC milling, based on digital copies, have also changed the way architects build physical models, as well as the manufacturing of construction parts (Leach, Turnbull & Williams, 2004).

While these aspects are not inherently related to the theory of tectonics, digital tools have also allowed architects to simulate real-world conditions such as gravity, solar irradiance, daylight and wind. These tools allow architects to design with a tectonic mindset, by form finding based on the forces that would affect the building, further linking the practices of architecture and engineering to reach designs of high performance.

The simulations of real-world conditions help architects and engineers in the design of structural concepts and are highly implemented in the work of architecture and engineering. Construction has in the past couple decades also seen the introduction of digitalization through methods such as CNC milling, robotics and prefabrication. These technologies help architects and engineers make the parts of a complex structure manufacturable for construction, as well as make it more efficient and economic to produce generic buildings.

Tectonics and Metabolism

If the final outcome of these processes is a building that serves both functional and aesthetic purposes, then each preceding step acts as a means to that end. The structure enables the form, the construction enables the structure, and digital tools facilitate construction. This chain extends back to the raw materials and the people who make such technologies possible. The German philosopher Martin Heidegger argued that, in the modern world, technology is often seen merely as a means to an end—for example, pressing a button to turn on a light. However, Heidegger viewed technology as a closed circuit in which progress perpetuates itself: technological advancement necessitates further technological advancement (Blitz, 2014). As discussed in the metabolism chapter, such cycles tend to increase consumption and highlight the problematic interface between nature and human activity. We drill for oil to build more, yet having built more, we must drill again. Ultimately, it is the ecosystem itself that bears the cost of this endless cycle.

As argued in the metabolism chapter, materials should not be seen as passive reserves awaiting use, but as components embedded within broader ecological systems. Tectonics already offers a framework for considering the physical and aesthetic dimensions of materials. Given the current carbon crisis, incorporating ecological properties into tectonic thinking may allow architects to approach form-finding with material flows in mind. Timber, often championed for its sustainability, is only carbon-storing when understood within its regenerative ecological cycle. Therefore, within architectural practice, tectonics and metabolism together may guide designers to consider not only functionality but also material availability.

Reclaiming Timber

As discussed in the preceding chapters, timber plays a central role in reducing carbon emissions. However, it is a finite resource, and its renewed prominence must be managed with care. In Denmark alone, 395,000 tons of recyclable wood are collected annually, yet only half is reused—primarily for particle boards. The remainder is incinerated for energy, despite approximately 100,000 tons being of sufficient quality for recycling (Hansen, 2023). Increasing the reuse of structural timber is therefore critical to optimizing its environmental potential.

Mitigating the initial carbon cost of construction is essential for achieving short-term CO_2 reduction targets. While concrete, steel, and masonry are all highly energy-intensive to produce, timber offers one of the lowest greenhouse gas emissions across its life cycle. Its regenerative nature also enables it to function as a carbon sink, unlike mineral-based materials, which are finite and inert (Amiri et al., 2020). For these reasons, timber appears to be the most viable candidate for future low-carbon construction.

However, as a natural material, timber presents unique challenges that complicate its structural reuse. Variability in moisture content, knots, fiber slope, and its inherent combustibility require stricter assessment procedures and regulatory oversight. As the construction industry transitions toward biobased materials, the supply of suitable timber must keep pace. As noted in the Metabolism chapter, Germany's projected demand for softwood is expected to exceed supply, highlighting the urgency of reuse.

One approach gaining traction is material cascading, a concept of prioritizing high-value applications like structural reuse over energy recovery. Although still in its early stages, research is increasingly exploring the use of reclaimed timber in engineered wood products such as glued laminated timber (GLT) and cross-laminated timber (CLT) (Risse et al., 2019; Llana et al., 2020; Szichta et al., 2022).

Concerns around fire safety and structural integrity over time have led to a reliance on destructive testing methods, which is only practical for large, uniform stockpiles (WE BUILD DENMARK, n.d.). In response, European countries are developing non-destructive testing techniques to evaluate timber properties without damaging the material. In Norway, a new standard allows for visual inspection of knots and fiber slope to assign strength classes equivalent to new timber of the same species (Standard Norge, 2025).

Complementary research into X-ray imaging, resistivity measurements, infrared spectroscopy, and load testing has shown promising results in accurately assessing timber performance. For fire resistance specifically, factors such as density, moisture content, and species type play more significant roles than age (Uldry et al., 2024). A study of weathered timber found no loss in fire performance after 24 months of exposure (Panek et al., 2021), while another comparison between historic timber and modern GLT attributed performance differences to the engineered density and adhesives used in the latter, not timber age (Chorlton & Gales, 2019).

Together, these developments suggest that standardization of non-destructive testing for structural timber reuse may be within reach. Nonetheless, substantial barriers remain, including liability concerns, inefficient deconstruction practices, storage and logistics challenges, contamination, poor documentation, and limited industry capacity (WE BUILD DENMARK, n.d.).

At first glance, keeping structural timber within a circular system may seem nearly impossible. However, such practices were standard in the 18th and 19th centuries. Back then, the primary concern was not resource scarcity or carbon emissions, but economics, as materials were more expensive than labor (Kristiansen, 2023).

An example of this mindset is Civiletatens Materialgård, a storage facility built in 1771 in Copenhagen, which was used to store reclaimed building materials for reuse in royal projects. This essentially functioned as a safe sink, however, as the economic issues switched from costly materials to costly labor, new materials were prioritized and used materials were disposed of. During the construction of Det Kongelige Palæ in Roskilde (1734–1736), architect Lauritz de Thurah was explicitly instructed by King Christian VI to reuse as many materials as possible (Kristiansen, 2023).

If reuse was essential for the monarchy, it was even more critical for farmers, who relied on salvaging costly structural components. In the 18th century, when farmers relocated from village communities to more isolated farms, they often dismantled and transported high-quality timber from old buildings to reuse in the new ones (Hyllestad, 2012). A notable example is Dovergaard, a farm in Thy originally built in the 1570s, which includes timber elements dating back to 1429. Its most recent barn was constructed in 1831, meaning some components had already been in use for several centuries at the time of their reuse (Koefoed, 2024).

Figure 9: Photograph of timber truss in Drigstrup Kirke. (Arnold Mikkelsen/Nationalmuseets Samlinger, CC BY-SA 4.0).

This long-standing tradition of reuse in Danish vernacular architecture offers valuable lessons for today's challenges. While the original motivation may have been economic—prioritizing the value of materials over labor—the underlying logic remains strikingly relevant: when resources are finite or costly, reuse becomes not only practical but necessary.

Today, the urgency has shifted from budget constraints to planetary boundaries. Yet, the principle is the same: if structurally sound timber already exists, it should be preserved and reintegrated into new construction.

A contemporary event demonstrates the sheer scale of the potential of reusing structural timber. In 2020, Denmark abruptly shut down its mink farming industry due to COVID-19 concerns. What followed was the largest coordinated demolition effort in the country's history, with over 8 million square meters of built area dismantled by 2023 (Bygningsstyrelsen, 2025). For context, this built area can fit ~2.5 times inside Central Park in New York, as seen in figure 10.

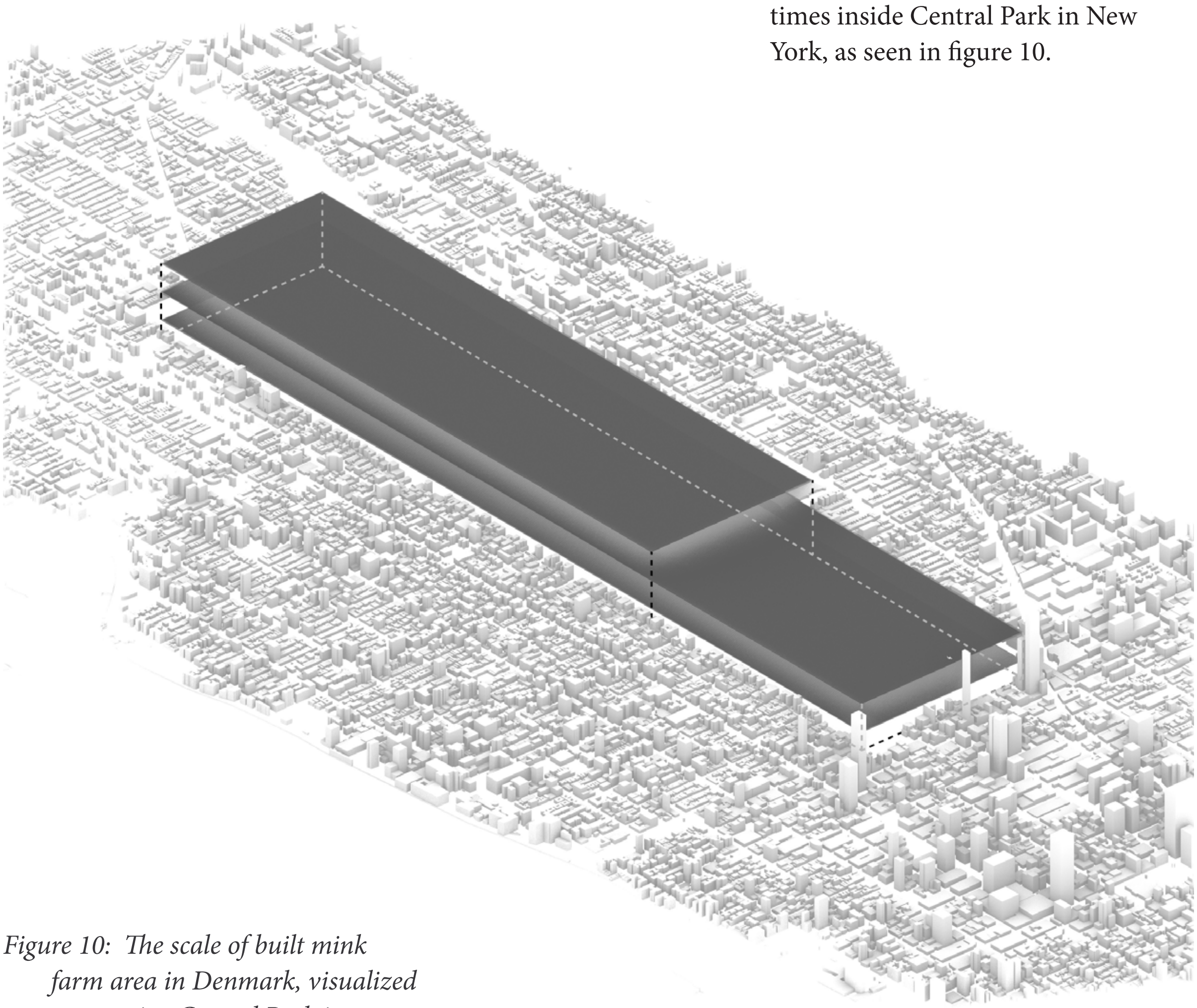


Figure 10: The scale of built mink farm area in Denmark, visualized as covering Central Park in Manhatten, New York City.

While the political and health-related dimensions of this event were well-publicized, the material implications remain largely overlooked. The structural timber embedded in these facilities—much of it standard, lightweight framing—represents a massive, underutilized stock. In this thesis, this stock will be used as a reference scenario in developing a methodology for structural timber reuse. A single structural frame from a mink farm and its specifications, can be seen in figure 11. These frames are arranged in wings with each wing having up to 59 frames. Further details can be found in Appendix B.

This chapter establishes timber as a crucial regenerative material for sustainable building, noting that while its reuse was historically common due to material costs, it is now underutilized despite significant potential. Although natural timber presents assessment challenges, developments in non-destructive testing are paving the way for its broader reclamation. Large-scale opportunities, such as the vast quantities of timber from Denmark's dismantled mink farms, demonstrate this feasibility, especially as studies confirm that well-maintained reclaimed timber can offer structural performance comparable to new material.

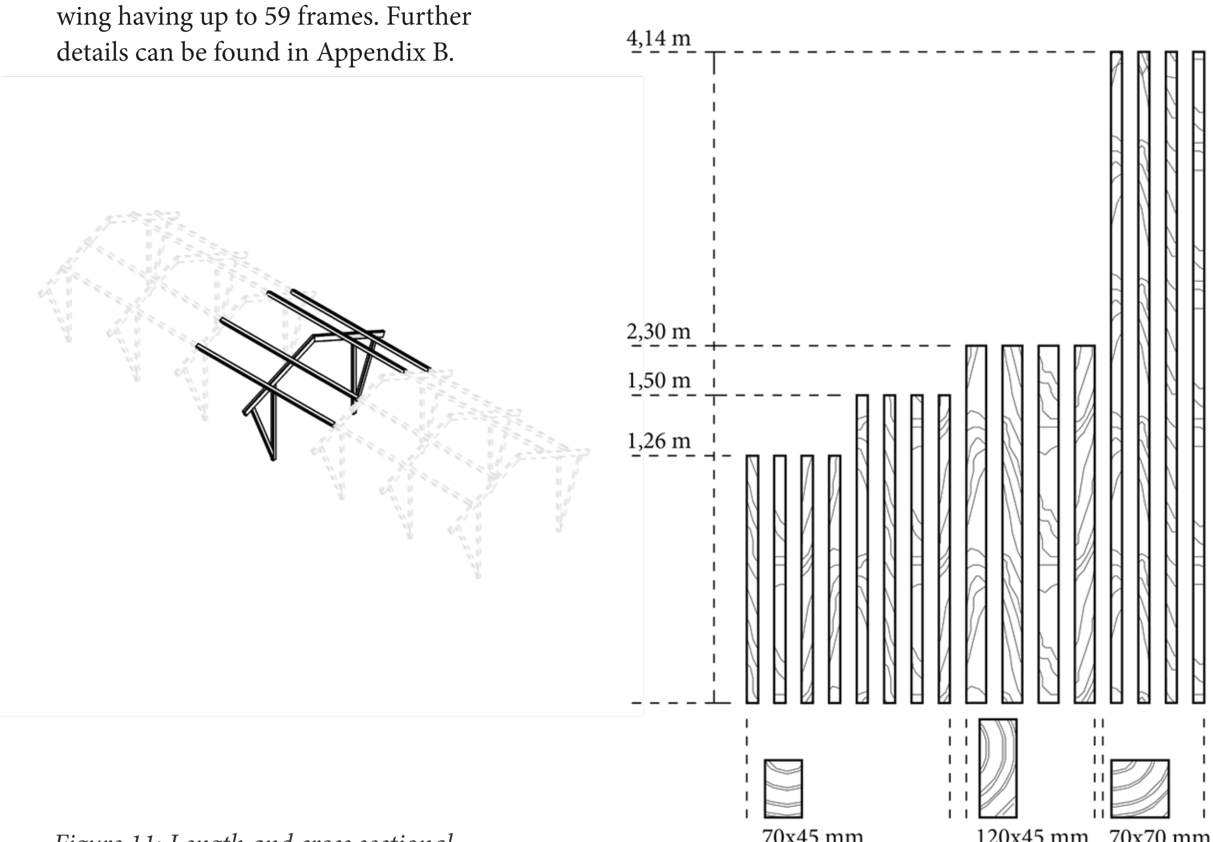


Figure 11: Length and cross sectional information of a mink farm timber frame.

Figure 12: Reclaimed mink farm timber. Author's own photograph.

Conclusion

As discussed in the preface, while timber is celebrated for its carbon-storing capacity, its growing scarcity presents a critical constraint. To sustain—or responsibly expand—its use in low-carbon construction, the building industry must shift from a reliance on virgin timber toward the structural reuse of existing materials.

The concept of the built environment as a safe sink offers a compelling framework for this shift. Once a practical norm, the deliberate storage and reuse of structural elements must be reintroduced, not only as a sustainable practice but as a design strategy embedded in contemporary digital workflows.

Within which reclaimed timber requires new tools capable of grading, assigning, and integrating diverse material stocks into coherent architectural systems. These systems must bridge the gap between structural logic and architectural intention.

By approaching architecture through the parallel lens of metabolism and tectonics, this thesis argues that form and assembly must be informed by the limitations and potentials of existing material stocks. Rather than treating reuse as a constraint, it becomes a driver of design by embedding material logic into architectural expression and opening new pathways for circular reuse in construction.

Figure 13: Mix of reclaimed timber. Author's own photograph.

Hypothesis

If architecture is to address ecological limits and material scarcity in a meaningful way, it must begin to align its design processes with the realities of finite and irregular materials. Reclaimed timber, with its inherent variability and availability of discrete parts, offers a compelling case through which to explore this shift. By considering how material constraints can influence form, structure, and assembly, new design approaches may emerge, ones that are both responsive to environmental challenges and grounded in the reuse of existing resources.

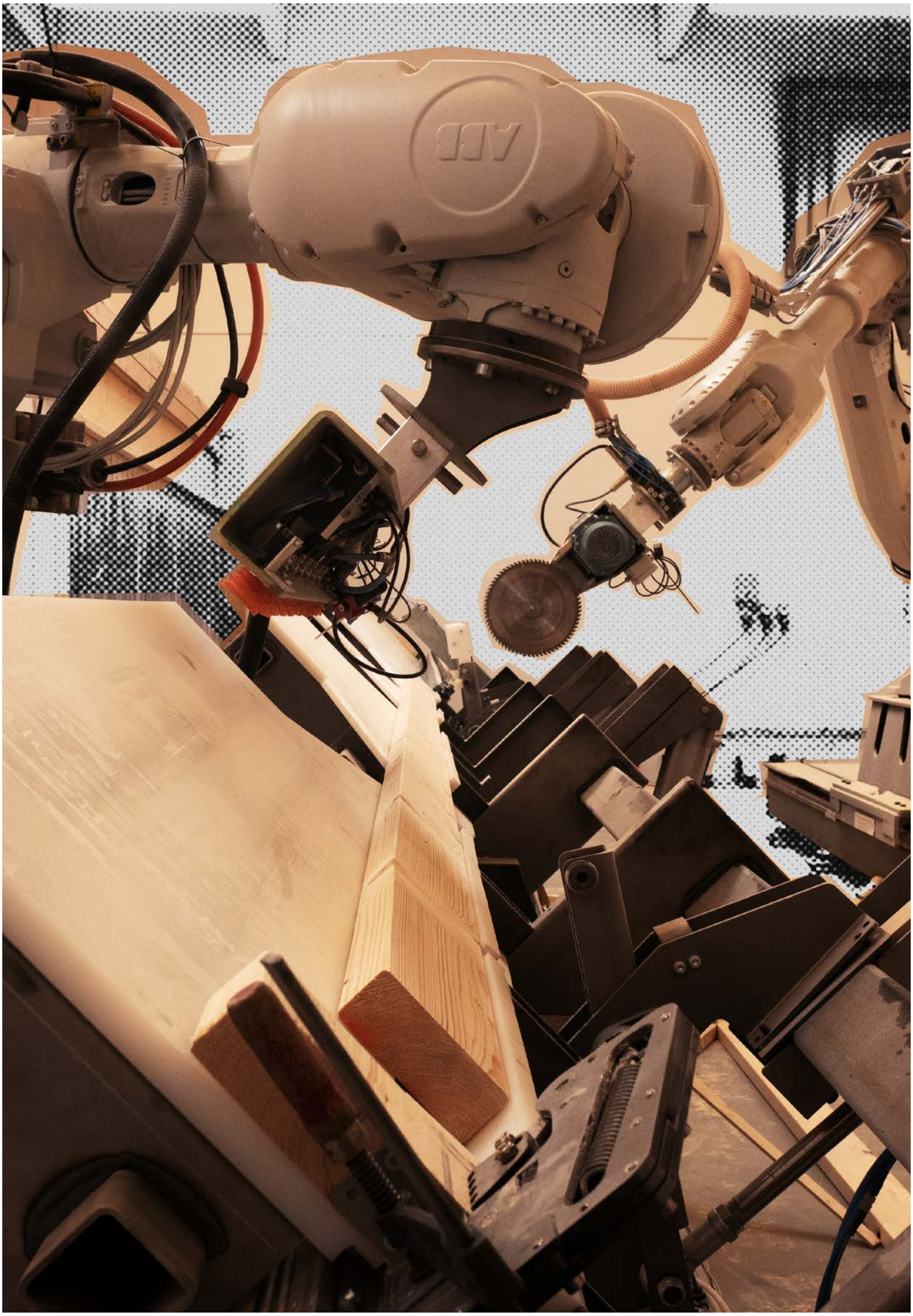


Figure 14: Woodstock Robotics. Author's own photograph.

State of the Art

To move from hypothesis to practical application, this thesis must situate itself within existing research and methodologies. As discussed, designing with reclaimed timber demands a reconsideration of form, structure, and assembly in response to irregular, finite material stocks. This challenge intersects multiple domains within architecture and engineering.

Therefore, the state of the art explores three key areas: (1) computational workflows that incorporate material availability into design generation, (2) structural typologies that are compatible with irregular or reclaimed timber elements, and (3) digital fabrication techniques capable of translating unconventional material assemblies into buildable architecture. Investigating these areas provides the technical and theoretical foundation for developing a design methodology that aligns architectural intention with material constraints.

Research of Form Follows Availability

Developing a methodology for reclaimed timber reuse requires building on existing research into material-driven design processes, as it may inform how existing material stock can actively shape both structural systems and spatial design. While literature on the structural reuse of timber remains limited, two studies have been identified as particularly relevant to this thesis, offering insights into computational strategies that integrate material availability into structural design.

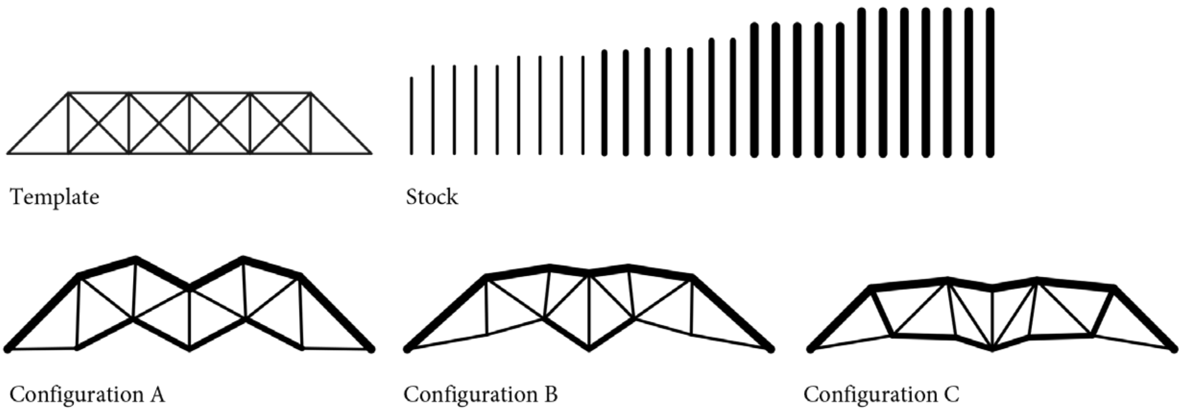


Figure 15: Diagram of the first approach, stock-constrained strutural analysis. Adapted from Brutting et al. (2019).

The research paper, "Form Follows Availability – Designing Structures Through Reuse," proposes a method for designing structures with reuse as the guiding principle (Brütting et al., 2019). This approach begins with a stock of reclaimed elements, using a baseline structural template to guide geometric optimization. These elements are then computationally assigned to the structure in various configurations, aiming to minimize cut-off waste, as illustrated in figure 15. The paper's conclusion highlights the value of this method, emphasizing the potential in researching the diverse design outcomes that can emerge from such a stock-constrained optimization process. This thesis finds this method particularly relevant. It aligns closely with the architectural design process by enabling the adaptation of reused materials to a variety of spatial and structural arrangements.

The second research paper is the thesis "Application of Reclaimed Elements in Structural Engineering Towards Circular Economy." As the title suggests, it explores a topic closely related to this thesis: the reuse of reclaimed timber in structural systems. While it employs an optimization process similar to the stock-constrained optimization process in the first paper—matching reclaimed stock to a template structure—its primary focus lies in the logistics of storing reclaimed elements and establishing a digital material bank composed of 3D-scanned representations (Dahl-Nielsen & Gundersen, 2024). A matching algorithm is then used to optimize the volumetric material utilization of each element, taking both length and cross-sectional dimensions into account when comparing the reclaimed stock to the template structure.

Together, these two papers lay important groundwork for understanding how reclaimed elements can be handled in structural systems. Both demonstrate that an established reference structure is needed in order to define minimum material requirements—such as length and cross section—and that this structure must first undergo an optimization process to minimize element sizes. Additionally, they highlight the importance of a matching algorithm to automate and optimize the assignment of reclaimed elements, particularly with respect to minimizing cut-off waste.

However, when compared to the hypothesis of this thesis, a gap becomes apparent: while both papers focus on the structural feasibility and logistical optimization of reclaimed elements, they overlook the architectural consequences of a stock-constrained optimization process. Specifically, neither addresses how structural reuse affects spatial design, aesthetic variation, or tectonic expression. Therefore, this thesis builds upon these methods while addressing an overlooked dimension: the architectural and tectonic consequences of designing with a reclaimed stock. To ground this investigation, the next chapter explores structural systems most compatible with timber.

Structures of Discrete Timber Elements

Building on the computational strategies of allocating reclaimed elements, this chapter examines the structural systems best suited to a methodology rooted in reclaimed timber. By narrowing the focus to timber elements recovered from mink farms—and the structural typologies appropriate for such materials—the thesis grounds its theoretical framework in a real-world, scalable context.

Each structural frame from the mink farms contains discrete, meaning individual and distinct, timber elements of varying lengths and cross sections, consistent with standardized dimensions typically used in truss construction. The standard timber truss is therefore a highly relevant structural type for this study, serving as the content of the safe sink that is to be transformed into new structures.
According to Eurostat data from 2018, 54% of Denmark's population lives in detached houses (Eurostat, 2021).

Although only 10–15% of these houses are constructed primarily from timber (Accsys, 2024), it is reasonable to assume that the majority incorporate timber roof structures, including trusses. In this context, the timber truss represents a structurally and statistically significant component of the Danish residential built environment.

Using reclaimed timber for standard truss design thus offers a compelling case study for evaluating its feasibility. It allows for an exploration of how such an approach can integrate reclaimed stock into conventional structural systems without compromising performance or practicality.

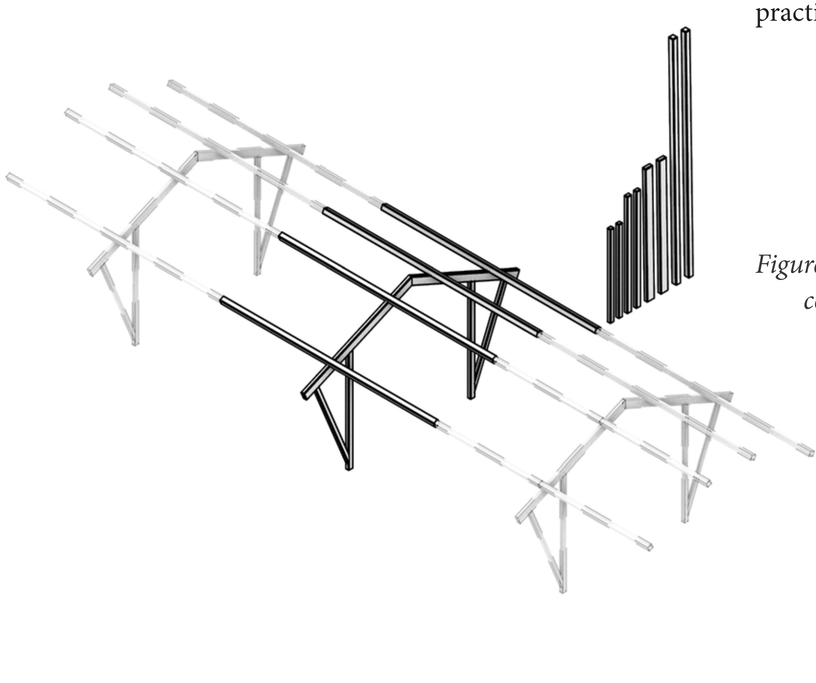


Figure 16: A mink farm frame and its corresponding timber elements.

The long-standing tradition of reusing structural timber in Danish vernacular architecture—defined here as architecture rooted in local techniques, and cultural practices—offers valuable inspiration for reintroducing this approach in response to today's challenges in the building industry. It also revives a forgotten practice of designing with available resources and acknowledges the history embedded in the materials.

Figure 17: Photograph of timber trusses. (Government of Prince Edward Island/Flickr, CC BY-SA 2.0).

Outside of vernacular timber trusses, most timber structures in formal, or "Extravagant", Architecture—where stylistic expression is prioritized—tend to rely on glue-laminated timber (GLT) to span long distances. Engineered wood products like GLT offer greater length and consistency than discrete timber elements, making them more practical for conventional construction.

While most complex timber structures rely on engineered wood, exceptions such as those developed for The Sequential Roof at ETH Zürich reveal how digital technologies and robotics can reintroduce discrete elements into contemporary structural design. These experimental approaches are the subject of the following chapter.

Figure 18: Photograph of The Sequential Roof. Photo by trevor.patt from Flickr, licensed under CC BY-SA 2.0.

Fabrication of Discrete Elements

As identified in the previous chapter, the reintroduction of discrete timber elements into complex structures is increasingly enabled by digital and robotic fabrication. This chapter examines how robotic systems, unlike traditional CNC methods, offer the precision and adaptability needed to work with non-standard timber, paving the way for high-performance structures crafted from reclaimed material.

The construction sector is increasingly benefiting from prefabrication, which streamlines project schedules and reduces on-site labor demands. However, architects are concerned that the shift toward prefabricated components might restrict design freedom. By relying on standardized building elements, they fear innovation and creativity is limited.

Balancing the efficiency of prefabrication with the desire for unique, expressive architecture has thus become a challenge in the industry. As Architect Lisa Wronski notes in an ArchDaily article, “By creating pieces off-site instead of on-site, there exists a disconnect between the architect and the land itself.” (Wronski, 2013).

Robots could challenge the idea that prefabrication limits architectural expression, as this technology can handle intricate shapes and complex geometries with a level of precision and speed once reserved for mass-produced parts. By integrating digital design tools with robotic fabrication techniques, the construction industry now has an opportunity to push the boundaries of what can be built by combining the efficiencies of prefabrication with the aesthetic and functional possibilities inherent in more complex, customized designs (Gramazio et al., 2014). As seen in figure 19, DFAB House by NCCR Digital Fabrication built in 2019, which is the first full scale multi-story building designed and built using advanced digital fabrication, with discrete timber elements assembled using robotics (Gramazio Kohler Research, 2024).

In timber construction, robots offer distinct advantages over traditional CNC systems, which struggle with tracking individual elements, require manual on-site assembly, and are restricted by limited workspaces. Robotic systems, by contrast, directly translate computational designs into physical assemblies, allowing for efficient handling of discrete timber components and reducing material waste and construction costs (Menges et al., 2017).

Thus, robotic fabrication merges the benefits of prefabrication with design flexibility, allowing the creation of complex, non-standard structures. These possibilities are best understood through real-world applications. The following case studies—The Sequential Roof and Woodstock Robotics—demonstrate how robotic fabrication has been deployed in both experimental and vernacular contexts to enable new forms of timber construction.

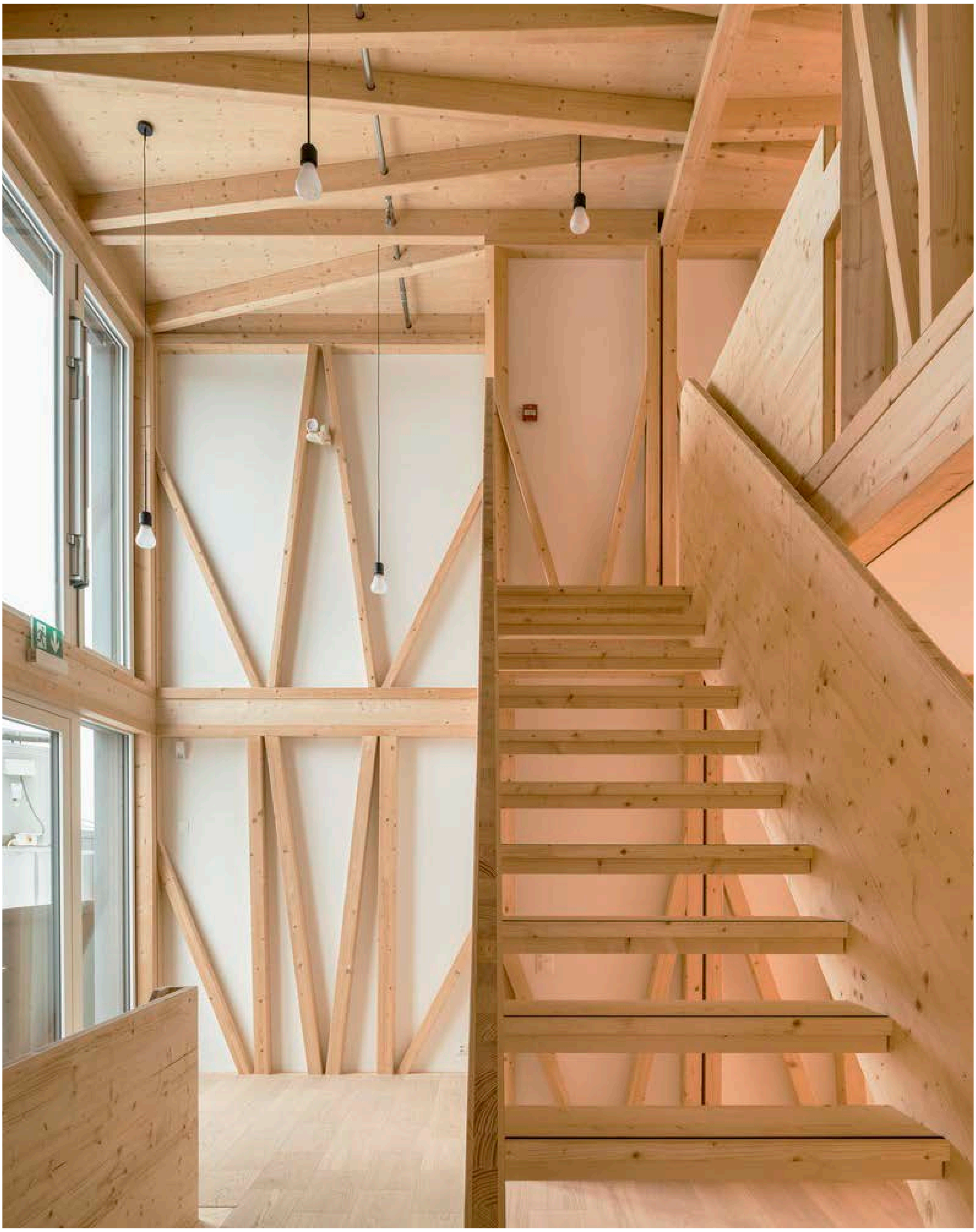


Figure 19: DFAB House by NCCR Digital Fabrication. Copyright 2019 by Roman Keller. Used with permission.

Cases

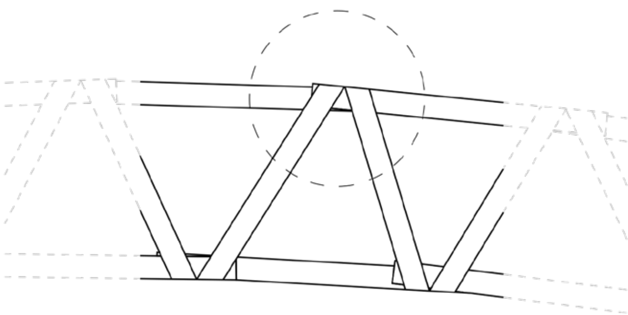
The Sequential Roof

Developed by Gramazio Kohler Research for the Arch_Tec_Lab at ETH Zurich's Institute of Technology in Architecture, the Sequential Roof is notable for its fully automated robotic fabrication process and robotic guided assembly process—one of the first of its kind implemented at this scale. The roof structure consists of 168 unique timber trusses, each composed of multiple layers of 50 mm thick timber slats.

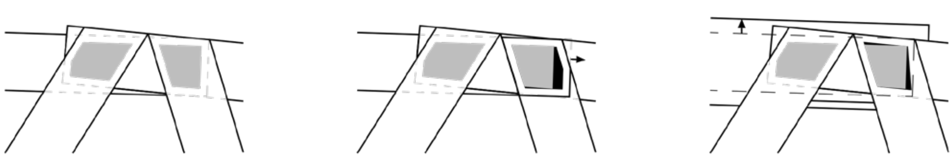
The primary goal of the project was to develop design methods that integrate geometric, structural, and fabrication requirements. A key structural challenge involved ensuring sufficient overlap area in each joint for effective nail placement. Addressing this required an iterative computational process, continually adjusting the geometry based on structural analysis and fabrication constraints.

Effective data management and clear interdisciplinary communication among architects, engineers, and robotic fabrication specialists were essential throughout this process (Apolinarska, 2018).

The core of the "sizing problem" involved evaluating each timber element based on structural utilization and ensuring every joint met a minimum nail quantity.



For the robot to perform the joinery efficiently, the timber elements are stacked, needing only nails for assembly. Computationally an optimization is performed on the feasible area for nail-fitting.



The baseline nail-fitting area | Increased end-cut length | Increased cross sectional area

Figure 20: Diagram of the optimization process of nail-fitting for The Sequental Roof project. Adapted from Apolinarska (2018).

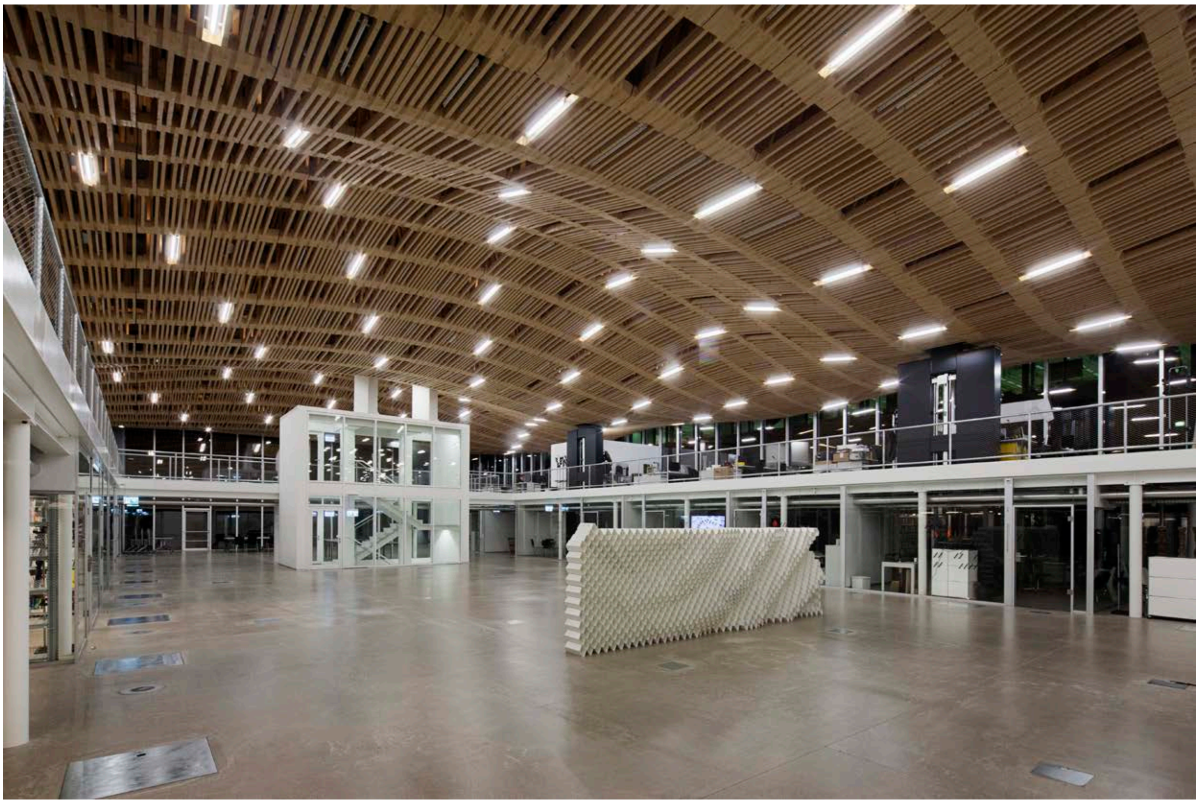


Figure 21: Photograph of The Sequential Roof. (Daniel Erne/Wikimedia Commons, CC BY-SA 4.0).

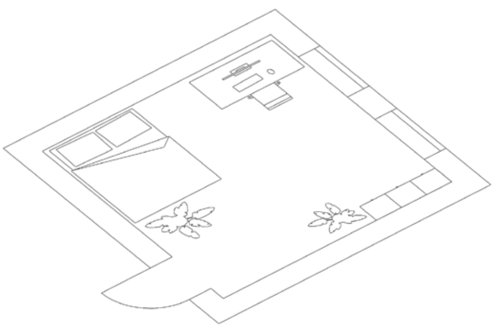
If a component failed to meet these requirements, the algorithm automatically adjusted its geometry, either by extending the element's length or increasing its cross-sectional height to enlarge the overlap area for nail connections as seen in figure 20. (Apolinarska, 2018).
Given the complexity of the structure—with 48,624 unique timber elements and 94,380 joints—the number of potential configurations was infinite.
Therefore, they employed a brute-force algorithm to find a valid solution. This approach successfully limited additional material use to just 13% using only three different cross-section sizes, significantly less than a worst-case scenario requiring a single, large cross-section size, which would have resulted in a 59% increase in material use (Apolinarska, 2018).
This case thus highlights the challenges and possibilities of fabricating large-scale structures composed of short, novel timber bars, emphasizing the critical role of data management, algorithmic problem formulation, and interdisciplinary communication in achieving a constructible design. For this thesis, such an approach to fabrication will play a large role in presenting feasible designs based on variable and reclaimed timber stocks.

Woodstock Robotics

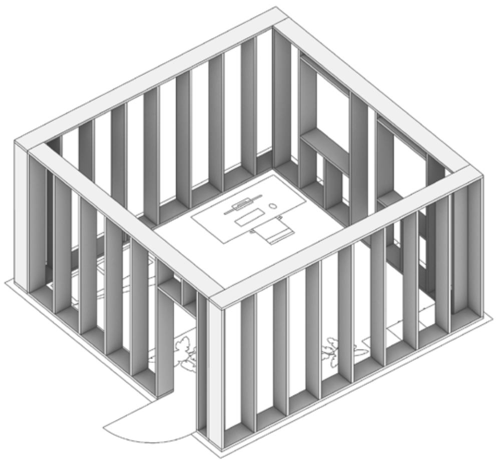
To complement the theoretical and technical investigations presented earlier, the following insights are drawn from a site visit to Woodstock Robotics and an interview with co-founder Alexander Nordhejm Andersen, conducted on February 26, 2025.

Woodstock Robotics specializes in robotic cutting for timber construction, drawing on the founders' experience at Odico, a robotics company that went bankrupt in 2024. From this background, they recognized the potential of robotics to improve efficiency, sustainability and reduce costs in conventional timber construction. Unlike prefabricated CLT modules, this approach is logistically more flexible, reducing the need for large-scale transportation and on-site maneuvering. It also generates considerably less waste, with off-cuts accounting for only 4% compared to the 10% typical of manual manufacturing. Additionally, the simplified assembly process lowers the required skill level of construction workers, making timber construction more accessible and less labor-intensive. By eliminating the need for cranes and reducing reliance on metal brackets by up to 50%, this method further streamlines the building process. Moreover, robotic cutting offers a more cost-effective alternative to CNC machining, requiring a smaller investment in both space and technology while maintaining precision and adaptability.

Digital



Woodstock Robotics receives architectural drawings or a 3D model of the design proposal.



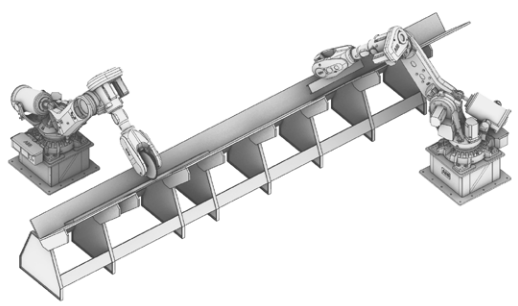
They create a digital model of the timber structure, estimating structural requirements for walls, trusses, and flooring.

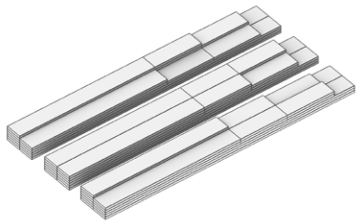
Figure 22: Woodstock Robotics workflow.

Beyond reducing waste and improving the efficiency of timber construction, Woodstock Robotics has also explored the potential of applying their workflow to reclaimed timber. For a project in Nordsjælland with Andelsgaarde, a farming community in Melby, they collaborated with the carpentry firm Anders Mainz to construct a farmhouse using reclaimed timber from the windmill industry. Their automated process efficiently allocated timber elements of varying lengths, minimizing waste to just 2,33% (Mainz, n.d.).

The materials arrived on-site, and within a day, the prefabricated elements were ready for shipment. When the elements are shipped to the site, they are already sorted into building kits corresponding to each frame and also stacked in the sequence of the construction, so the first kit is on top of the pile. This process effectively streamlines the on-site assembly of the timber construction, where each element in the kits are already marked and pre-cut. This case illustrates how robotic workflows could be scaled and adapted to handle reclaimed materials with precision, efficiency, and minimal waste which offers a pragmatic model for integrating circular practices into everyday construction processes.

Physical





Based on this model, timber elements are sourced in exact lengths. ABB robotic arms then cut joints and mark assembly positions.

The processed elements are sorted into sections for on-site assembly, with carpenters receiving a building manual.

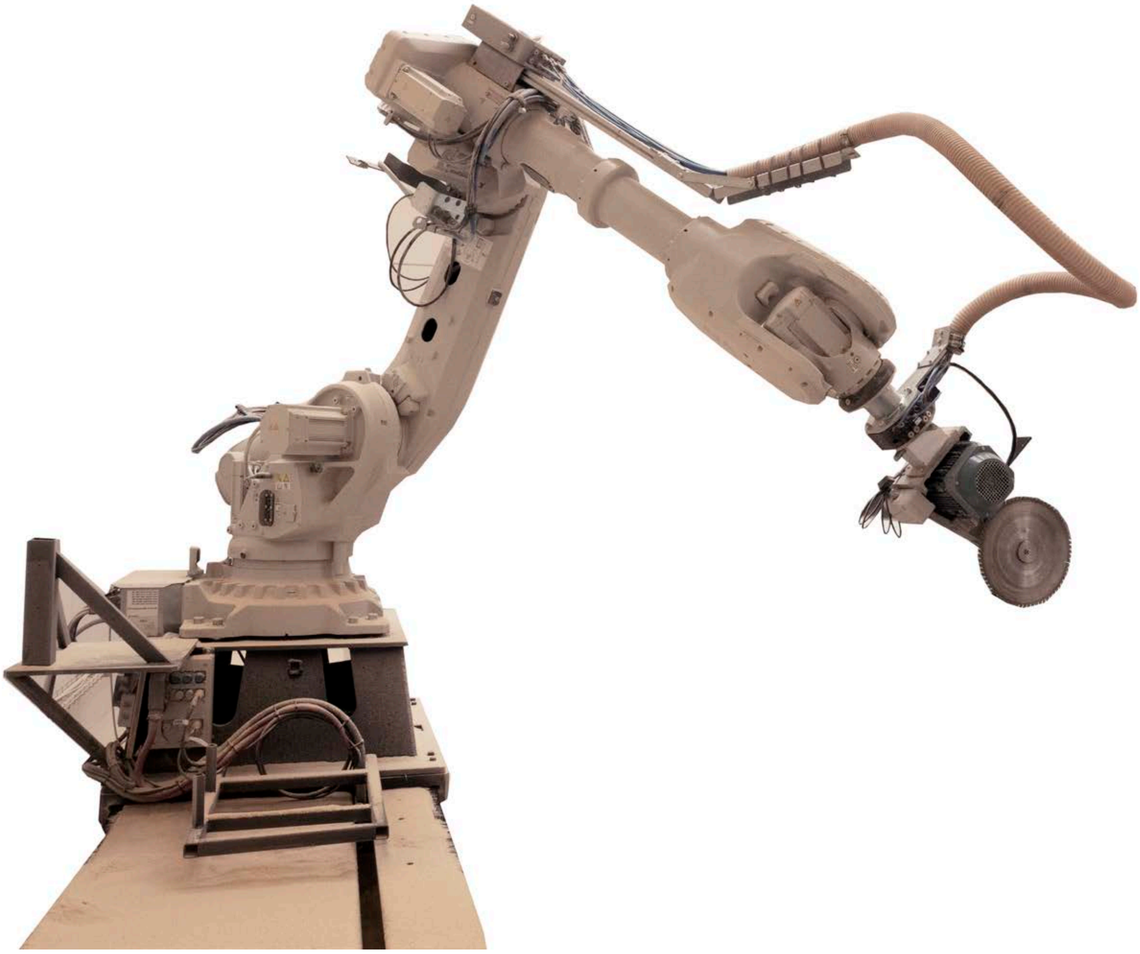


Figure 23: Picture of an ABB robot used at Woodstock Robotics. Author's own photograph.

Conclusion

To conclude the foregoing chapters, it is evident that all the necessary tools for designing with reclaimed timber in a feasible and systematic manner are already in place. The methodology presented in Research of Form Follows Availability outlines principles for computationally assigning elements from a reclaimed stock to a designed structure.

The structural framework discussed in Structures of Discrete Timber Elements, along with the technological insights from the Woodstock Robotics case study, demonstrates the broad potential for integrating reclaimed mink farm timber into vernacular architecture. Furthermore, Robotic Fabrication and the case study The Sequential Roof extend these possibilities to highly complex and expressive structures. With these foundations established, a problem statement can be formulated.

Figure 24: Photograph of a mink farm and man. Author's own photograph.

Problem Statement

How might algorithmic workflows be integrated into the architectural design process to adaptively allocate reclaimed timber for structurally sound and spatially expressive buildings by leveraging material scarcity as a driver of form rather than a limitation.

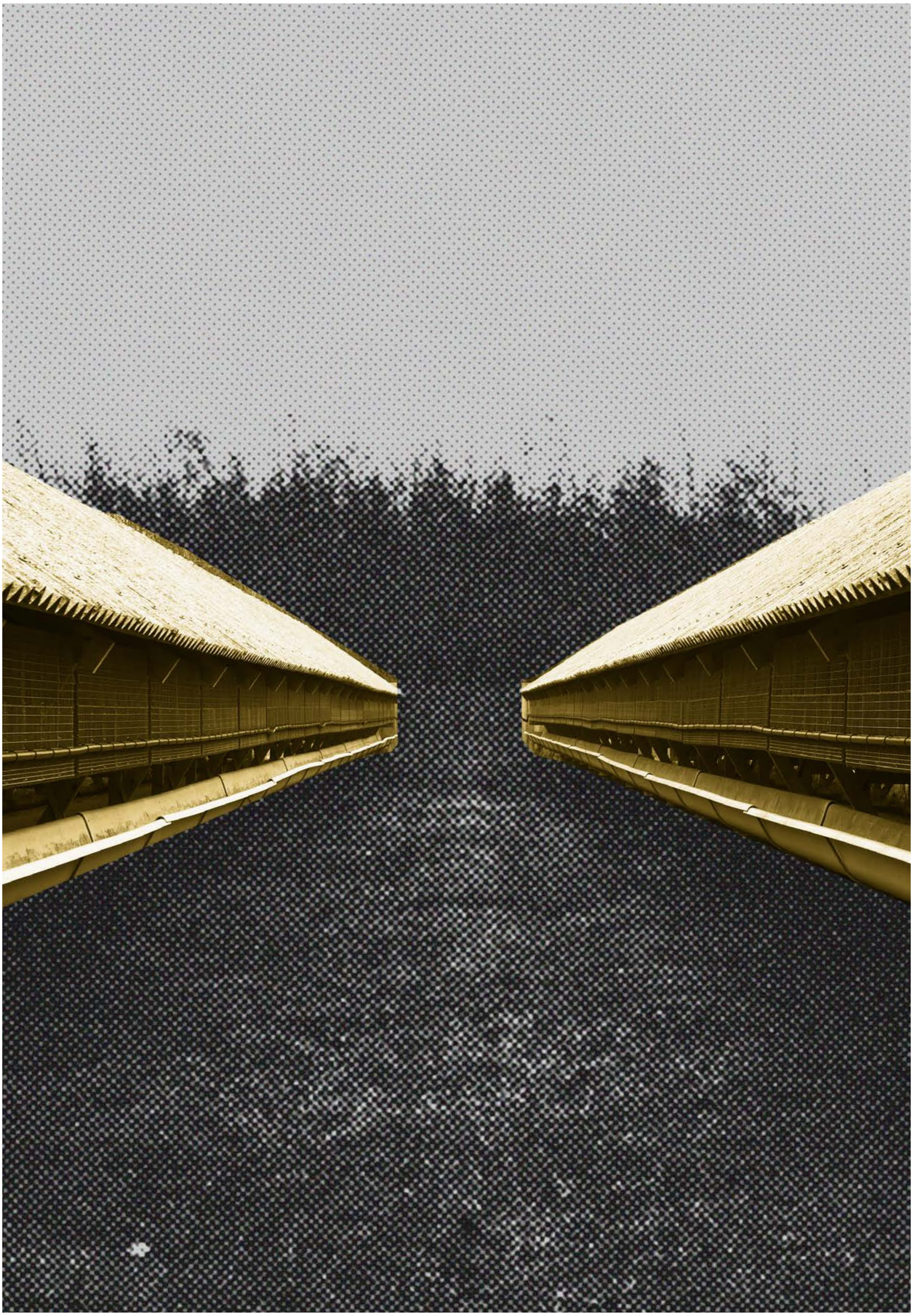


Figure 25: Photograph of a mink farm. Author's own photograph.

Methodo-logical Approach

To answer the problem statement, the thesis must situate itself into the context of the AEC industry for a methodological approach must be crafted.

The state of the AEC industry is one where competencies are often segregated, while there are historical and operational reasons for this structure, one key driver is the pursuit of efficiency due to the focus on highly specialized workflows where everything is imagined to glide smoothly from department to department. However, it can be observed that this linear model rarely holds. The constant re-evaluation inherent in design processes is often overlooked, and back-and-forth collaboration becomes inefficient or fragmented.

The Integrated Design Process (IDP) emphasizes interdisciplinary collaboration, combining architecture and architectural engineering knowledge to solve complex design challenges in a group-based context. The method's objective is to encourage innovative solutions which combine qualitative and quantitative approaches.
The goal is to foster the creation and design of climate-adapted, energy-efficient buildings that integrate aesthetic, functional, and technical qualities (Knudstrup, 2004).

However, in reality, this level of integration is rare. The continued separation of disciplines— this can be referred to as "competency silos"—allows firms to offer highly tailored services but limits the flow of knowledge between teams. This fragmentation becomes especially problematic when addressing multifaceted issues such as the climate crisis, where interdisciplinary coordination is crucial (Gleeson 2013).

Effective information flow is essential for navigating the new design dilemmas posed by climate adaptation and material scarcity. While the types and domains of knowledge are vast, this thesis focuses specifically on digital information exchange between key players in structural design: architects, engineers, manufacturers and contractors.

Traditional design workflows often view material flow and material constraints as limitations, but within this methodological framework, they become the driver. The design space is not a rigid set of predefined forms but a fluid environment where material availability, structural needs, and digital workflows intersect.

By leveraging algorithmic processes, architects and engineers can push the use of reclaimed timber demonstrating its potential not just as a sustainable metabolistic alternative, but as a foundation for new structural and aesthetic possibilities.

This chapter addresses how to reconfigure the relationship between design and material flow, by changing the information flow and shifting the architectural production toward a circular, resource-aware design methodology. One in which scarcity is not a constraint to be overcome, but a condition that drives architectural innovation.

Focus of Inquiry

To further contextualize the problem statement it will be partitioned into separate inquiries.

- How can material reuse reshape the design process, particularly in relation to form and performance?

- Can algorithmic tools bridge the gap between architectural intent and structural viability, without undermining either?

In which frameworks will these inquiries be managed and how will said framework guide the conception of a tool?

Computational Framework

To determine the theoretical framework underlying the tool development and its relations to the designer, this thesis refers to Rivka Oxman's paper "Theory and Design in the First Digital Age". Oxman is a professor and researcher in the field of Digital Design, Cognition and Computation. (Oxman, 2006).

The aim is to situate the tool to be developed within one of Oxman's models to ensure a straight path of development.
Oxman argued that the growth of digital design and production practices necessitated new conceptual models, a shift she termed digital design thinking. In her 2006 paper, she introduces a generic schema of design models and highlights how digital paradigms diverge from traditional, paper-based approaches. From the six models she describes, two are particularly relevant to this thesis: the Performance-Based Generation Model and the Compound Generation Model.

In the Performance-based generation model, as seen in figure 26, performance data drives the generation and/or formation of form. The designer interacts with three key modules—representation, generation, and performance—defining both the generation and performance logic, while interaction occurs through the representation module.

The Compound model s based on integrated processes including formation, generation, evaluation and performance and allows the designer to interact with all four modules, defining them while interacting with the representation.

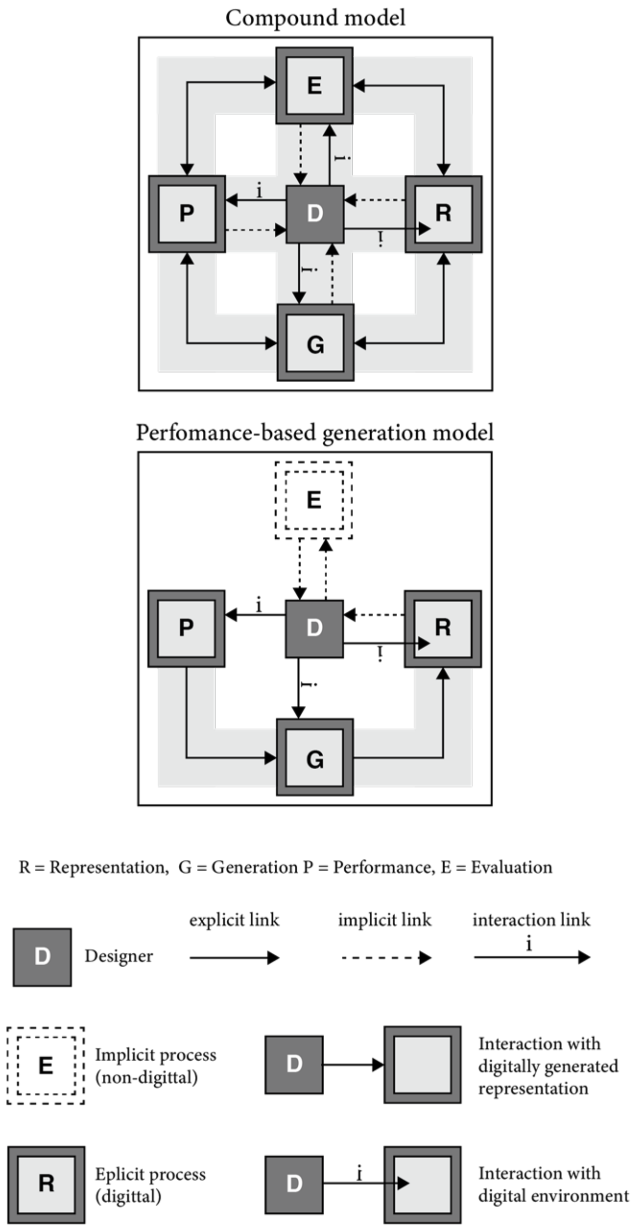


Figure 26: Diagram of the digital design models. Adapted from Oxman (2006).

Oxam stated that “Compound models represent a class of future paradigmatic digital design media that have important potential implications for future design media.” (Oxman, 2006)

The Compound models would Ideally provide interaction with any of the activity modules with the possibility of the data and information to flow in multiple directions.
The Compound model would be the most desirable framework based upon it compound information flow.
Now that the digital framework of the tools relation to the designer has been set, further advancing the methodological approach: how the tool is developed, how it functions within the design process, and what role it plays in bridging architectural thinking with computational logic.

Parallel Development and Design

For the development of the tool a process of continuous testing will be used, a baseline structure will be set up for continuous testing for each process, structural analysis, stock matching and visualization and evaluation. The process thus employs a circular testing practice.

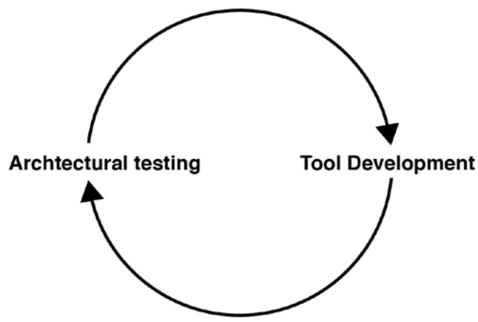


Figure 27: The parallel approach of iteratively developing and designing.

The tool to be developed in this thesis is designed for architects and engineers as a collaborative bridge mostly in the early design phase. After the early design phase, the tool is meant to relay geometrical information to a robotic sawmill for fabrication. Relevant data is logged in a 3D-model and an adhering raw-data file. This data contains the position of elements in the given structure as well as the elements materials classification and its dimensions.

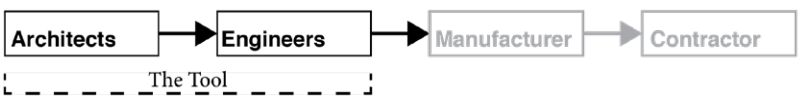


Figure 28: The focus area of development.

In the material flow, if the building is relayed as the fulcrum, the tool sits as the mediator for evaluation of the proposed structures and its material availability between architects and engineers.
In figure 29 a hypothetical scenario is highlighted where no new pieces are added to the material flow, the flow only considers pre used elements.

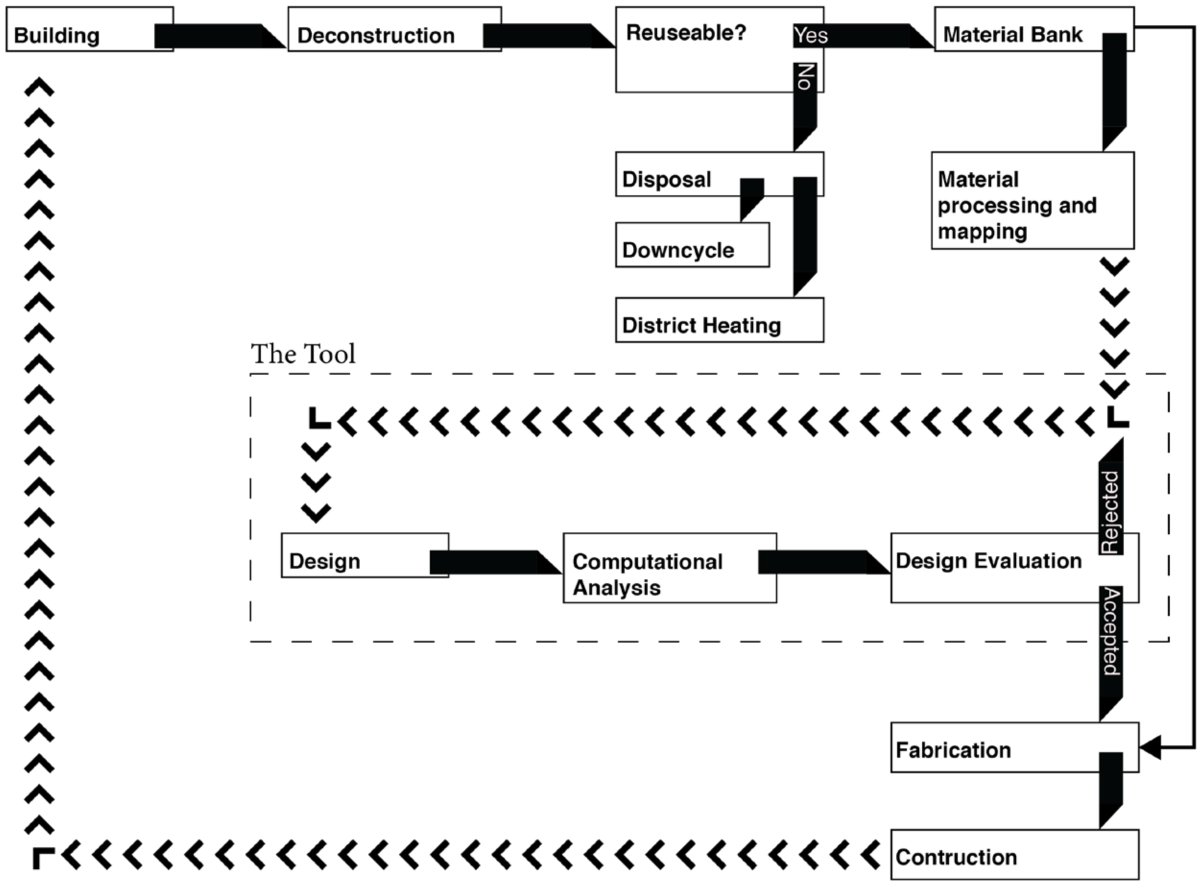


Figure 29: The ideal flow of the building industry in a material-flow-first scenario.

At the end of a building's lifetime its structural components are evaluated and distributed either as an output (disposal, downcycling or energy extraction) or as an addition to a material bank where the data, lengths, cross section and class is saved while the element is given an ID. In this imagined material flow the tool could reassure the use of said material bank to ensure optimal use.

By following the logic above the design space becomes not as a fixed geometric framework, but as a fluid system shaped by available material stock and performance requirements. The design process becomes grounded in, again, a parallel approach where design development, feasibility analysis, and structural performance are explored simultaneously rather than sequentially.

Architectural, computational, and structural considerations are developed iteratively. Each informing the others to arrive at a cohesive and optimized solution.

For the design phase this allows early architectural decisions, such as spatial intent or daylight goals, to inform, and be informed by, material constraints and structural logic. Rather than resolving one domain before addressing the next, this methodology seeks balance across competing objectives.

Design Studies

To evaluate the range and capabilities of this tool—as well as its resulting tectonic expression—two design studies are developed to explore the practical outcomes of the algorithm and assess its applicability within the architectural design process. In the chapter "Structures of discrete timber elements" two indices were highlighted, Vernacular Architecture and Extravagant Architecture.

- Design Study #1 investigates the potential for algorithmically allocating reclaimed structural timber within a vernacular context, emphasizing practical implementation and scalability in a highly standardized industry.

- Design Study #2 examines the algorithm's use in the context of Extravagant Architecture, aiming to understand its implications for advanced form-finding and expressive structural systems.

Scope: Thesis Process

To return to the inquiries and elaborate this thesis focuses on the development of an algorithmic workflow for the structural optimization of timber structures in relation to form and performance while bridging the gap between architectural intent and structural viability in the design process, specifically by assigning reclaimed timber elements

Referring back to the method used by Jan Butting in Research of Form Follows Availability the proposed tool will evaluate architecturally defined timber structures and match them with available reclaimed elements based on performance criteria and geometric constraints.
The central challenge addressed is the integration of material scarcity and variability into the architectural design process by evaluating structural efficiency, material efficiency and spatial expression. The thesis proposes a workflow where design is not solely driven by spatial intent or programmatic enclosure, but also by the real-world availability and characteristics of reclaimed materials. In doing so, it repositions scarcity as a generative design condition.

These problems are thus the focus of the thesis, which in turn leaves many aspects outside of design and evaluation out of the picture. Aspects such as the material harvesting, processing and inventory management of reclaimed materials are important and entirely necessary but are not included in the focus of the thesis. Research in previous chapters, such as the thesis by Dahl-Nielsen & Gundersen (2024), provide valuable insight into creating such systems.

Another critical aspect of the workflow includes the fabrication of structures with high variability. The research into robotic fabrication provides insight into the design considerations that must be considered in accordance with the precision of robotics, such as limiting the number of elements in the same joint and the lack of accuracy with joints such as half-lap joints. While important, the thesis remains focused on the design and evaluation of such a structure, relying on the proof-of-concept structures such as The Sequential Roof.

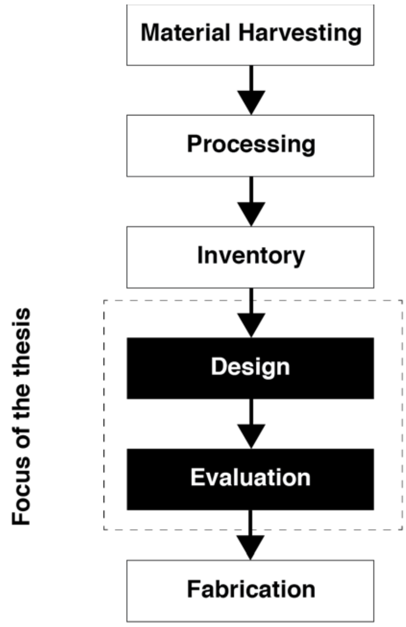


Figure 30: Scope of the thesis, focusing on design and evaluation while being informed by the entire process.

In summary, the scope of the thesis is limited to the computational generation and evaluation of timber structures using reclaimed elements. It situates itself within the early design phase, contributing a workflow that supports structurally sound and materially responsive architectural design without addressing the full logistical, regulatory, or fabrication implementation.

Within this scope, the degree to which optimization of the structures is pursued varies across a spectrum, from minimal disruption to conventional construction practices, to highly customized, computationally driven. Understanding this gradient is critical for evaluating the practical viability of the proposed workflow. This spectrum is illustrated by degrees of intervention on a desired structure, by the developed tool, in the process of allocating reclaimed timber elements.

The effectiveness of optimization methods differs significantly between theoretical potential and real-world implementation. For computational optimization to yield feasible and cost-effective results, it must be reconciled with construction industry norms, particularly economic efficiency and established standards. For example, center-to-center spacing in timber structures governs downstream components like façade elements and insulation dimensions. Deviating from these standards can initiate a cascade of adjustments, increasing material costs and labor requirements.

At the baseline level, optimization may simply involve replacing as many elements in a standardized truss structure as possible with available reclaimed timber. This minimizes disruption to industry conventions while introducing reclaimed material.

The primary logistical challenge at this level lies in sorting, storing, and assigning the timber stock, as well as the joining of elements with varying cross sections

A moderate level of optimization involves adapting the structure itself—repositioning or adding members and joints to better match the material availability. While this increases the reuse potential and reduces waste, it also requires higher craftsmanship and tolerance management but remains compatible with current construction systems.

At the advanced level, optimization could entail designing entirely around the reclaimed material stock using robotic fabrication methods and generative algorithms. This would allow for maximized material use and highly specific structural geometries but would also require a paradigm shift in construction practice, digital planning, and fabrication infrastructure as seen in companies like Woodstock robotics and the research from ETH Zürich.

This thesis operates under the assumption that the optimization of the advanced level is not only plausible but the necessary advancement to fully utilize reclaimed material to the fullest. But will not pursue joint design or manufacturing. The selection and assignment of reclaimed elements to meet the structural and spatial requirements of a given design remains a central concern, regardless of the optimization level pursued.

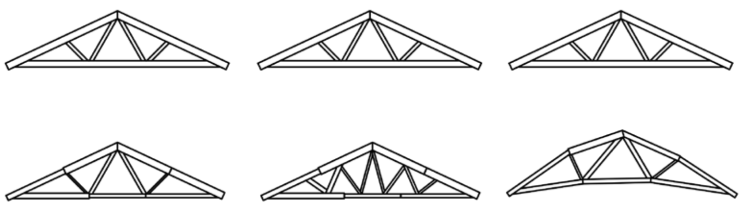


Figure 31: Diagram of the baseline, moderate and advanced levels of optimization, gradually increasing the impact on the design.

Algorithms

To develop the tool, it is necessary to understand the underlying processes of effective optimization in the material utilization of an existing stock of materials. To further probe into the specifics of tool development this chapter is an exploration of established algorithms that are commonly used for effectively limiting material waste, when transforming raw materials into products. Such a challenge is formally categorized as a packing problem, see figure 32, where the goal is to fit a set of items as efficiently as possible into a constrained space. In this context, the “items” are the reclaimed timber elements, and the “containers” are the structural members in the architectural design.

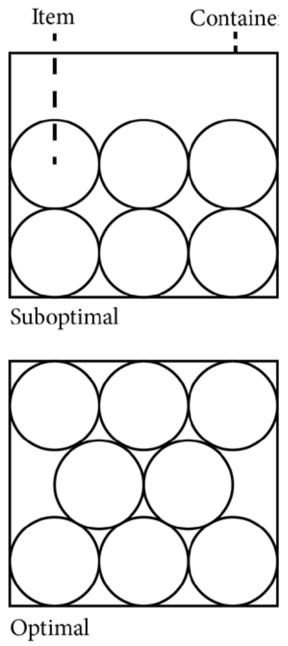


Figure 32: The packing problem.

From a computational perspective, this is an NP-hard (nondeterministic polynomial-time hard) problem, meaning there is no known algorithm capable of solving it efficiently for larger problem sizes (Johnson, 1973). A classic example of such a problem is the traveling salesman problem, as seen in figure 33, where the goal is to determine the shortest possible route visiting multiple cities exactly once. With a small number of cities, this problem remains relatively simple, but as the number of cities increases, the required computational time grows exponentially.

Depending on the intended application, this complexity can render the problem computationally impractical to solve directly, necessitating simplification. This thesis proposes to simplify the problem in two ways: first, by reducing the dimensional complexity of the geometry, and second, by initially employing simpler algorithms.

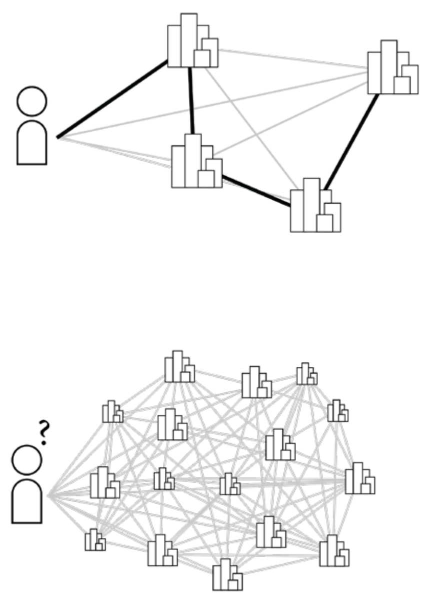


Figure 33: The Travelling Salesman problem.

Deducing the Algorithmic Problem

The bin packing problem can be divided into several specific sub-problems, often distinguished by the dimensions of the geometry or the characteristics of the containers and objects involved. In two-dimensional space, an example is the guillotine cutting problem, frequently encountered in industries such as glass, steel, and paper manufacturing. This problem aims to maximize the number of objects cut from a single container and is commonly referred to as the nesting problem. Reducing the problem further to one-dimension results in the cutting-stock problem, which focuses on efficiently cutting standardized pieces from stock material to minimize waste.

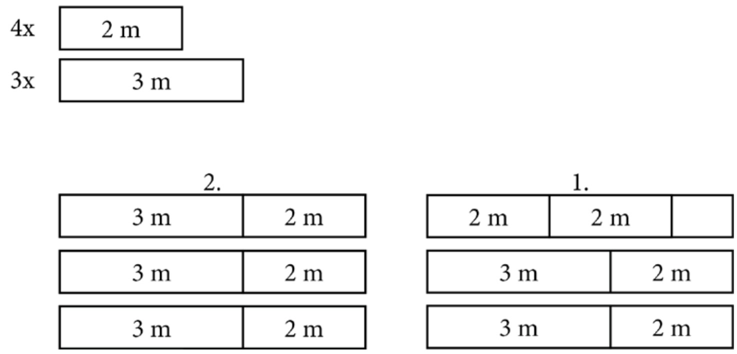


Figure 34: The cutting-stock problem.

In the cutting-stock problem, as seen in figure 34, the aim is to minimize leftover waste when cutting stock material to satisfy demand lengths. While traditional cutting-stock models emphasize length optimization, they often neglect volume efficiency and joint constraints, which are critical in timber structures. For instance, selecting a timber member solely based on minimal length waste may result in using unnecessarily large cross sections, thereby reducing the overall utility of the remaining stock. Therefore, this thesis proposes a multi-criteria matching algorithm that accounts for both cut-off minimization and volume utilization.

Heuristic Methods for Stock Assignment

To handle this problem within a feasible computational time, heuristic methods are adopted, meaning it is a practical method designed to find a sufficiently good solution rather than the best possible solution. A basic but effective example is the First-Fit Decreasing (FFD) algorithm, where supply elements are sorted by descending length and sequentially assigned to the first matching demand (Johnson, 1973).

The optimization problem defined in this thesis cannot be strictly classified as a bin-packing or cutting-stock problem, because the list of available containers is predetermined by a specific structure, and additional containers cannot be introduced. Moreover, the items to be fitted into these containers can be divided into multiple pieces, potentially leading to solutions with better material utilization and reduced waste.

Depending on the data provided, the first-fit-decreasing algorithm can sometimes result in substantial waste. Consider the illustrated example in figure 35.

While this solution successfully meets the demands, a more optimal solution can be achieved if the algorithm considers leftover lengths. For instance, if Demand 1 uses half of Stock 1, Demand 2 can utilize the remaining half.

This solution fulfills all demands using only two stock elements. However, since Stock 2 precedes Stock 3, the algorithm selects the longer stock, resulting in substantial waste. To further optimize the solution, the algorithm must assess each stock with a sufficient length and pick the one with the least waste. This insight informs the algorithm used in this thesis, which seeks to select the stock element with the lowest residual waste across all eligible matches with the demands.

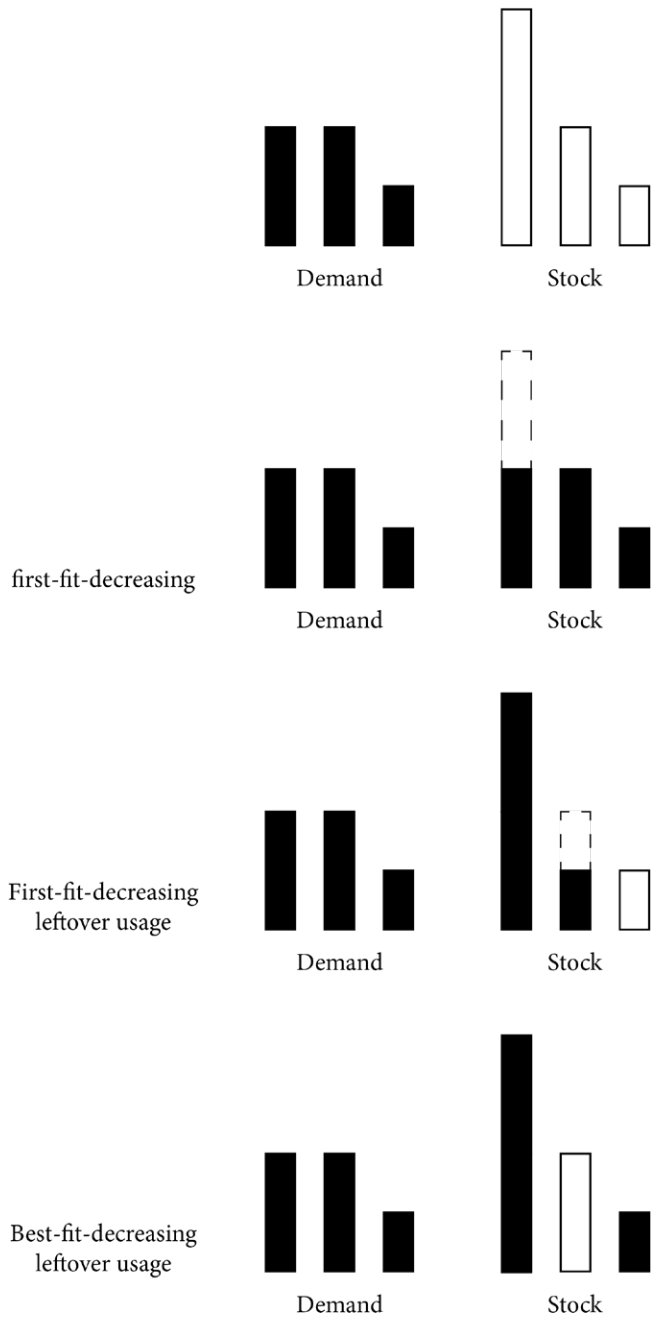


Figure 35: Algorithms for solving the cutting-stock problem in relation to the problem of the thesis.

Meta-heuristic Algorithms for Adaptive Design

While heuristic algorithms such as First-Fit Decreasing provide efficient methods for matching reclaimed elements to predefined structural members, they are limited by fixed values. However, when the structure itself becomes flexible—capable of adapting its geometric shape in response to available material—more advanced optimization strategies are required.

In such cases, meta-heuristic algorithms become valuable tools. Unlike heuristics, which follow deterministic rules, meta-heuristics enable a broader and often stochastic search across the design space. Techniques such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) do not rely on predefined paths; instead, they evolve candidate solutions over time, balancing exploration and exploitation to navigate toward global optima (Gendreau & Potvin, 2010).

This is particularly relevant in architectural scenarios where reclaimed timber stocks impose constraints on both cross-section, length and material strength. By iteratively modifying the form of the structure, meta-heuristics can optimize for performance (e.g., material waste or weight) while remaining within the bounds of available stock.

Here, the typical sizing optimization is reinterpreted. Since material dimensions are fixed, optimization is no longer about minimizing cross-sectional area but about discrete assignment: selecting the right piece for the right structural role. The design challenge is thus multi-faceted, and not just of efficient packing, but also of achieving structural, spatial, and tectonic coherence from finite means.

The challenge is thus approached in two layers as illustrated in figure 36:

The core algorithmic strategy for solving this challenge, is the heuristic assignment of reclaimed timber elements to a designed structure. This algorithm purely compares numbers thus it is not effected by geometry.

The second algorithmic strategy is the meta-heuristic optimization of the structural input, iteratively changing the geometrical shape based on architectural design constraints, providing a strategy that consolidates quantitative performance with qualitative architectural design considerations.

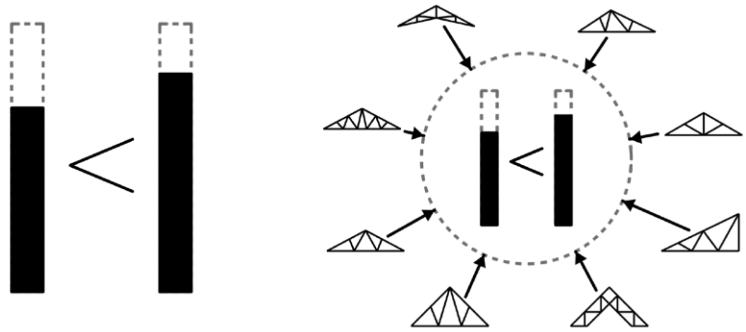


Figure 36: Heuristic strategy of quickly finding the best volumetric utilization and the meta-heuristic strategy of finding the best structure.

This parallel approach—material-aware and structure-adaptive—enables a more resilient and circular workflow, where reclaimed timber is not merely accommodated but actively shapes the architectural and structural outcomes. The methodology in its entirety is illustrated in figure 37, highlighting this parallel approach as an iterative feedback loop of development informing design, and design informing development.

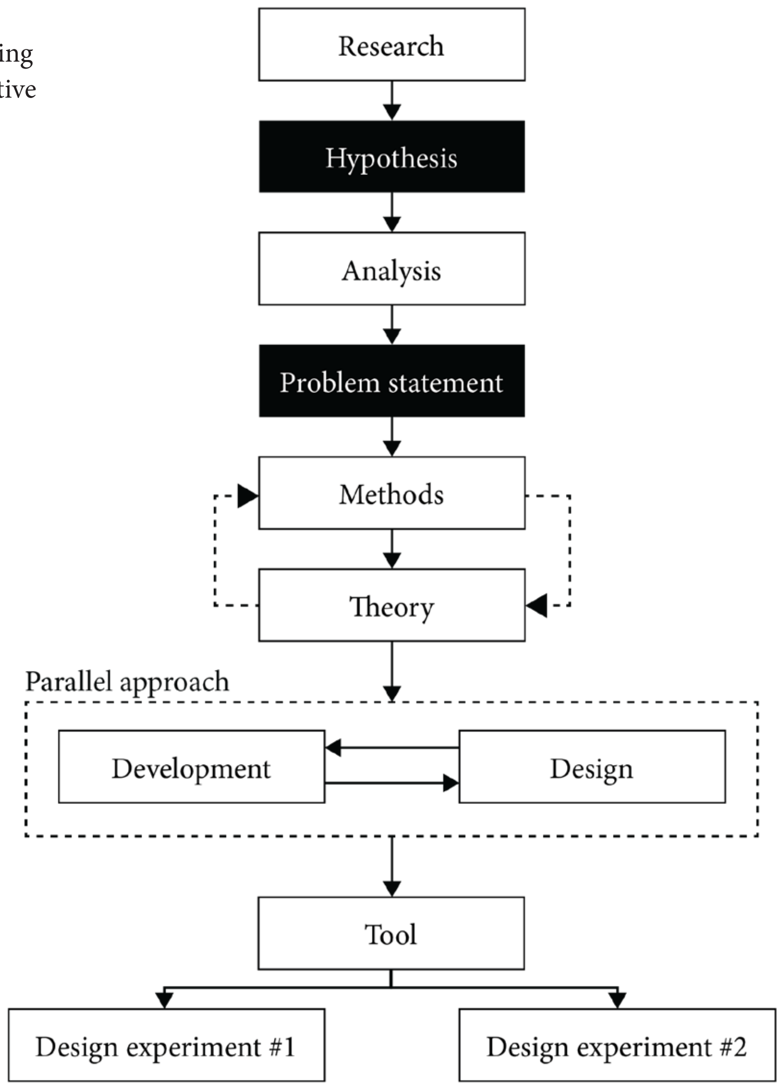


Figure 37: Diagrammatized methodology

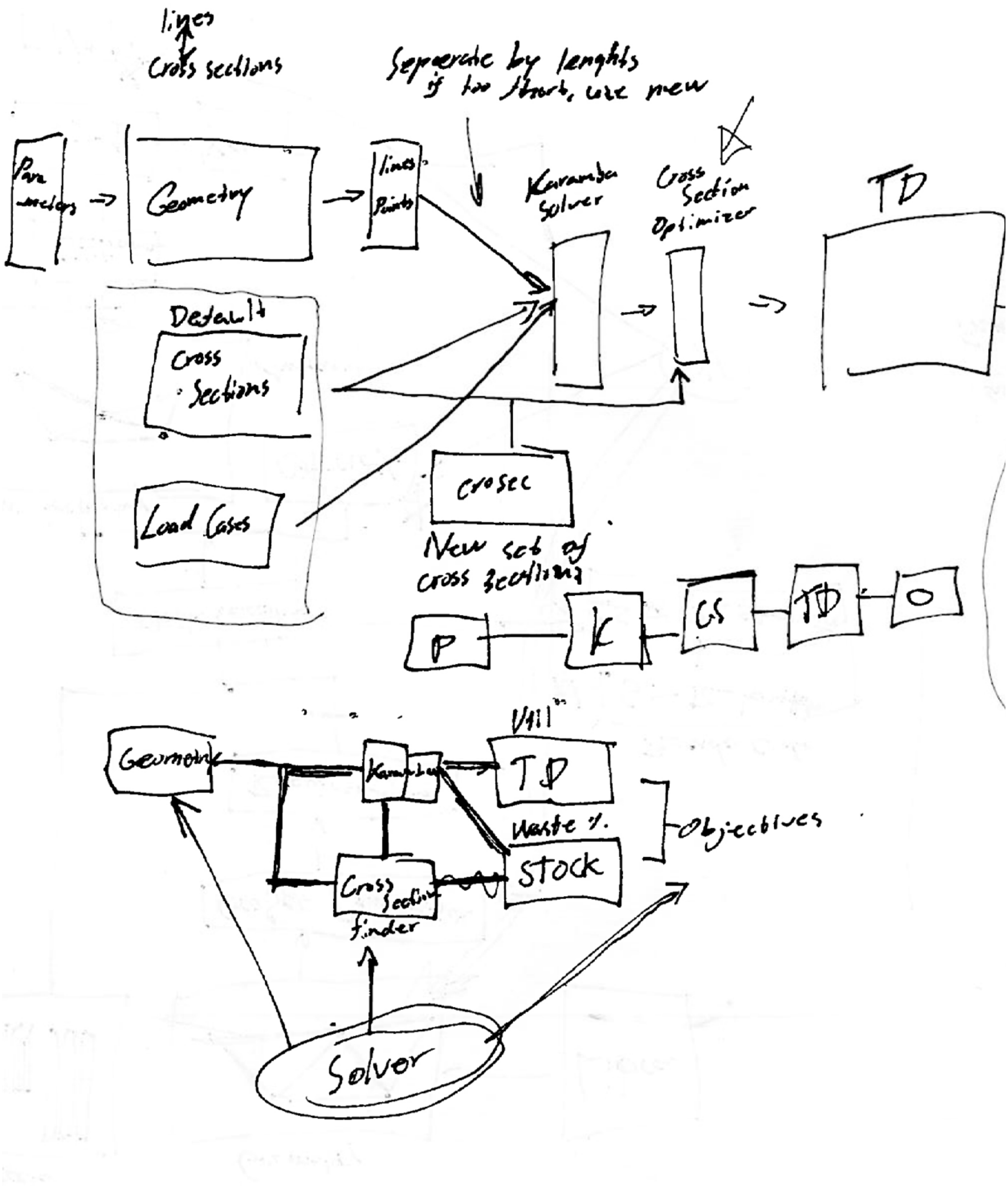


Figure 38: Sketching of tool components.

Tool Development

This chapter presents the algorithmic iterations developed during the creation of a tool designed to allocate reclaimed timber to a reference structure. The earliest results were generated using methods similar to those discussed in the research papers reviewed in Research on Form Follows Availability, serving to establish a baseline model. This baseline was subsequently refined through iterative processes to accommodate both the available timber stock and a structural system composed of discrete elements, as outlined in Structures of Discrete Elements.

Managing the complexity of sorting and assigning variable timber elements requires the use of Computational Design, particularly Algorithmic Design. Tools such as Rhino Grasshopper, Karamba3D, and custom C#/Python scripts form the computational backbone of the development. These are used for: Structural analysis and performance optimization, Material matching and allocation and Multi-objective form exploration.

Rhinoceros 3D, known as Rhino, is a CAD program based on the non-uniform rational B-spline (NURBS) mathematical model (Rhino3d, 2025). Grasshopper is a visual programmed language that runs within Rhino, and is primarily used to build generative algorithms (Rhino3d, 2025). Karamba3D is a plugin for Grasshopper and is used for structural analysis by Finite Element Analysis (FEA) (Karamba3D, n.d.). Using these programs in conjunction allows the user to visually and iteratively generate designs and simultaneously perform structural optimization. C# scripting is used within Grasshopper with the Karamba3D library.

Matching a Reclaimed Element to a Structure

To develop and test the matching algorithm, a standard Fink truss was selected as the reference structure. The truss was structurally analysed in Karamba3D using the "Cross Section Optimizer" component. While Karamba3D evaluates elements according to Eurocode 3—intended for steel structures—this results in an inaccurate representation of timber behaviour (Preisinger, 2013;CEN, 2005). However, for the purposes of algorithm development, the structural output was sufficient, as the primary focus was on the matching logic rather than structural performance accuracy.

The initial algorithmic iterations employed a best-fit decreasing (BFD) strategy. The first iteration aimed to minimize cut-off waste when assigning reclaimed elements to the structural demand. The second iteration retained the same assignment logic but shifted the optimization criterion toward maximizing volumetric utilization.

This distinction is illustrated through a comparison in figure 39: consider two reclaimed elements, one with a small cross-section and the other with a larger cross-section. While the larger piece may be longer and theoretically more flexible in use, its allocation could result in a higher volume of unused material. Prioritizing the smaller element may reduce waste even if it leads to more offcuts in terms of length.

These iterations ask a key question in material optimization: what defines the value of reclaimed elements? The first iteration implies that length is the deciding metric, which aligns with market logic, as longer timber pieces are typically more expensive and scarcer. The second iteration expands this evaluation by also considering cross-sectional dimensions, avoiding the inefficient allocation of oversized members to elements that require minimal structural capacity.

As further discussed in Deducing the Algorithmic Problem, volumetric utilization is adopted as the principal metric for evaluating material efficiency in this study.

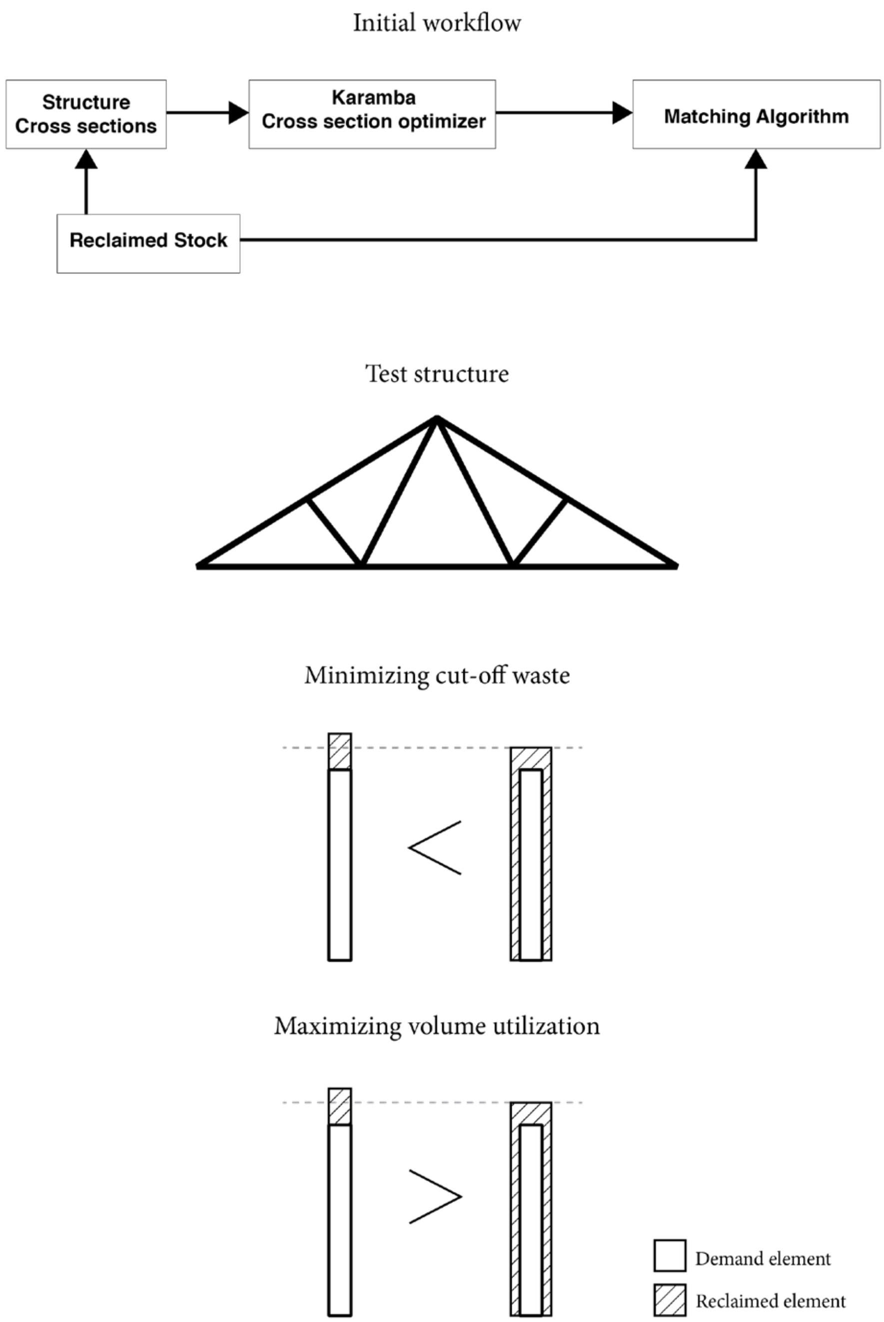


Figure 39: Inital setup for developing the tool including just the core components, a simple structure and simple matching algorithms.

Optimizing Material Efficiency

With volumetric utilization established as the optimization metric, and the objective of assigning reclaimed elements to a predefined structure, the fundamental logic of the tool was in place. To enhance material efficiency, were heuristic strategies from the Algorithms chapter applied. The chapter Heuristic Methods for Stock Assignment presents a simplified example of the algorithm needed to address this challenge. However, once a real-world reclaimed stock and a designed Fink truss were introduced, it became evident that the initially assumed algorithm needed to be more advanced.

The frames from the mink farm used in this thesis each consist of six elements, encompassing three cross-sections and four distinct lengths. Each of these variables increases the algorithm's complexity by introducing additional constraints. An early improvement to the initial algorithm involved saving the leftover length from a used reclaimed element as a new, reclaimed stock element, effectively allowing a single reclaimed element to be used multiple times.

While this adjustment improved efficiency, dynamically generating new stock elements mid-process somewhat contradicts the purpose of an algorithm meant to adapt a fixed reclaimed stock to a given structure.
Once demands have been assigned, they fall outside the scope of remaining material, increasing the risk of inefficiencies or excess waste, particularly with larger stocks.

To address this, the algorithm was restructured to evaluate multiple packing configurations holistically, comparing different ways of assigning demand elements to reclaimed stock. This process is illustrated in figure 40, where a selected demand element is allocated to both reclaimed stock element 1 and reclaimed stock element 2. The algorithm then packs subsequent demands into different configurations, tracking the volumetric utilization of each one. In this example, configuration 2D results in the least waste and is therefore selected. The corresponding demand and reclaimed stock elements are then removed from the working lists, and the algorithm proceeds to the next unassigned demands.

The diagram also illustrates the situations where the reclaimed stock elements are structurally insufficient, resulting in the algorithm skipping the demand stock element with a large cross section for reclaimed stock element 1. Conversely, for reclaimed stock slement 2, demand stock elements requiring a significantly smaller cross-section are bypassed, as assigning them would result in excessive material use.

These decisions are controlled by adjustable threshold ratios, allowing the user to define how much smaller a demand stock element's cross-section can be relative to the reclaimed stock elements. This flexibility ensures that the allocation logic can be adapted to the specific characteristics and variability of the available stock.

The significant change in the structure of the algorithm, changes the definition from a heuristic method to a metaheuristic method. This advancement was not initially planned for the allocation of reclaimed elements to a designed structure, but provides more optimal results. The change also increases computational time exponentially. Therefore, depending on the application, the algorithm can be separated into two functions, heuristic and metaheuristic, depending on the structural complexity.

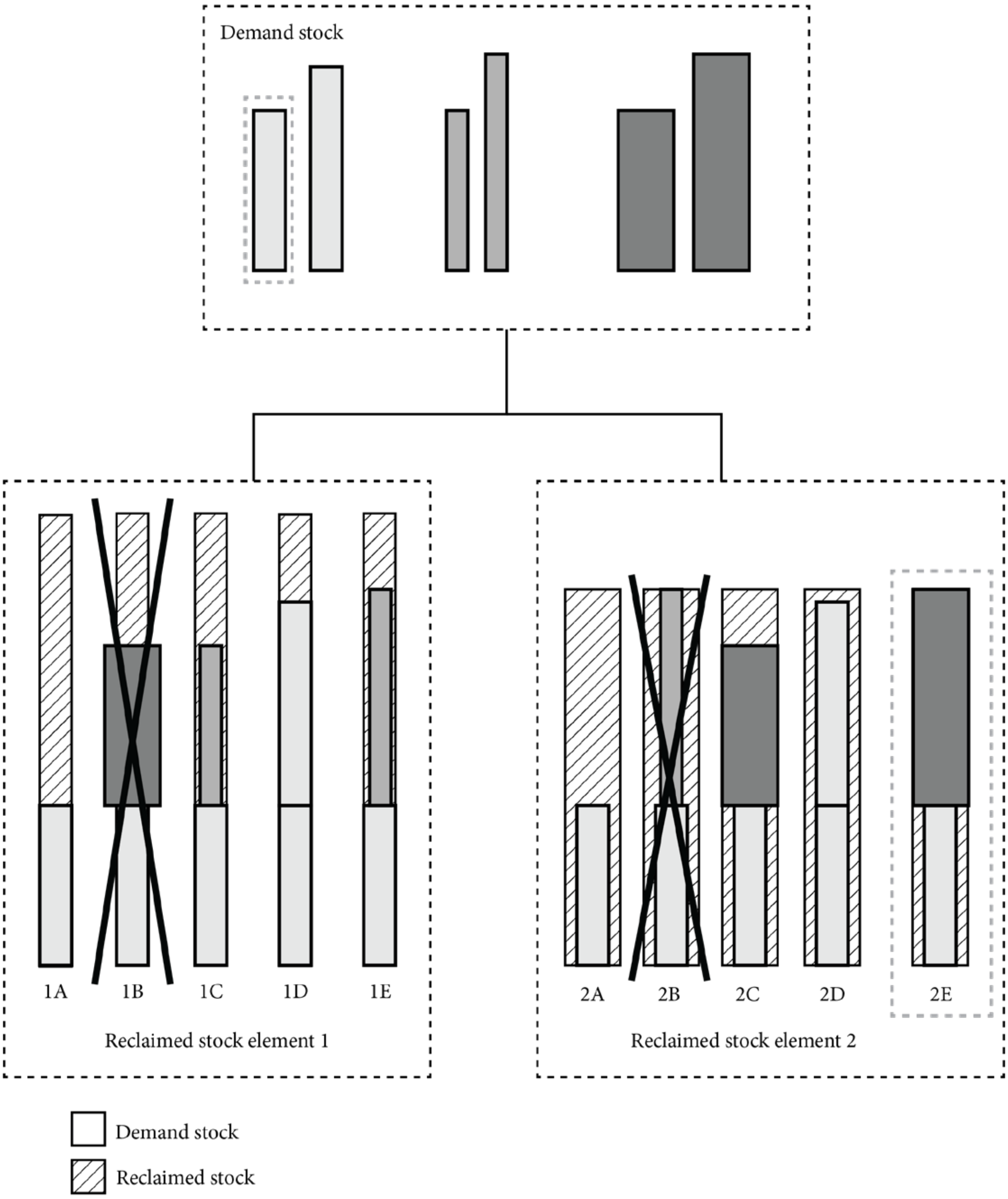


Figure 40: Meta-heuristic strategy of testing a demand stock against two different reclaimed stock elements in different packing arrangements. First demand element in the stock is packed with subsequent demand elements in each available reclaimed stock element, picking the arrangement with least volumetric material waste.

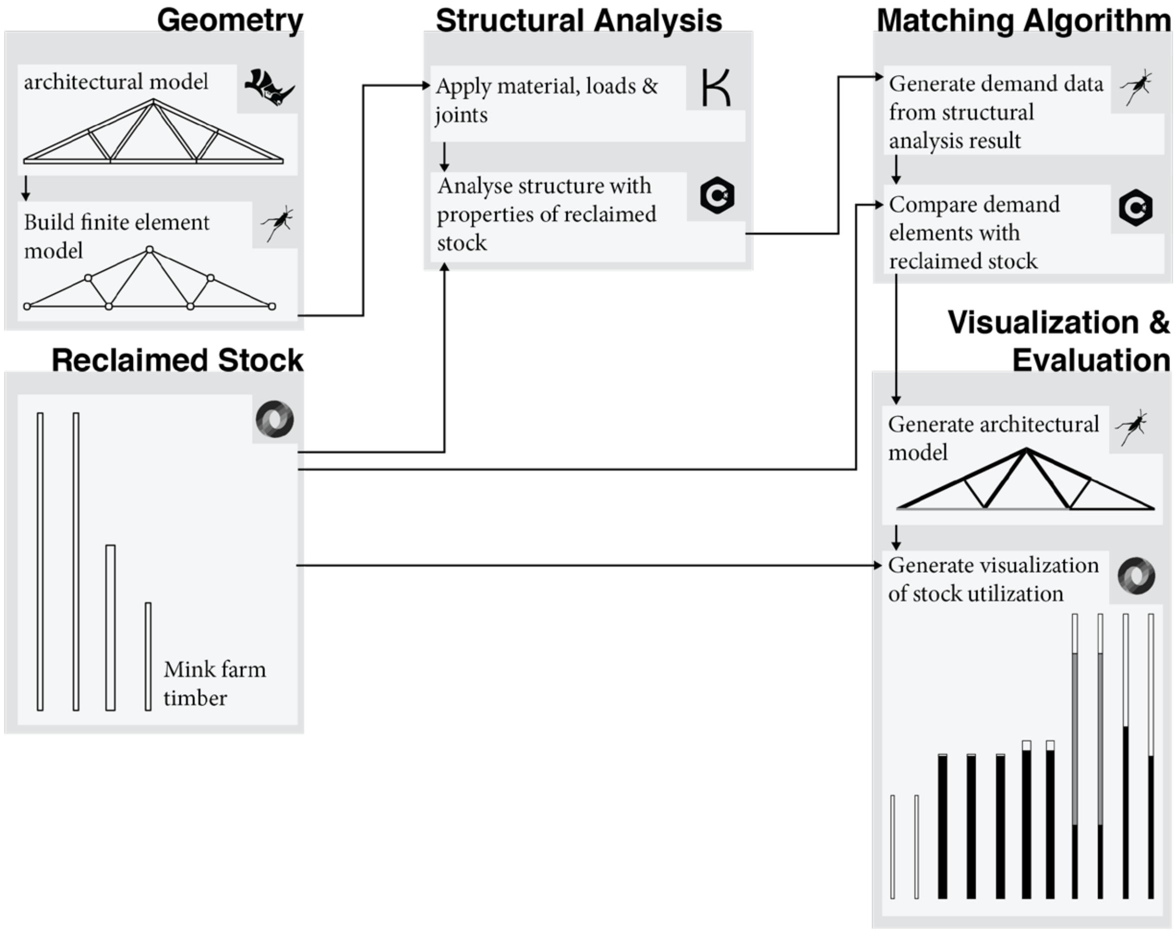


Figure 41: Overview of the tool, illustrating the role of each component and their associated software.

Tool Presentation

This chapter details the computational tool developed to facilitate designing with reclaimed timber, a central element of this thesis's exploration into a stock-constrained form-finding process. The tool is systematically outlined by presenting each component's function, specifying its inputs, core processes, and outputs. Through this, the chapter intends to demonstrate how the tool relates material availability with architectural form, thereby substantiating the potential for reclaimed stock to actively shape design.

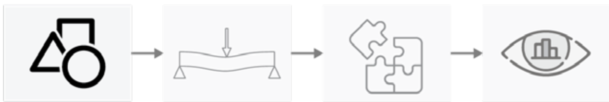
I. The geometry itself has an architectural representation, showing spatial and material qualities, of which a finite element of lines, points and intersections needs to be built
II. The structural analysis is conducted with Karamba3D, which calculates the sectional forces for a beam optimization algorithm, following Eurocode 5, to search for any cross sections of the reclaimed stock that may be utilized.

III. A matching algorithm compares the dimensions and material of the structurally optimized model, to the dimensions and material of a stock of reclaimed elements and picks the best candidates that result in the least amount of waste wood.

IV. The architectural model is rebuilt using the result of the matching algorithm, as well as a visualization of which stock element was used for which demand element.

V. Evaluation of the final model is conducted by use of selected performance parameters. Performance as well as the geometrical metadata from the model is saved to a JSON file format for documentation.

Geometry & Reclaimed Stock



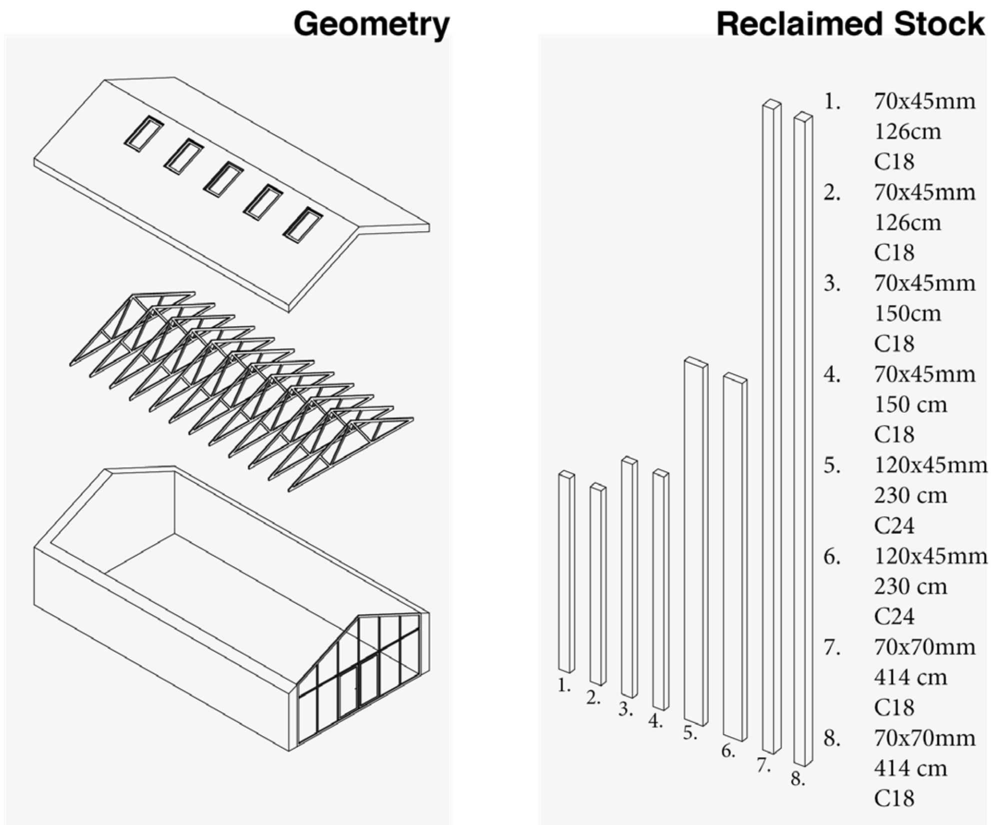


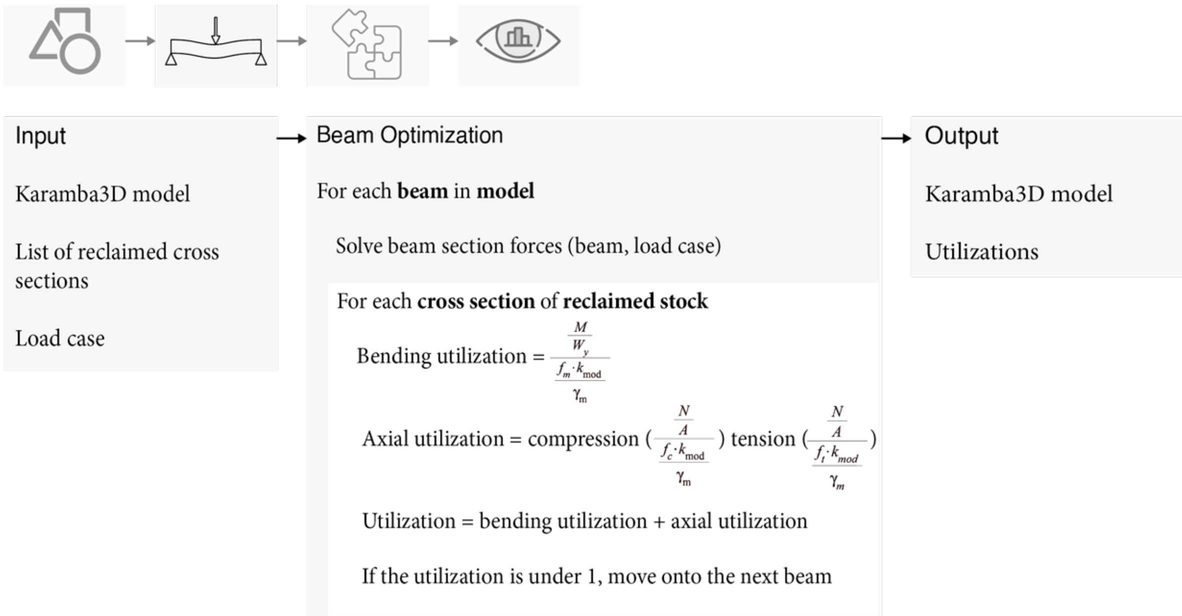
Figure 42: The first components include preparing an architecturally drawn timber structure for FE-analysis and provoding a stock of available reclaimed timber elements.

During testing and development of the algorithm, a regular fink truss was used. This structure represents a typical roof structure in residential housing, of which, construction wood is typically used. In this scenario, the span of the structure is 7,5 meter, with a standard spacing of 1,2 meters.

In order to test the material utilization of stock elements, a relatively well documented stock of elements had to be used. During development of the algorithm, the case of a mink farm was used as mentioned in Reclaiming Timber.

As methods of non-destructive testing are still under evaluation, the thesis will take safety precautions, such as the degradation of strength classes. The algorithm will therefore assume a strength class of C16 for every reclaimed timber element in the mink farm.

Structural Analysis



In order to evaluate which elements in the structure can be replaced with reclaimed elements, a reference structure must be analyzed using cross sections and strength classes of the reclaimed stock. To avoid the tedious process of manually evaluating each element and which cross section can be used for them, an algorithm can quickly find the candidates.

The algorithm requires three inputs: a Karamba3D structural model, a list of available reclaimed cross sections with their strength classes, and the selected load cases. Using these inputs, the algorithm performs iterative structural calculations according to Eurocode 5: Design of timber structures (CEN, 2004a).

As Karamba3D calculates in accordance with Eurocode 3: Design of steel structures (CEN, 2005), a script had to be written for iteratively comparing each element with each cross section of the reclaimed stock, utilizing the Karamba3D library for evaluating section forces (Preisinger, 2013). The full script can be found in Appendix A.

The process begins with analyzing the reference model to determine internal forces in each element. The algorithm then evaluates each potential reclaimed cross section against these forces, calculating structural utilization ratios for critical stress conditions. This is done by comparing the sectional forces calculated from the FE-analysis done by Karamba3D and comparing it to the strength characteristics of the reclaimed timber elements as specified in Appendix B.

Through multiple iterations, the algorithm optimizes the assignment of cross sections to elements, continuing until it identifies a 'bare minimum' structure where each element uses the smallest appropriate reclaimed cross section. This computational approach efficiently matches available reclaimed timber resources to structural needs while ensuring compliance with design standards.

The structural evaluation conducted in this thesis, is not intended to be final and verifiable, but simply to closely approximate the possibility of reusing the reclaimed timber. If the structural analysis is roughly within the range of a verifiable result, then that is enough, as the intended use of the tool is during the design phase.

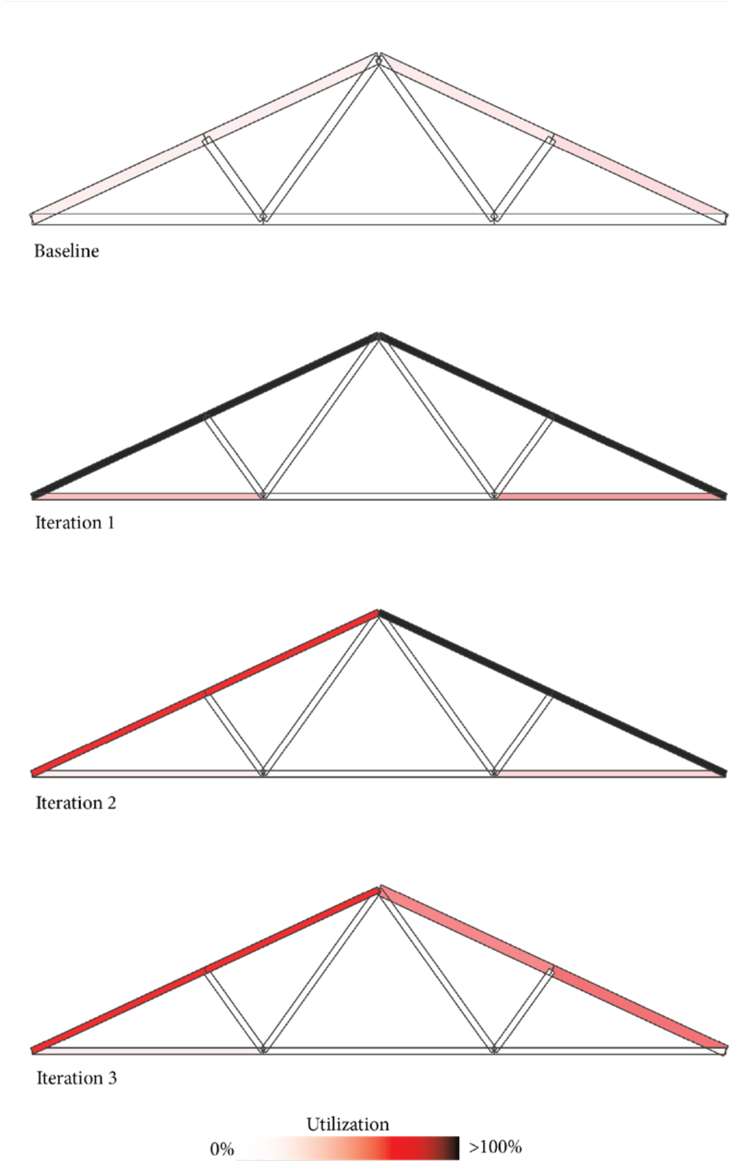
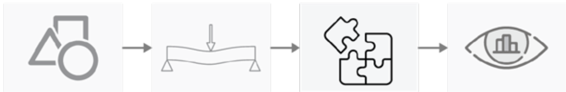


Figure 43: The cross section optimization algorithm iteratively replaces structurally overutilized elements with a stronger cross section. The structural analysis needs to be iterative, as the forces transfer in different ways each time a cross section is replaced. The algorithm is done once every element is below 100% utilization, in this case needing three iterations.

Matching Algorithm



Input

Demand structure
- ID
- Length
- Height
- Width
- Class

Reclaimed stock
- ID
- Length
- Height
- Width
- Class

Matching Algorithm

For each **demandElement** by descending length:

Compare each **reclaimedElement** with the **demandElement** and create a list of each eligible element:

A reclaimedElement is eligible if its long enough, has the same strength class and a cross section between 100% and 140% of the demandElement

For each **eligibleElement** in **reclaimed stock:**

Try to to pack more demands into the eligibleElement in different configurations

A demand is eligible for packing, if its cross section is between 80% and 100% of the eligibleElement cross section

Pick the configuration with the least leftover length and move onto the next demandElement. Used demand and stock elements are removed from the lists before next pass.

If no match is found, upgrade the strength class and try again, if ultimately there is no match, a new timber element must be used.

Output

Reclaimed matches
- StockID
- DemandIDs
- Leftover length
- Length
- Height
- Width
- Class

New timber matches
- StockID
- DemandIDs
- Leftover length
- Length
- Height
- Width
- Class

The matching algorithm compares demand structure data with reclaimed stock inventory to optimize element reuse. Taking inputs from a reference structure and available reclaimed components (from a mink farm frame), it identifies which reclaimed elements can satisfy structural requirements while minimizing waste.

The algorithm works by methodically comparing dimensional properties of each demand element against the available stock. It evaluates not only whether a reclaimed element can be used but also if multiple demand elements might fit within a single reclaimed component.

Through iterative calculations, it determines optimal assignment scenarios. It does this by comparing the volumetric utilization of each reclaimed demand.

This evaluation is to avoid the assignment of larger, and therefore stronger, cross sections to demands with smaller cross sections.

Figure 44 illustrates multiple valid solutions, with iteration 4 selected as optimal based on these efficiency criteria. While iteration 3 also has a low amount of waste wood, the solution is significantly worse, as two of the assigned demands are matched with stock elements that have a larger cross section than necessary. The full script can be found in Appendix A.

By maximising the volumetric utilization of the used reclaimed stock elements, the algorithm achieves precise matching between demand requirements and available reclaimed stock. The algorithm thus serves as a design-phase tool that approximates reuse potential based on existing materials, and provides a method for incorporating them into new structural designs while complying with necessary performance requirements.

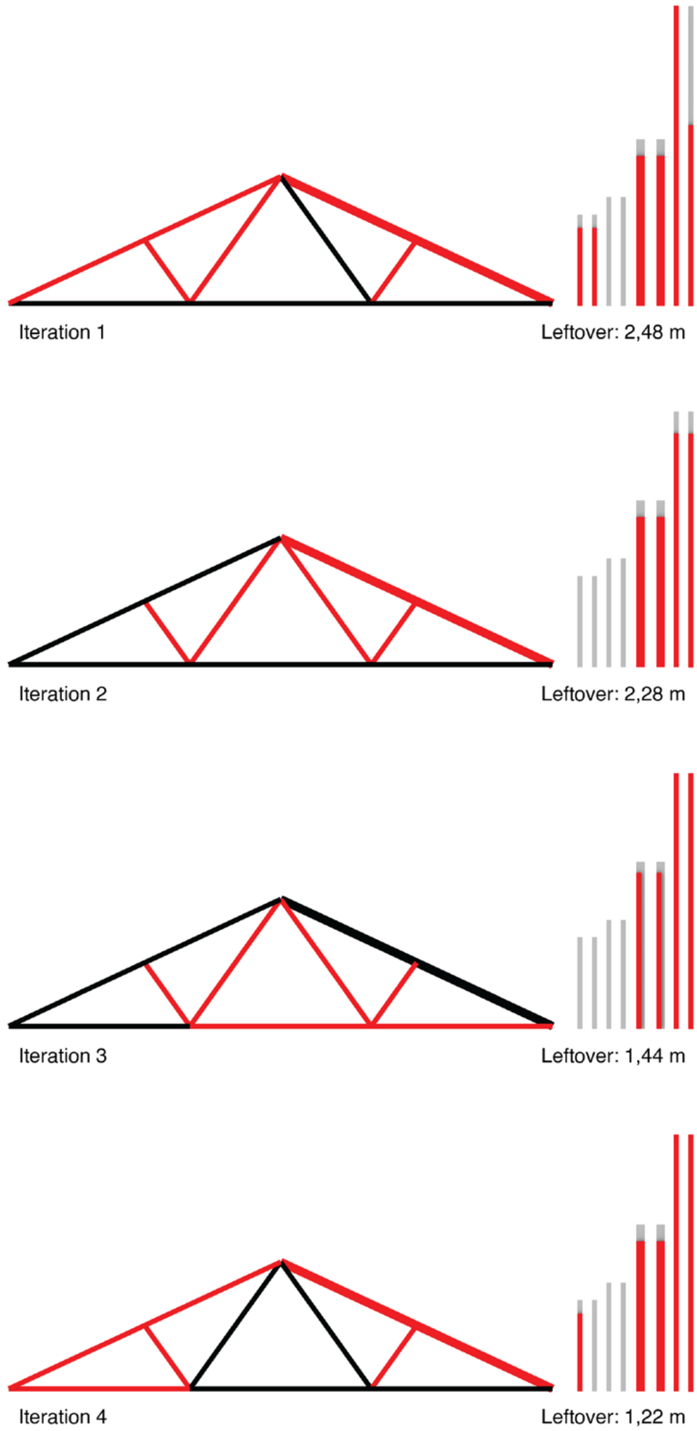
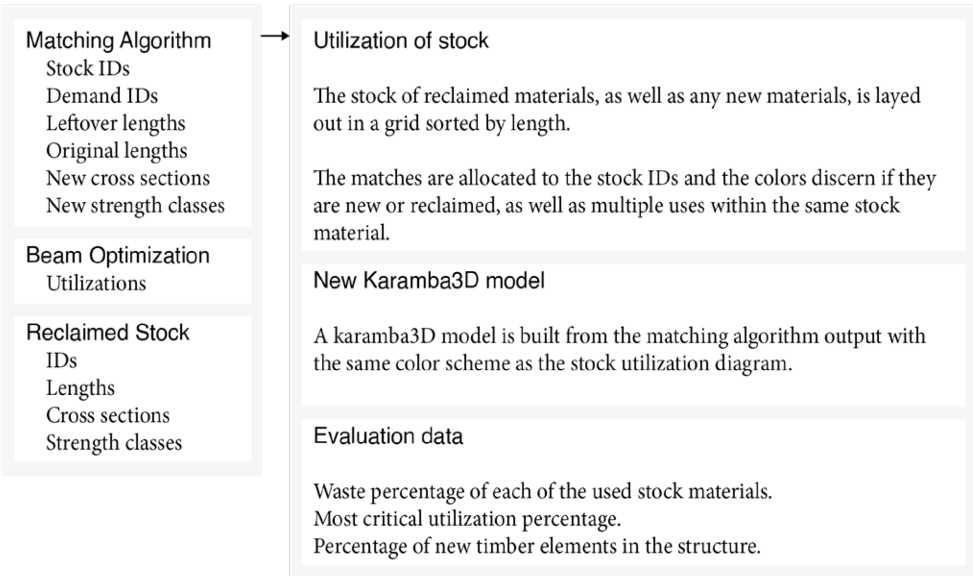


Figure 44: The matching algorithm uses the meta-heuristic strategy of packing multiple demand elements in different configurations in different reclaimed timber elements. In this case, comparing the cross sections, found by the cross section optimizer, and the lengths of a fink truss frame to the reclaimed timber elements of a single mink farm frame.

Visualization



The visualization of the output of the algorithm is grouped into three categories. The first is a visualization of the material utilization of the stock, this can help discern if there is a large amount of unused stock elements. In figure 45, it can be seen that the example structure can only match demands 4 and 7 to the two types of 70x45 mm elements, as every other demand is too long to use these stock elements. To better utilize the stock, the geometry in figure xx has introduced more segments in the truss, shortening each element.

The second category is the rebuilding of a Karamba3D model using the data output from the matching algorithm. This produces an architectural model in which the user can see the new elements and their cross sections. The elements are initially color coded in the same manner as the stock utilization diagram, so one can see where each element went in the list of stock elements.

The third category is the data relevant to such an optimization process. It tells the user in percentage, how much of the structure has been replaced with reclaimed timber, the average waste, or cut-off, from the stock elements, as well as the most critical structural utilization in the structure. Each of these values help the user compare and evaluate different results, for example, a low structural utilization value lets the user know that the structure can carry more load without needing to use more new timber.

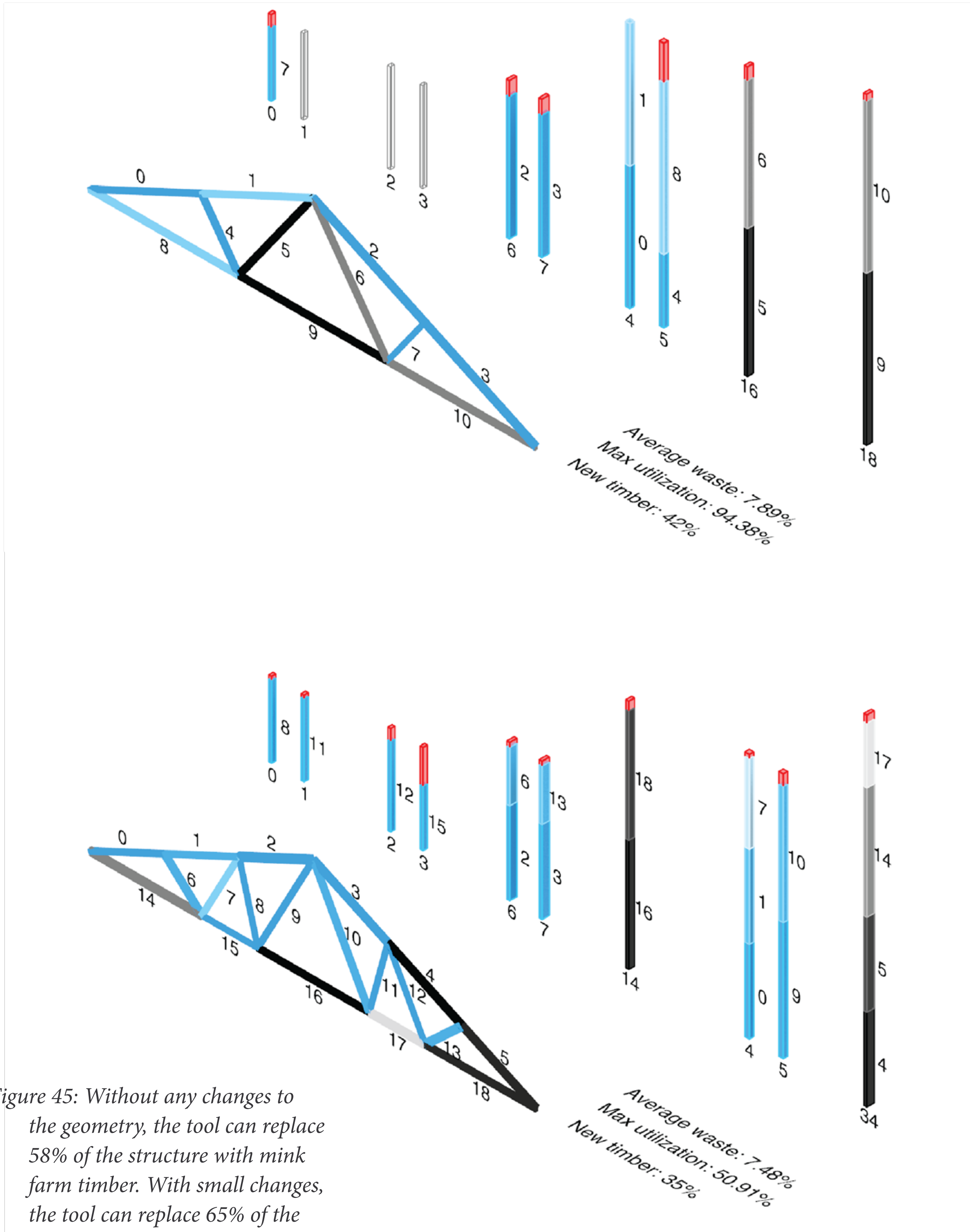


Figure 45: Without any changes to the geometry, the tool can replace 58% of the structure with mink farm timber. With small changes, the tool can replace 65% of the structure with mink farm timber.

Evaluation and Optimization

The structural analysis and matching algorithm aim to ensure that the structural performance meets optimal criteria for the given loads. This evaluation is conducted by The Tool, with the option for the designer to manually fine-tune aspects of the form to either improve structural efficiency or increase the use of reclaimed timber.

Further processing is not strictly necessary for the tool to guarantee structural soundness. However, if the form remains variable and additional subjective or contextual factors come into play, the complexity of the design space increases. This complexity grows as more parameters or performance goals are introduced—such as daylight availability, material usage and waste, total construction weight, or even estimated fabrication and assembly time based on the number of joints.

To navigate this expanding design domain, an optimization engine is required. For this thesis, Wallacei was selected. Wallacei is an evolutionary multi-objective optimization and analytics engine for Grasshopper. It was chosen because it supports complex, multi-objective design processes, aligning well with the computational framework of this thesis. Rather than producing a single optimal solution, Wallacei can generate and evaluate multiple solutions.

The number of outputs can be configured based on the generation size (number of design variations per cycle) and the number of generations (iterations of refinement).

In Wallacei, parameters, also known as genes, drive the geometry and form of the structure. These must be defined parametrically in the model, allowing Wallacei to vary them within a given range. The objectives, or performance metrics, are the outputs that Wallacei seeks to either maximize or minimize. These can include external simulations (e.g., daylight analysis) or internal performance data from the structural model.

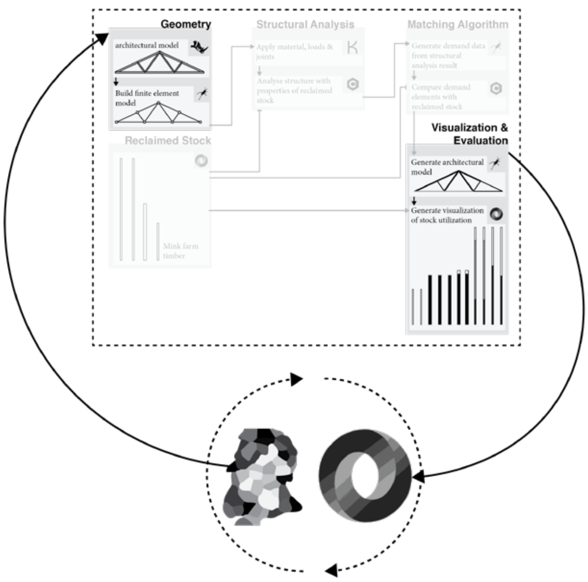
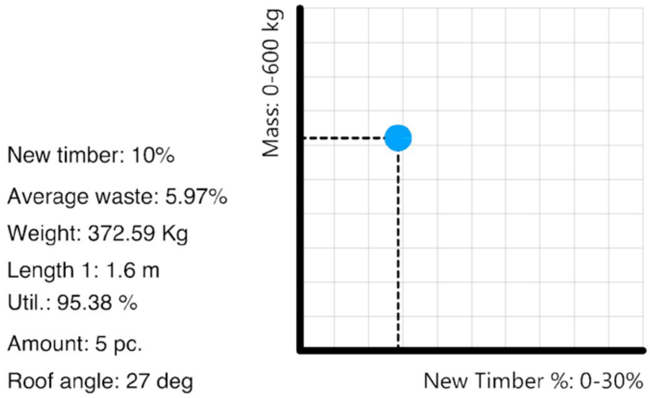
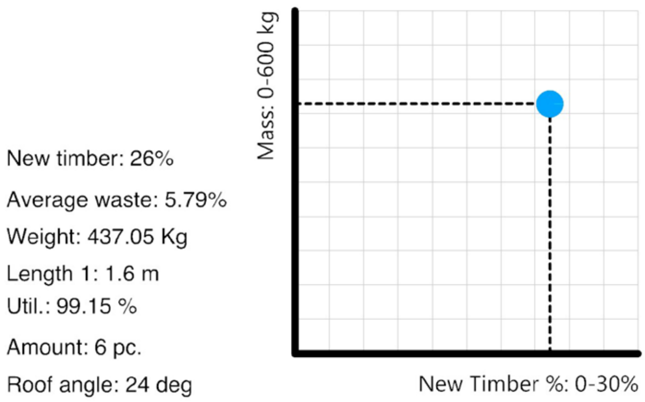


Figure 46: Wallacei iteratively changes the geometry in order to approximate the best performing structure, this data is saved by JSON, allowing each iteration to be recorded and reinstated.

The evaluation is based on both the visualizations presented in the previous chapter and selected numerical data outputs. Wallacei allows two objectives to be plotted in an XY graph, see figure 47, highlighting trade-offs and helping to visualize which solutions best satisfy the top-ranking performance criteria.

For both the evaluation plots example given here and the upcoming Design Studies, two key objectives have been selected: total weight of the structure and the percentage of new (non-reclaimed) timber used.





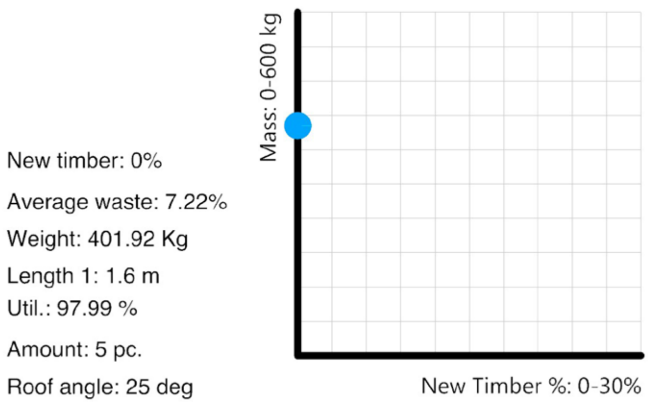


Figure 47: The results compared in relation to mass and the percentage of new timber, these are essential for minimizing material use and maximizing the utilization of reclaimed timber.

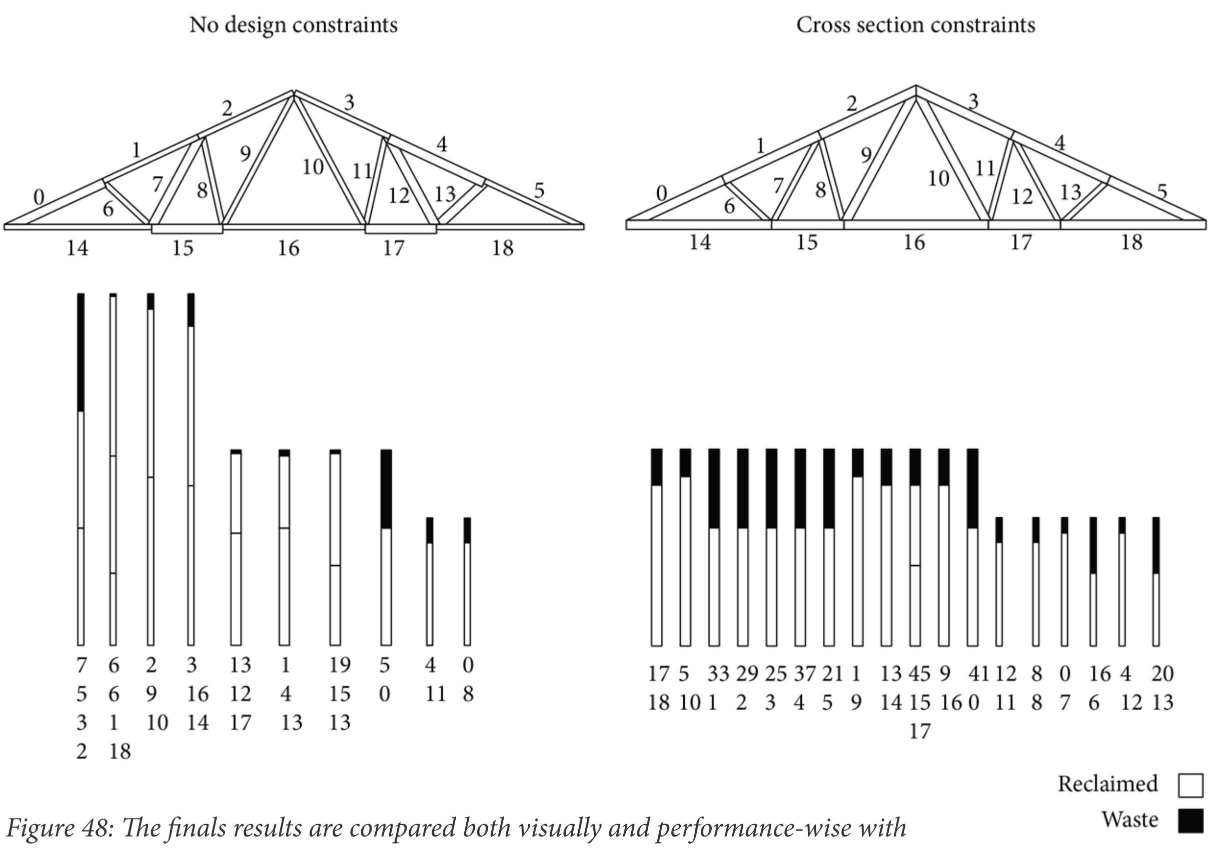


Figure 48: The finals results are compared both visually and performance-wise with the use of visualizations and material efficiency.

Since architectural expression and aesthetics cannot yet be quantitatively measured, Wallacei allows the designer to select solutions that are optimized according to chosen parameters, while also retaining the freedom to make qualitative, architectural judgments. This enables a balance between quantitative optimization and design intent. In the example of the fink truss, visualizations of different iterations informed possible design constraints introduced to the tool as can be seen in figure 48.

An initial visualization of the baseline structure, before tool implementation, gives a visual reference for the changes introduced by both the matching algorithm and Wallacei.

The structure was chosen, as it is a regular structure for residential homes and follows construction standards that contractors are accustomed to, thus functioning as a control.

The second visualization is the result of giving Wallacei control over the geometrical properties of the fink truss. Iterating over different roof angles and number of elements in order to optimize the amount of reclaimed timber used in the structure. This iteration results in just 6,6% of cut-off waste.

The third visualization is the result of introducing design constraints to the tool. Rather than freely picking cross sections and elements in the pursuit of less material waste, it was constrained to only using specific cross sections for top chord, web members and bottom chord. This constraint leads to a form more aligned with the initial structure by maintaining symmetry. This design constraint also leads to the cut-off reaching 27%, significantly more than the result with no design constraints.

As this example illustrates, when the tool is applied within such a design scenario, it is crucial to first define the design priorities. A clear hierarchy of objectives helps guide the optimization process. While it is possible to include a broad set of performance goals, doing so without prioritization can lead to a blurred design space, making it more difficult to identify a compelling final solution.

Documentation

The evaluation data as well as the set parameters for a given solution is saved to a JSON file format for documentation. Thus by saving the Rhino Grasshopper modelling file and said JSON file, one can recreate the total model to locate the position of timber elements and their cross-sections in the future when the structure gets deconstructed. This eases the process of reusing structural elements in new constructions or adding it to a stock, making the structure a functional safe sink in the context of metabolism as mentioned in the “Safe Sink” chapter.

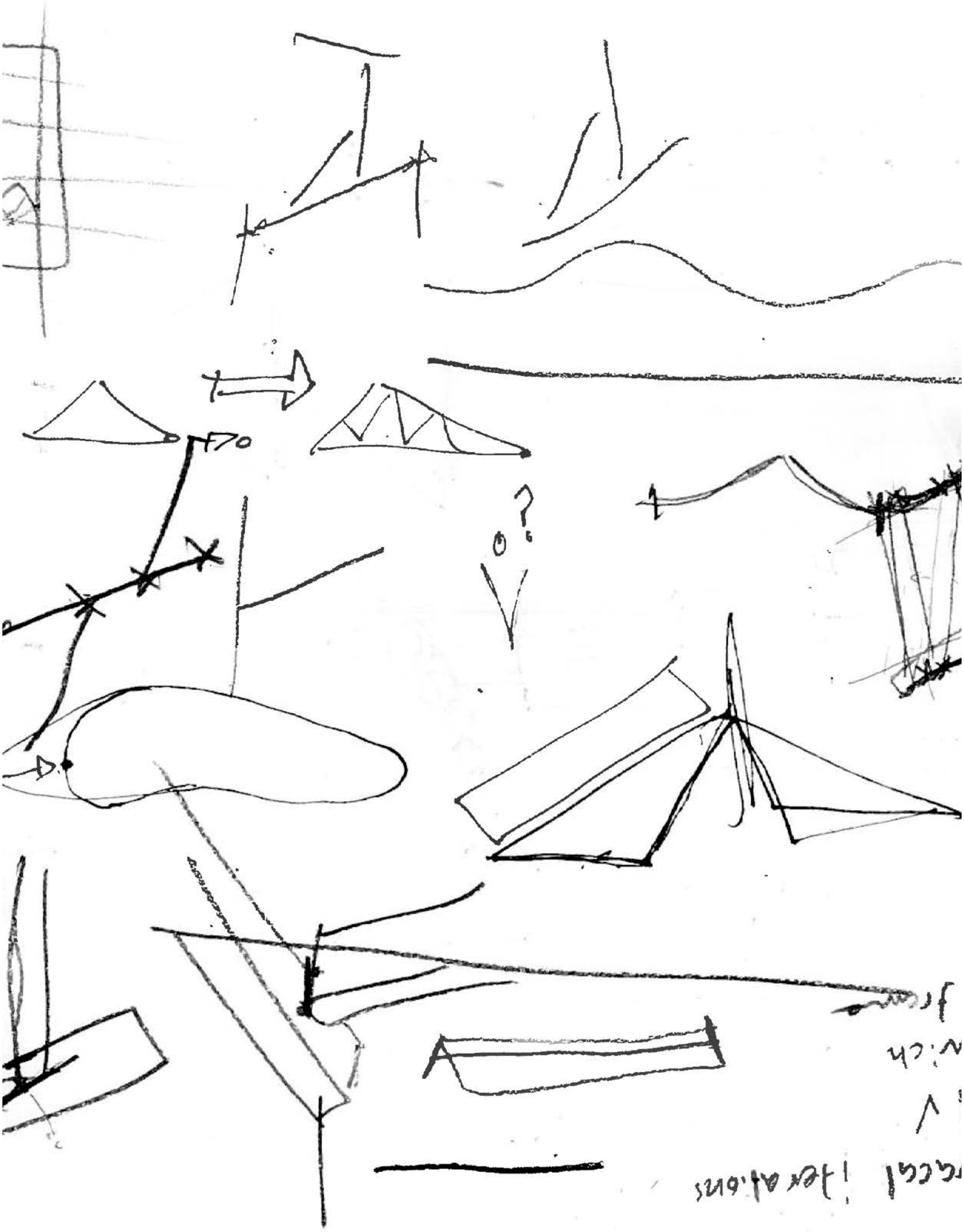


Figure 49: Sketches

Re-Design

This chapter investigates how the tool performs when placed within the workflow of an architectural design process. While the previous experiments focused primarily on structural systems and material logic, this phase tests the tool in a setting where architectural intent, spatial considerations, and formal expression come into play.

The aim is to evaluate whether the tool can support the architect's process without dictating it, acting as a guide for working within conditions of material scarcity, rather than as a generator of fixed outcomes. The re-design serves to explore how structural decisions, driven by reclaimed timber availability, can integrate with and influence the architectural design process.

Scenario

For clarification, the following experiment works on the assumption that developments in the near future will allow for reclaimed timber to be visually graded, similar to the approach proposed by Norwegian Standards, as discussed in the Reclaiming Timber chapter. Regulatory bodies are assumed to actively promote the use of reclaimed materials, making them legally acceptable for both new structural systems and the renovation of existing buildings. Specialized companies are also presumed to exist, handling the processing and classification of reclaimed timber into an organized stock.

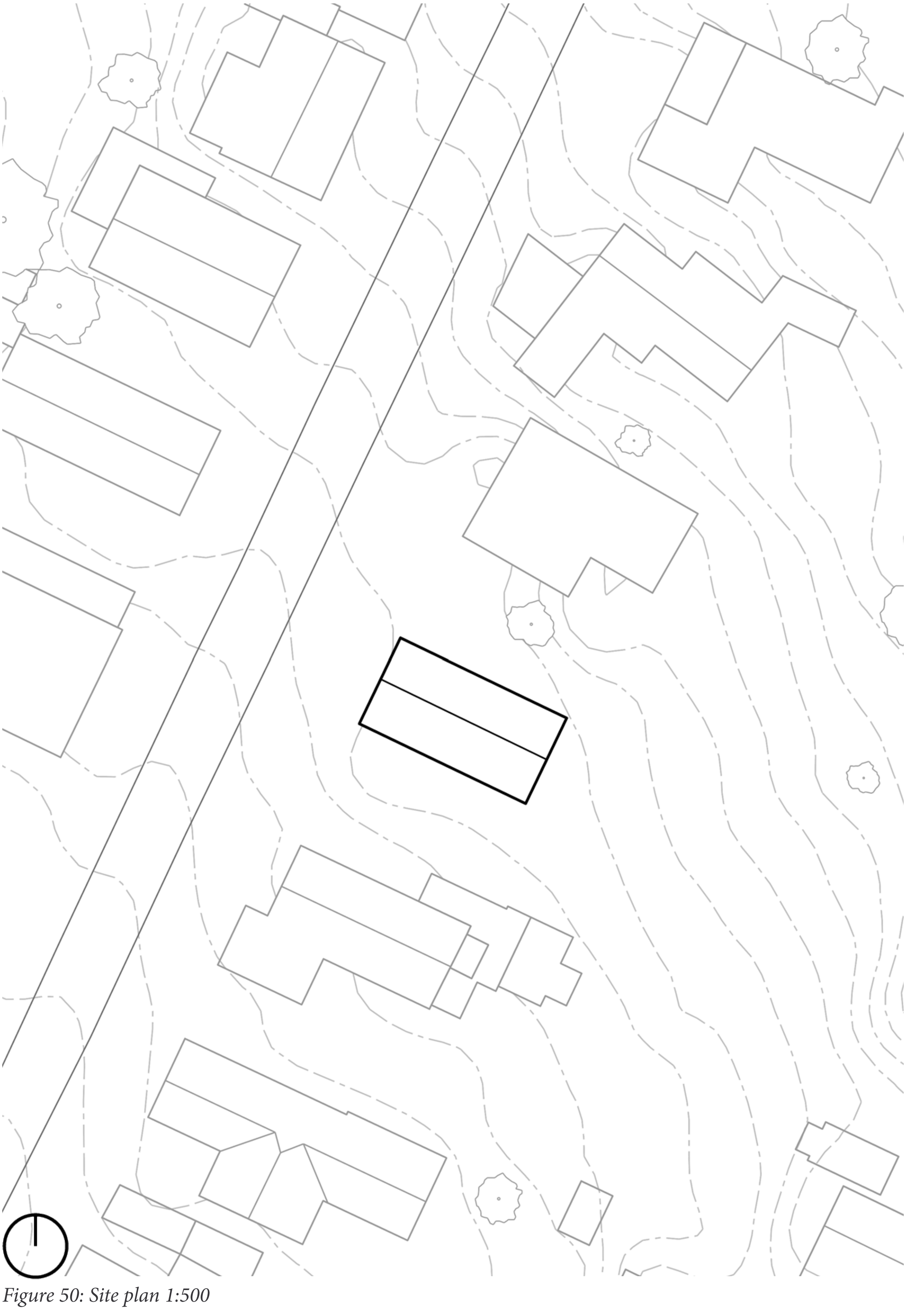


Figure 50: Site plan 1:500

Design Study #1

Figure 51: Design Study area of focus

This first Design Study serves as a controlled test of the tool's core functionality as well as its ability to maintain the integrity of the workflow. This is done in a simulated design phase with a parallel approach in a relatively simple structural context.

Daylight is chosen as being the criteria of utmost importance through the unit of Useful daylight illuminance, and will be the guide to start the design process.

The residential house itself was picked at random from a Danish neighborhood, in order to work with a realistic baseline. The residential house was originally built in 1964.

One mink farm wing, which consists of 60 frames, was allocated as available material.

Accessible stock

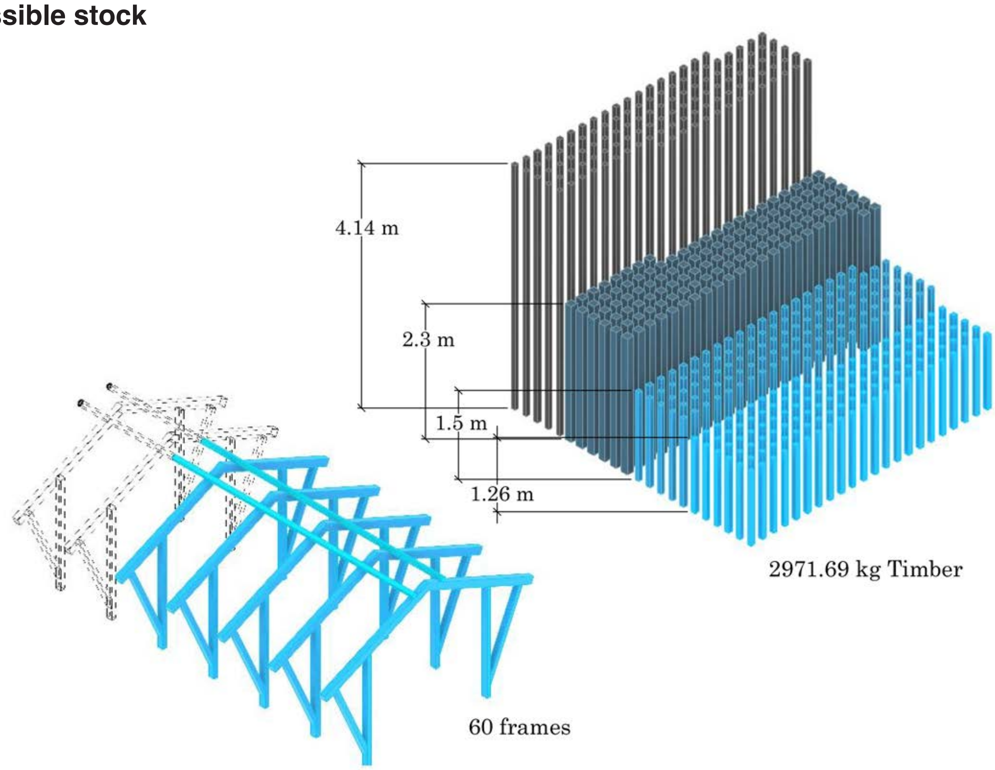


Figure 52: Accessible stock for Design Study #1 equivalent to a single wing.

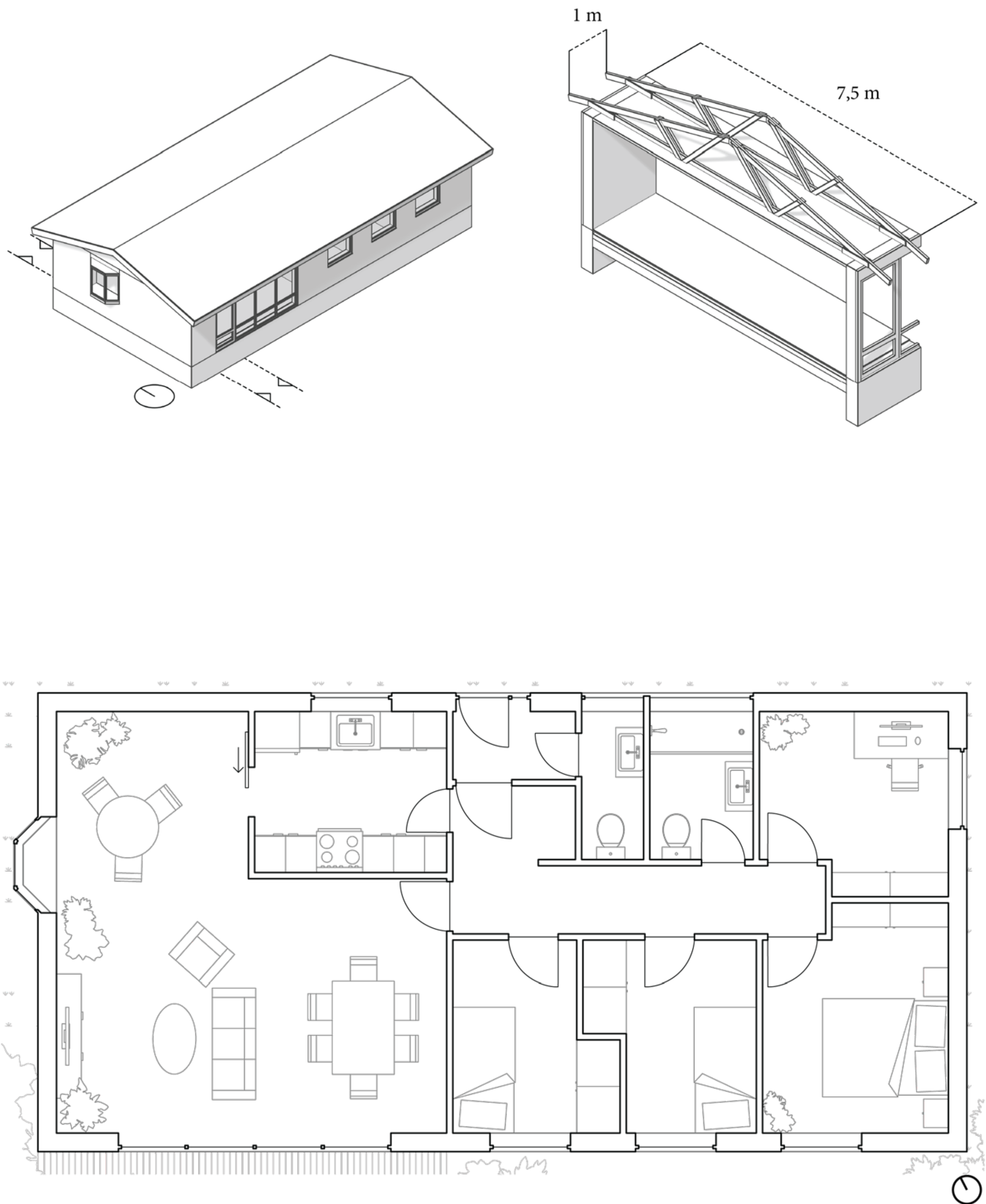


Figure 53: The residental house as it stands before renovation. Axonometric (above) of the exterior and existing structure. Plan (below) in 1:100.

Brief

Renovation of a typical parcel home from the 1960s.
The new owners wish for a modern renovation of the main building with skylights and open kitchen-living space, as well as a visible structure. They wish this renovation be done in the most sustainable manner.

Criteria

- Must have three bedrooms, one master bedroom for the adults and two bedrooms for the children.
- The outer wall must remain.
- There must be an open kitchen-living space
- The Useful daylight illuminance in the open kitchen-living space must be in the range of 300 lux - 2000 lux/3000 lux 80% of the occupancy time (Mardaljevic et al, 2012)

Initial Sketches

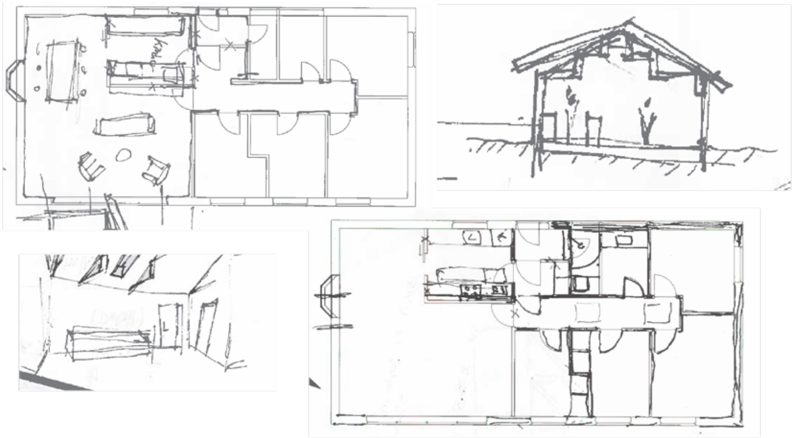


Figure 54: Intial sketches of the plan.

The first plans for the renovation were to open up the kitchen, allowing for a more open and modern configuration, as well as allowing for more daylight in the kitchen. The bedrooms and bathrooms were not changed much, except for the removal of the bathroom by the entrance door.

A couple partition walls were chosen to remain, such as the partition wall between the entrance and kitchen and a partition wall between the entrance and hallway.

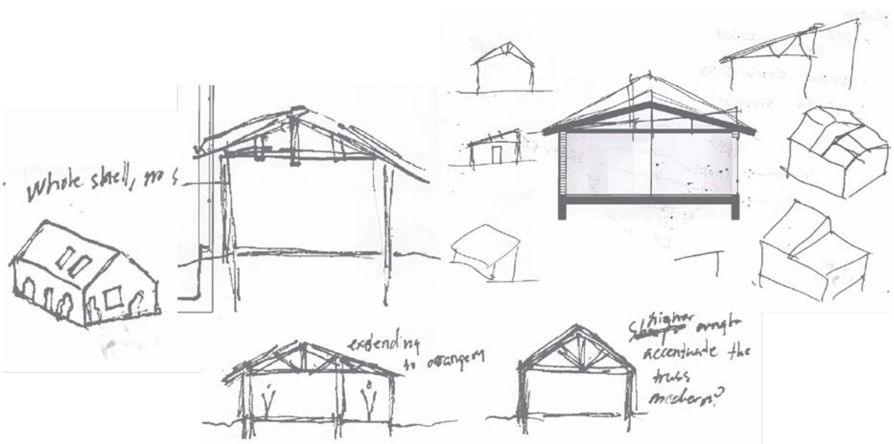


Figure 55: Intial sketches of the plan.

The most impactful change in the renovation was the introduction of skylights, in order to introduce more daylight to the shared rooms. Those being the hallway, entrance, kitchen and living room. This decision thus required the house to need a new structure, as any exposed timber structure also needs to be fire resistant.

According to BR18, the load bearing structure in a single story residence needs to keep its structural integrity while being on fire for 30 minutes (BR18, 2018).

Case

In the exploration of alternative shapes for the roof inspiration was drawn from Living Places by EFFEKT and VELUX (VELUX, n.d.). These buildings feature pitched roofs with flat skylights positioned along the roof ridge.

In the renovation of the house, introducing a flat section along the ridge would help limit the interior room height and fit neatly between the partition walls, allowing daylight to wash down the walls and into the hallway.

Figure 56: Living Places by EFFEKT and VELUX. Author's own photograph.

Daylight Simulation

The requirement for a new structure to support the skylights also presents an opportunity to further optimize daylight conditions. First, a daylight analysis was conducted on the house before renovation, to serve as a baseline for comparison with new roof iterations. The chosen method is Useful Daylight Illuminance (UDI), which calculates the illuminance (in lux) at a given point over time.

The results are expressed as the percentage of time that a point falls within three categories: UDI (300–2000 lux), UDI-low (<300 lux), and UDI-high (>2000 lux). The goal is to maximize the UDI range, as UDI-low indicates insufficient daylight and UDI-high suggests glare or potential overheating.

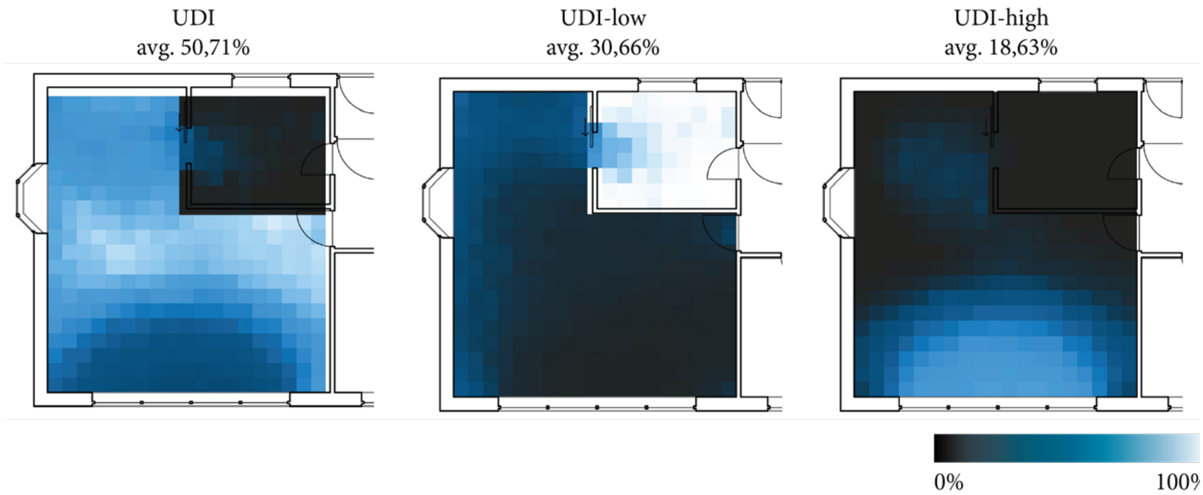


Figure 57: UDI analysis showing daylight availability in the kitchen and living room between 8:00 and 20:00, from April 1 to September 30.

In the living room, the skylights were moved down to the north-facing slope of the roof, as this side receives little daylight, as shown in figure 57. This design leaves two main variables that influence the shape of the structure: the roof angle and the window sizes. The window sizes determine the maximum distance between trusses, while the roof angle affects the length of the structural elements.

Chosen Roof Shape

Based on these variables, an optimized roof shape was derived through the use of Wallacei. It features a roof angle of 25 degrees and three 140 × 70 cm skylights, as seen in figure 59.

These design choices result in an average UDI of 74.72%, just 0.35% lower than the most optimal solution within the given design space, and 24.01% higher than the initial daylight conditions as seen in figure 58.

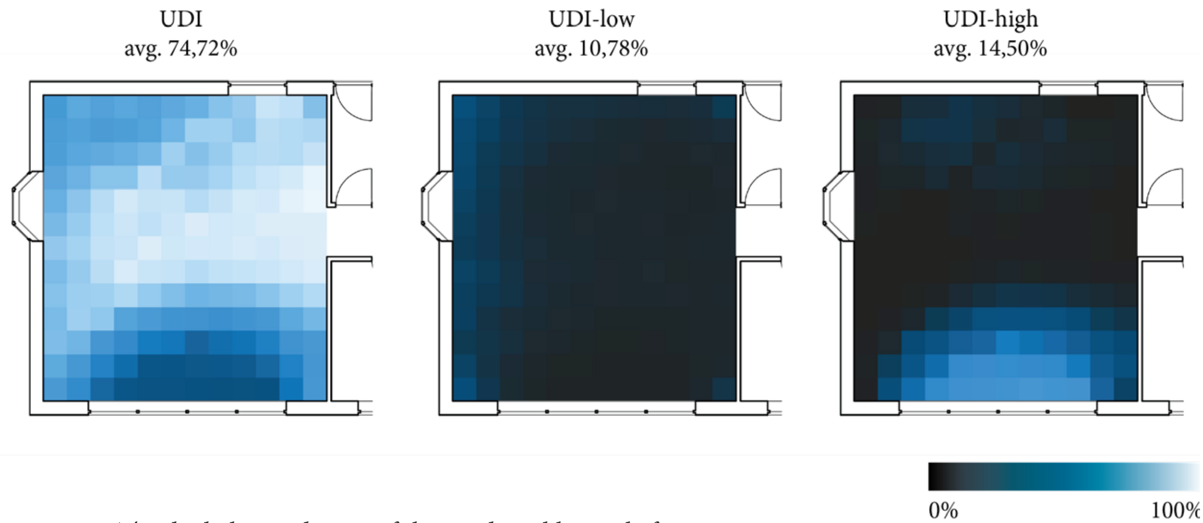


Figure 58: The daylight conditions of the residental house before renovation.

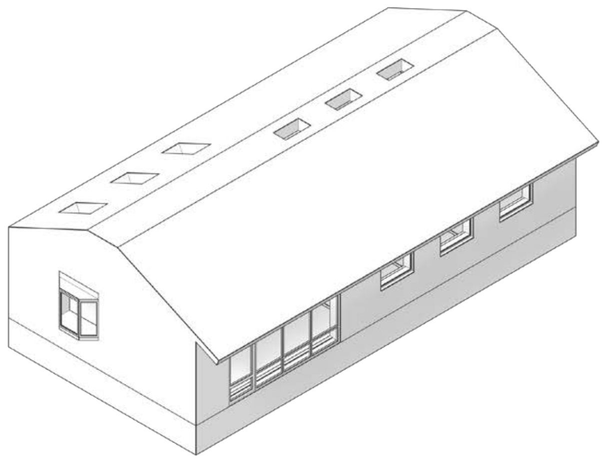


Figure 59: The daylight conditions of the residental house before renovation.

Structural Iterations

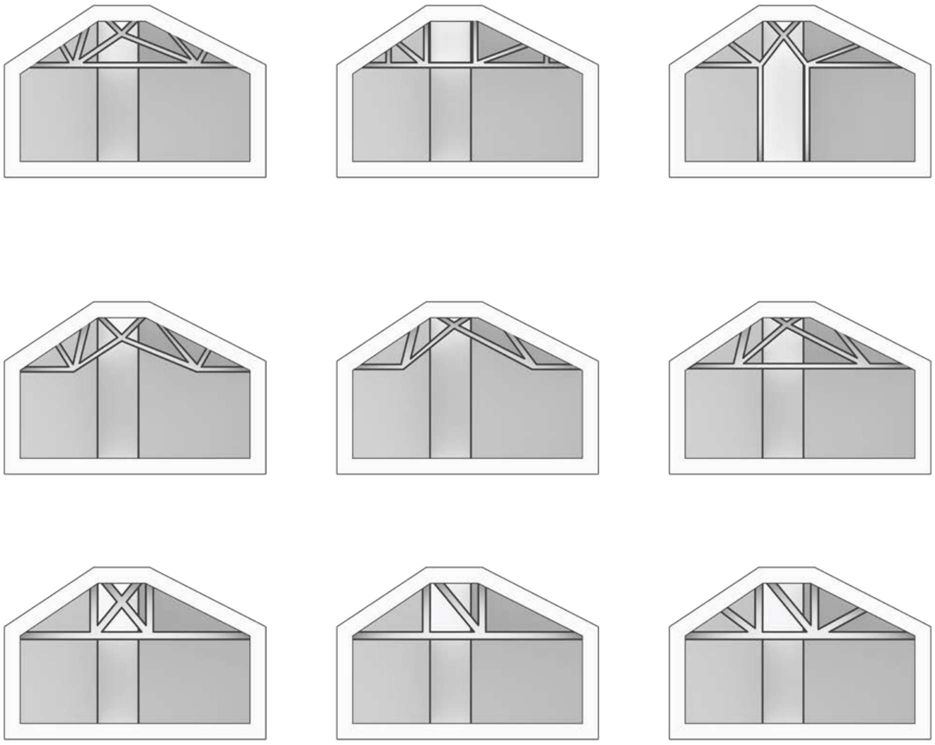


Figure 60: Iterations of trusses accommodating the selected roof shape.

Within a new building envelope, various structural concepts were explored through 3D modeling to understand their spatial implications. Iterations were increasingly guided by the existing interior partitions, skylights, and desired floor plan.

By combining the features of several of the iterations, a final structure could be derived. This design, as seen in figure 61, features two trusses resting on each other in a scissor joint, meaning the top chords are supported by the bottom chord of the opposing truss. The features highlighting its selection were the reduction of volume along the hallway, blocking less light, as well was its ability to create a more spacious room as it does not have a horizontal beam spanning the room.

In order to withstand 30 minutes of burning as previously mentioned, the cross sections will need to increase, demanding a method of stacking elements. The method employed in this case is Brettstapel, or dowel-laminated timber (DLT).
By drilling through layers of elements and assembling them with dowels, the cross section of each element can be increased to withstand the burning rate, as seen in figure 62. The burning rate for hardwood and softwood is between 0,5 - 0,65 mm/min, in this case 0,65 mm/min was used, resulting in 19,5 mm reduction on each side of each cross section (CEN, 2004b).

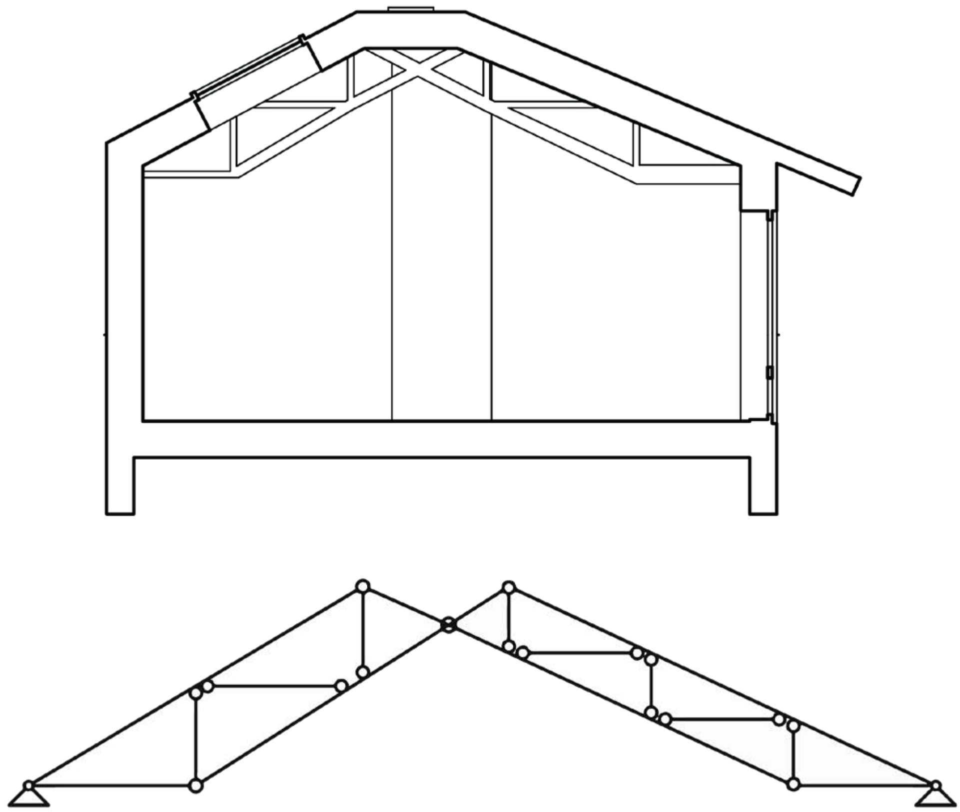


Figure 61: The selected truss and a freebody-diagram representing the joints and supports of the structure.

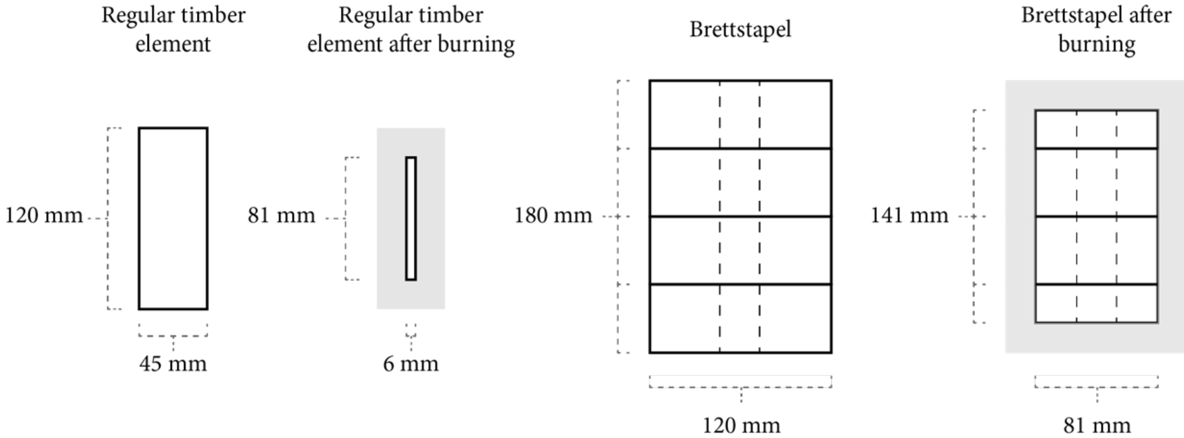


Figure 62: Comparison of a mink farm timber element and four of the same element assembled by dowels, after 30 minutes of burning.

Tool Application

Following the initial sketching phase of the structure, the tool was applied to identify which structural elements could be substituted with reclaimed timber from the mink farm. By setting up the model in Karamba3D and integrating it with the tool, an initial analysis was conducted. As shown in figure 63, without any geometric changes, the baseline structure already achieves a reuse rate of 75%, with only 25% requiring new timber.

To determine whether a better-performing structural shape might be achievable, minor geometric adjustments were explored. These variations could potentially optimize the compatibility with the reclaimed timber. While the floor plan remains fixed due to project constraints, several parameters could be altered.

In this particular design scenario, these included the roof angle, the width of the roof ridge, the number of web elements in the trusses, and the total number of trusses, as illustrated in figure 64. Although a roof angle of 25 degrees may be optimal for daylight performance, a slight reduction in daylight could be justified if it introduces more reclaimed timber.

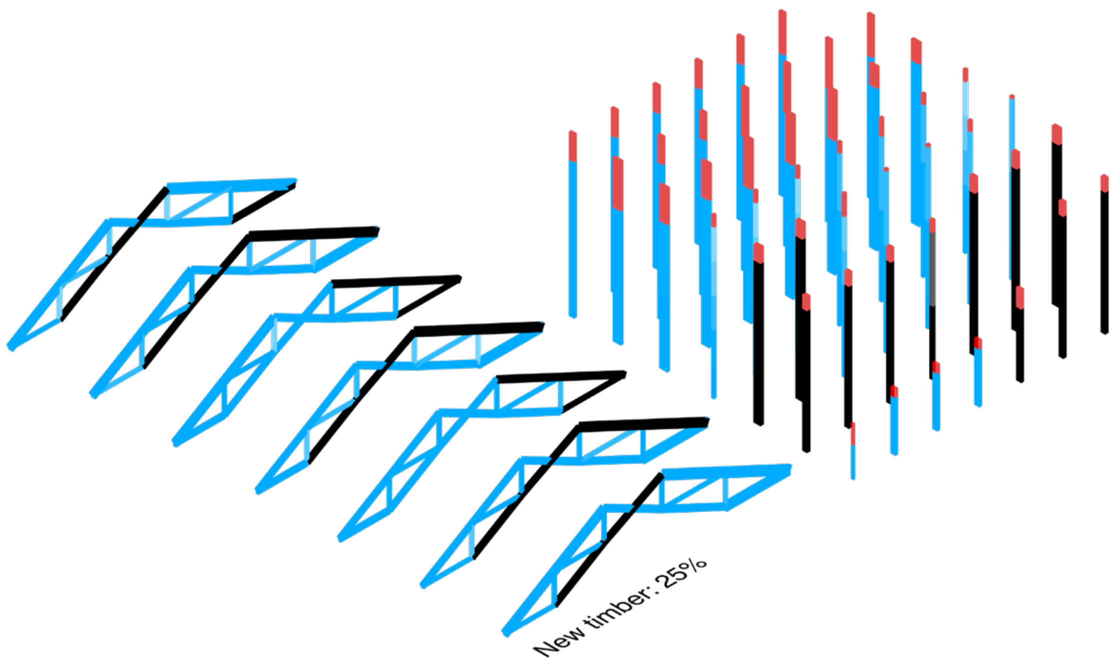


Figure 63: Result of The Tool after applying it to the structure without any geometric changes.

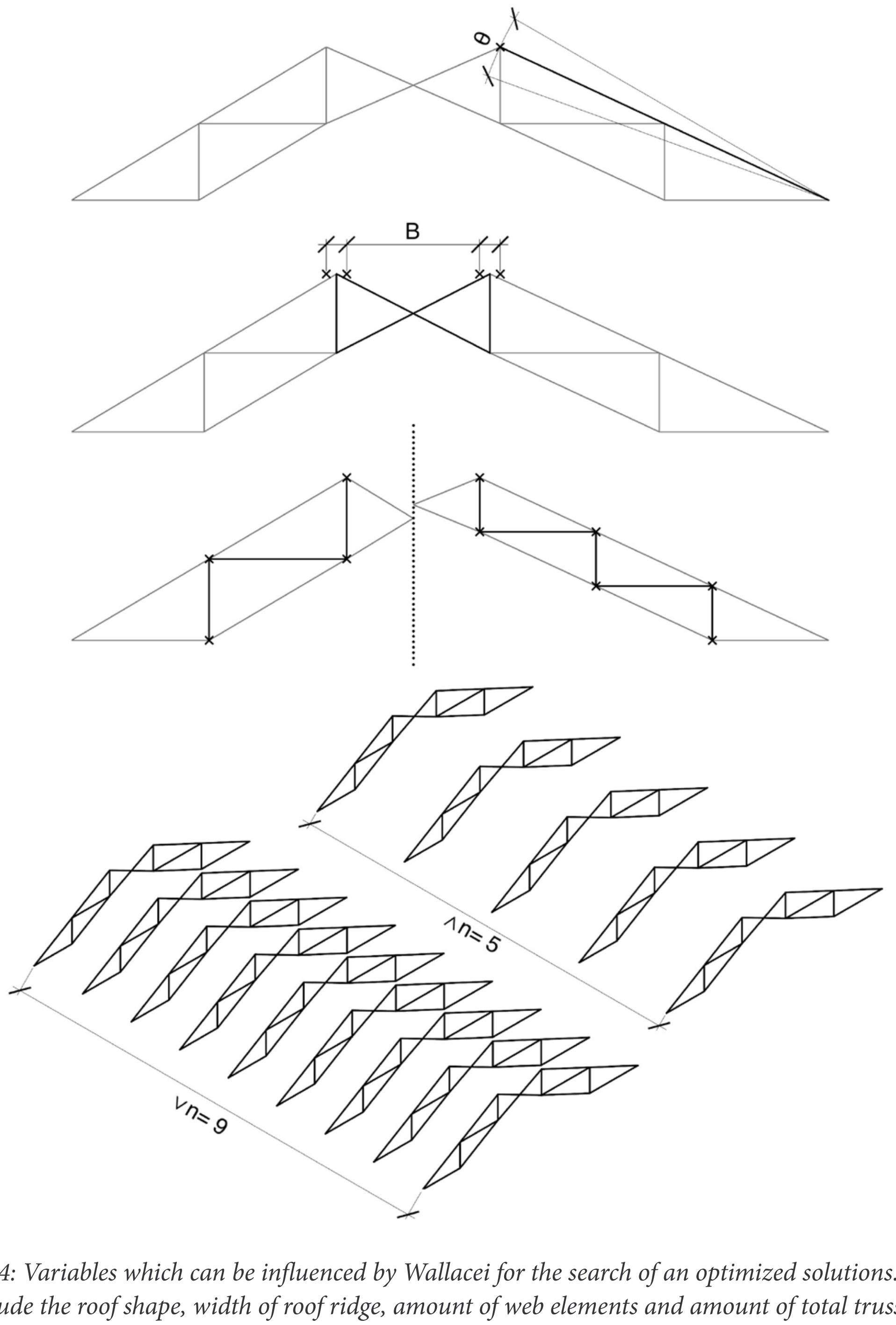


Figure 64: Variables which can be influenced by Wallacei for the search of an optimized solutions. These include the roof shape, width of roof ridge, amount of web elements and amount of total trusses.

Using an evolutionary algorithm, several hundred structural iterations were evaluated with the objective of minimizing the use of new timber. Since the algorithm might favor denser structures—reducing the percentage of new timber by increasing the total number of elements—structural weight was introduced as a secondary optimization goal.

The algorithm generated successive generations of structural variants, each informed by the best-performing solutions of the previous generation. From the final generation, two distinct variations emerged, shown in figure 66, as iterations B and A/D (identical). As illustrated in the graph in figure 65, iteration B achieved the lowest total weight but required 10% new timber, while iteration A/D used 100% reclaimed timber.

Given that iteration A/D consists entirely of reclaimed timber and maintains the preferred roof angle of 25 degrees, it was selected as the final structural configuration.

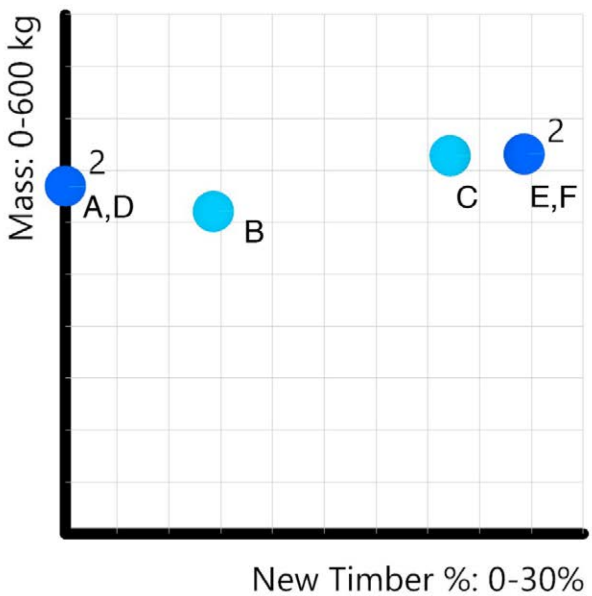


Figure 65: Final generation from Wallacei, showing the best results from the given design space.

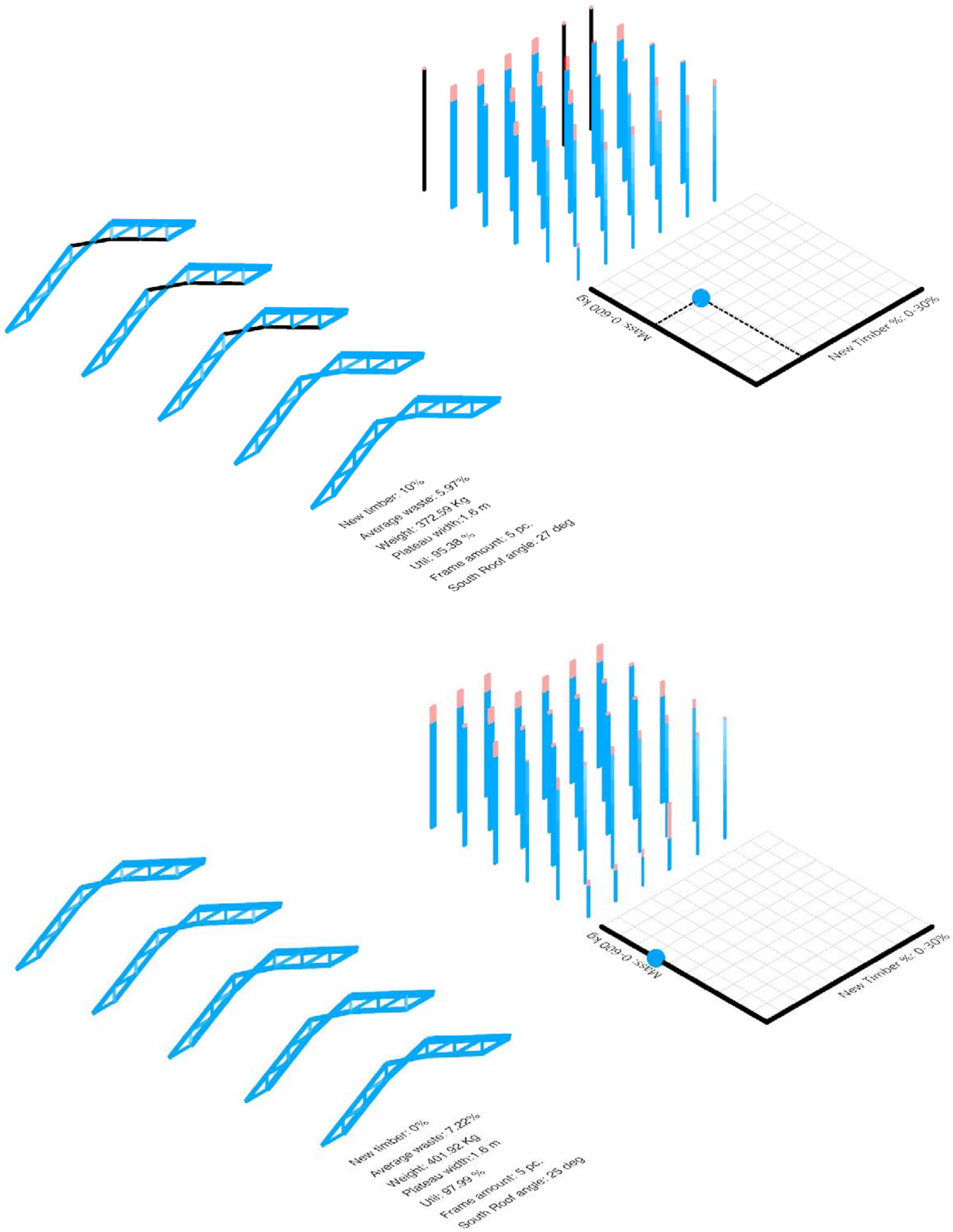


Figure 66: Diagram of the two best performing structures, iteration A/D (above) and iteration B (below), showing their utilization of the stock and notable data associated with the iterations, particularly the percentage of new timber, average cut-off waste and weight.

Evaluation

From a purely performance-based perspective, the optimized structure offers a clear improvement over the baseline, reducing the proportion of new timber from 25% to 0%. However, this quantitative improvement must also be weighed against qualitative spatial differences. Despite the minimal geometric adjustments—none of which alter the overall building envelope—the resulting structures present distinct spatial expressions.

As illustrated in figure 68, the same room is shown with the two structures, the initial structure and the optimized structure. In the optimized version, the increased number of members raises the bottom chord of the truss, concealing the structure to a greater degree and obscuring the visually engaging scissor joint where the trusses intersect. In contrast, the initial structure, with fewer elements, places the bottom chord lower, making the scissor joint visible and the structure more prominent within the space.

The difference in reclaimed timber and new timber, may also result in a more desaturated aesthetic, revealing the age and wear of the elements.

While the final decision may ultimately depend on the client's preferences, this thesis prioritizes material efficiency as a guiding principle. On that basis, the optimized structure of 0% new timber is selected as the final proposal.

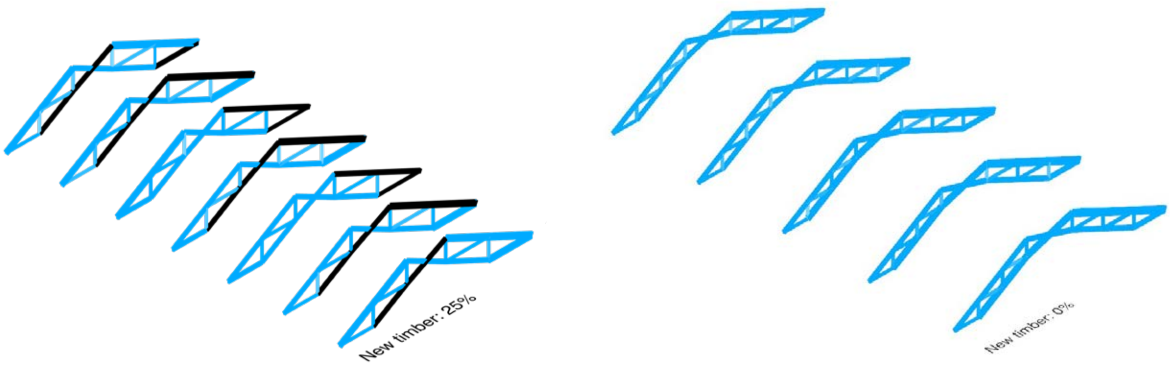


Figure 67: Diagram of the initial structure (left) and the optimized structure (right).

Figure 68: Visualizations of the inital structure (above) and the optimized structure (below).

Figure 69: Exterior render of the renovated house

Presentation

The brief has been met with a design proposal for the parcel home renovation. Skylights and open kitchen-living space increasing the average UDI, as well as a visible structure has been introduced. The proposal introduces trusses of 100% reclaimed timber from mink farms. Using 402 kg of reclaimed frames corresponding to 14% of the total 2972 kg stock given.

The trusses are made of both timber elements with altered cross sections using Brettstapel, or dowel-laminated timber (DLT), and timber elements of non-altered cross sections, as seen in figure 70.

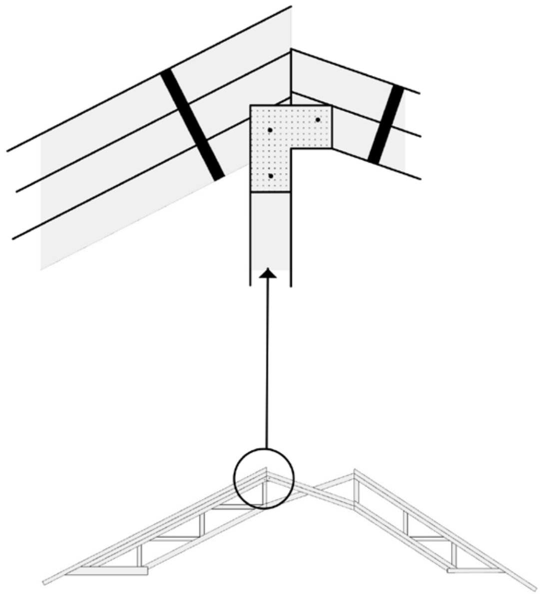


Figure 70: Detail of a joint connecting a top chord, bottom chord and web member.

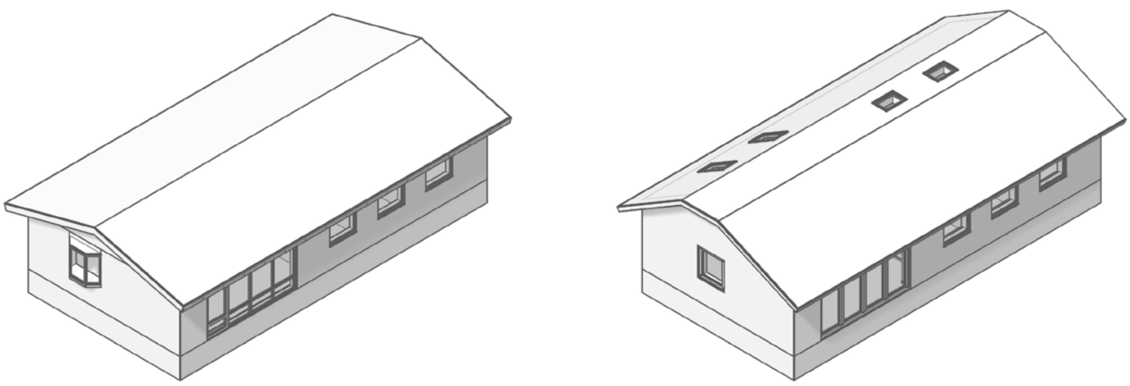
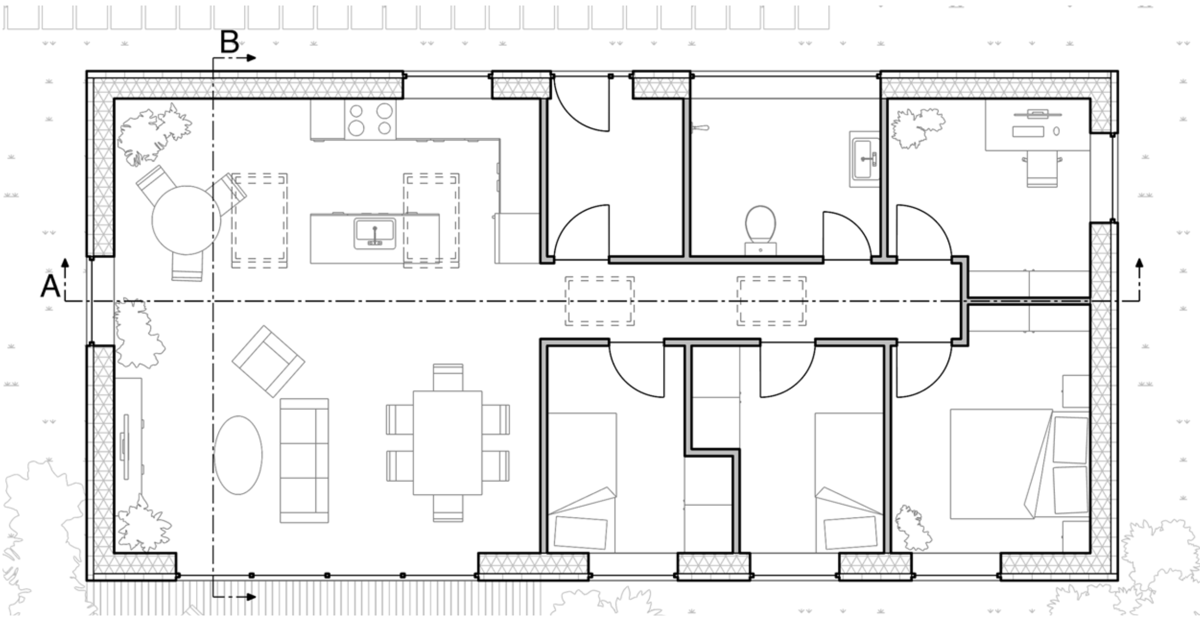
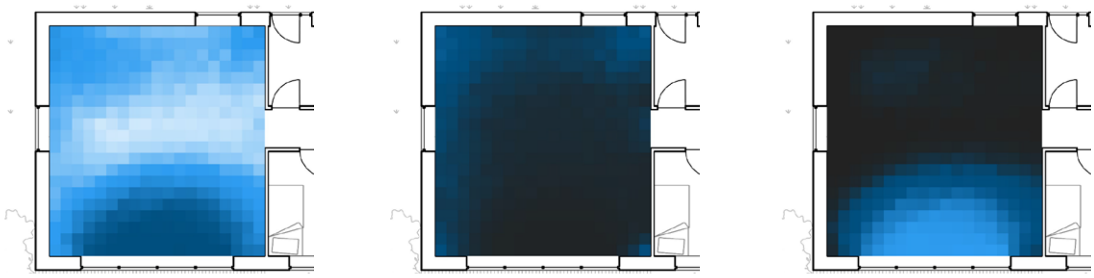


Figure 71: Axonometric of the residential house before (left) and after renovation (right).





UDI 68,67% | UDI-low 13,39% | UDI-low 17,94%

Figure 72: Plan in 1:100 after renovation along with the daylight results, seen below the plan.

A daylight analysis is conducted to evaluate the final design proposal. The number of structural frames directly influences the position and number of windows, as only one window is permitted between each pair of trusses. This constraint affects the final UDI results, preventing the structure from achieving the same performance levels seen in the "Daylight Optimization" chapter.

In the renovated design, the average UDI (Useful Daylight Illuminance) in the open kitchen-living space increases by approximately 18% compared to the baseline.

Simultaneously, the proportion of the space receiving less than 300 lux decreases by a similar margin, while the share of areas exceeding 3000 lux remains stable at around 18%.

This analysis concludes that the final design achieves a satisfactory increase of the daylight level, with the UDI reaching approximately 70%, up from the pre-renovation level of ~50%.

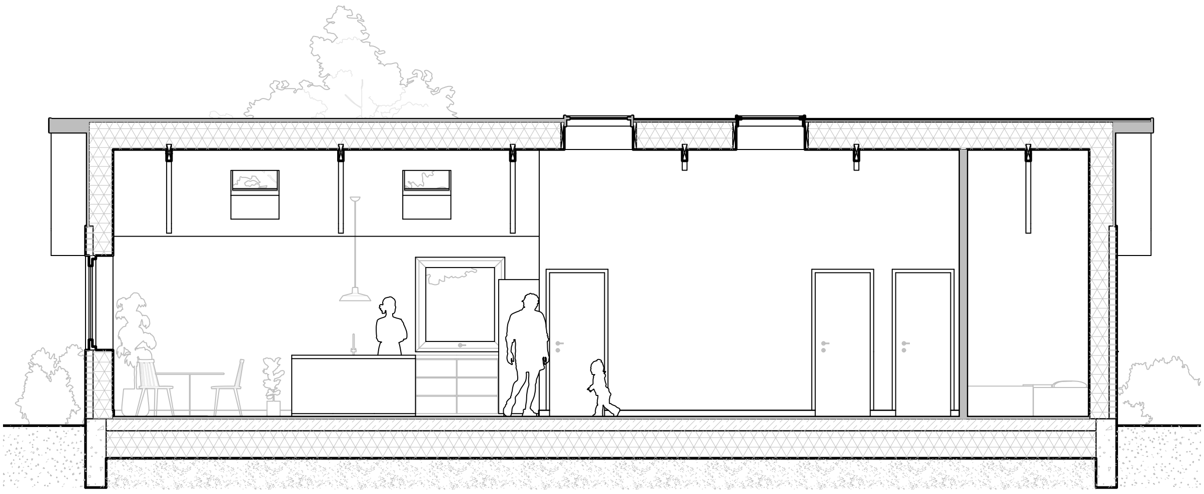


Figure 73: Longitudal section A in 1:100.

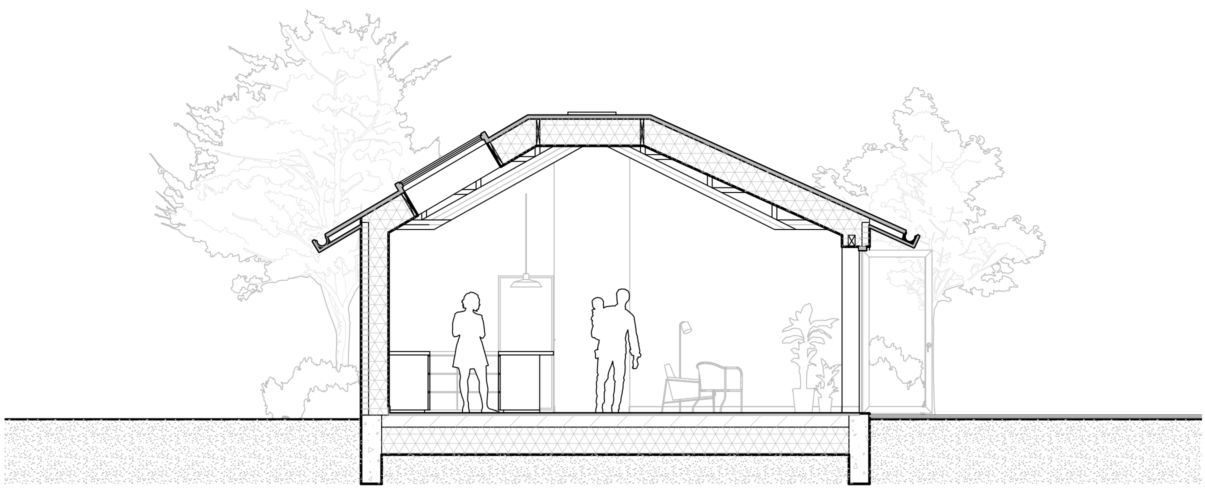
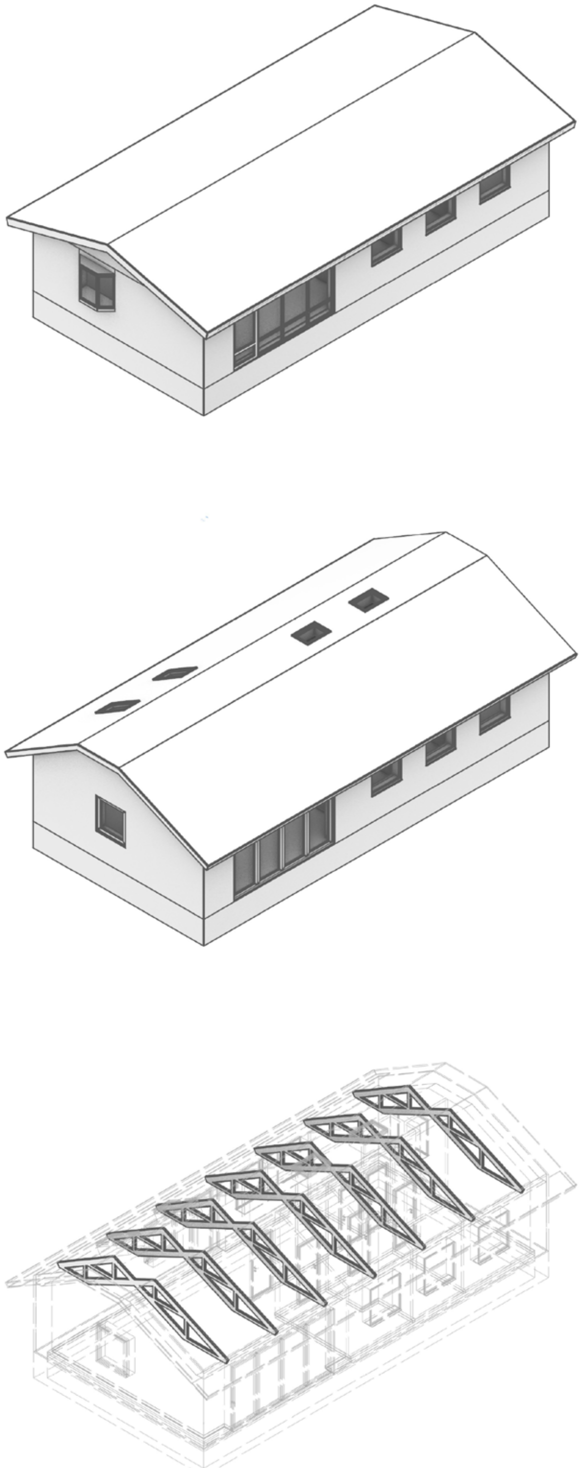


Figure 74: Lateral section B in 1:100.

This design study explores how the tool performs within a typical architectural workflow, where spatial intent, structural demands, and material constraints intersect. The case explores how the tool supports early design decisions without overriding architectural control.



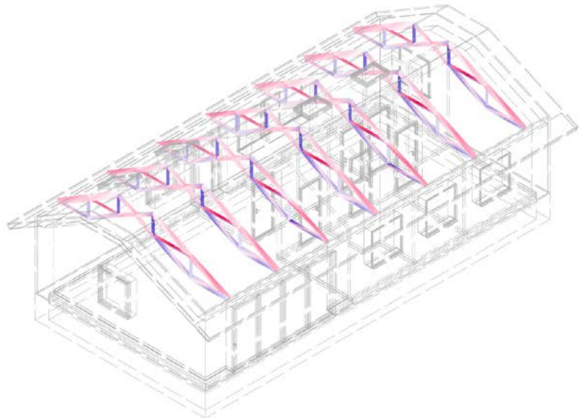
Architectural Intent & Daylight
The project began with an analysis of the parcel home. Plan adjustments were made based on predefined criteria, including a modern, open-plan living space with visible timber structure and skylights. Daylight performance was defined as the primary design driver, measured through Useful Daylight Illuminance (UDI), which established the baseline for roof and structural redesign.

Roof Form Generation Using Evolutionary algorithm
To maximize daylight in the open-plan space, multiple roof geometries were generated using an evolutionary algorithm. Variables such as roof pitch and skylight size were adjusted to find an optimal configuration. The selected roof angled at 25 degrees achieved a UDI of 74.72%, a 24% improvement over the original condition.

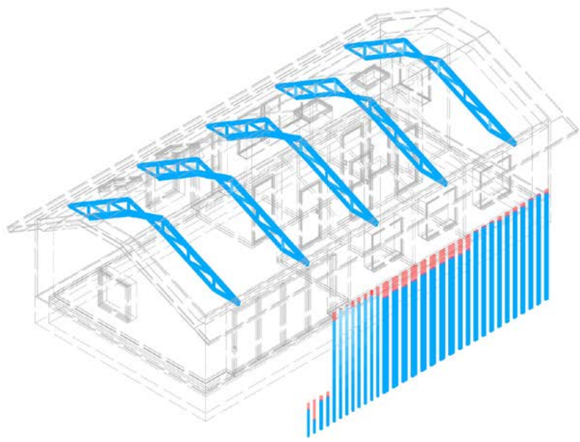
Structural Exploration
With the new roof form in place, different truss structures were explored in 3D, accounting for spatial intent and daylight access. A scissor-truss solution was selected for its spatial expression.

Figure 75: Diagram showing a summary of the design process.

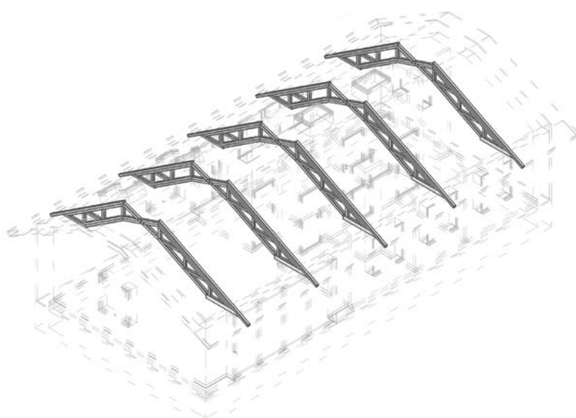
Tool Integration for Cross Section Optimization
To meet fire safety regulations (30-minute integrity), the reclaimed timber elements were assembled using the Brettstapel (DLT) method. This increased cross-sectional mass, compensating for the lower performance of aged timber and enabling its use in exposed structural applications. The tool was used to calculate the needed cross sections to prepare for matching with the stock.



Tool Integration for Timber Matching & Optimization
Continuing the tool-based workflow, structural members were matched with the available reclaimed stock, allocating necessary cross-sections sourced from the mink farm inventory. Initial results showed a 75% reuse rate.



To improve this, parameters like truss density, spacing, and ridge width were adjusted and evaluated with the tool. Hundreds of structural variants were generated using multi-objective optimization, balancing the goals of minimizing both new timber use and overall weight. Two optimal outcomes were identified: one minimizing structural weight, and the other achieving 100% reclaimed timber use.



Result
The structure with 100% reclaimed elements was selected as the final design, aligning with the thesis' sustainability objectives, despite spatial compromises.

Figure 76: Interior render.

Conclusion

Design Study#1, the renovation of a standardized parcel home, demonstrates how the tool can operate within a conventional architectural design process, balancing spatial intentions, structural logic, material scarcity, and formal exploration. By integrating the tool early in the design phase, the study reveals its capacity to guide key design decisions without overriding architectural intent.

Through the incorporation of reclaimed timber stock, and structural optimization, the tool enables iterative evaluation of geometry. This allowed for a shift from the baseline structure—achieving 75% reuse in the initial tool pass—to a fully reclaimed timber solution, following the optimization of key geometrical parameters using Wallacei.

While the optimized structure prioritizes material efficiency, the qualitative impact—such as the visibility of the structural system and the overall spatial experience—may be compromised. If design parameters or constraints are not properly aligned with architectural intentions, the resulting solution may be undesirable. In this case, the truss structures, originally intended to express visible joints, became largely concealed within the roof structure.

Ultimately, the tool proves effective for structural allocation and optimization, serving as a valuable design companion, particularly for architects with a computational mindset. It supports architectural reasoning within the constraints of reclaimed material availability and structural logic. Design Study#1 suggests that algorithmic workflows can be meaningfully integrated into architectural practice when guided by clear priorities and spatial intentions

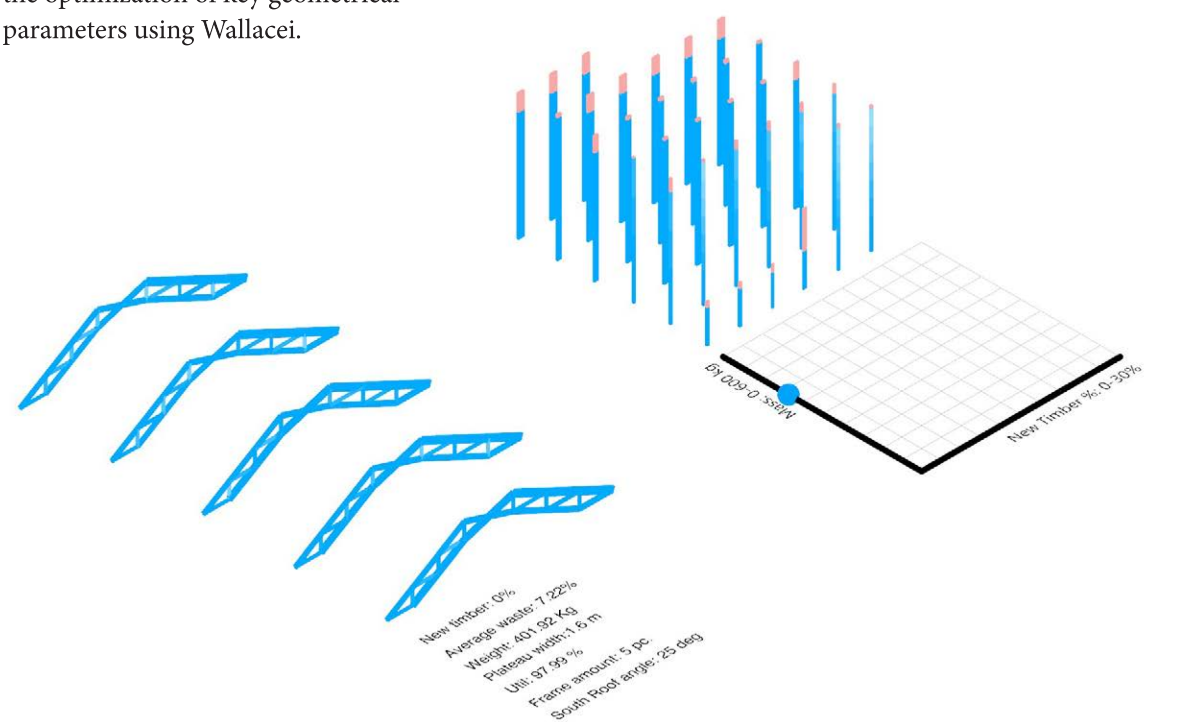


Figure 77: Diagram of the structure, stock usage and associated data.

Figure 78: Photograph of Neue Nationalgalerie. (Hans Knips/Wikimedia Commons, CC BY-SA 3.0).

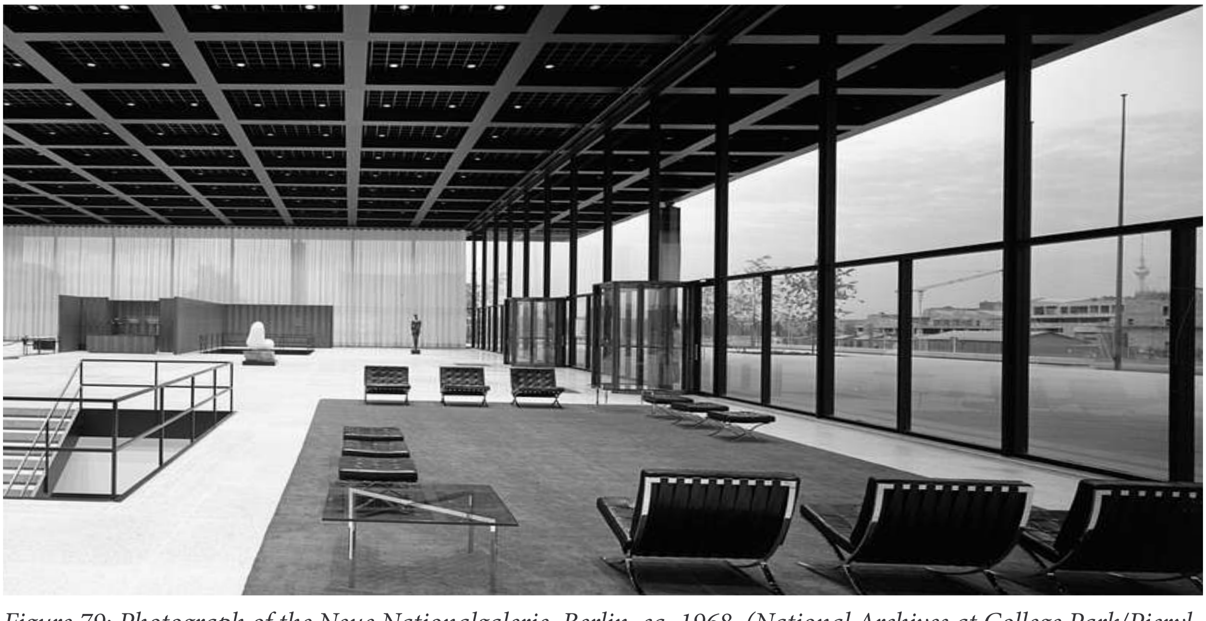


Figure 79: Photograph of the Neue Nationalgalerie, Berlin, ca. 1968. (National Archives at College Park/Picryl, Public Domain).

Design Study #2

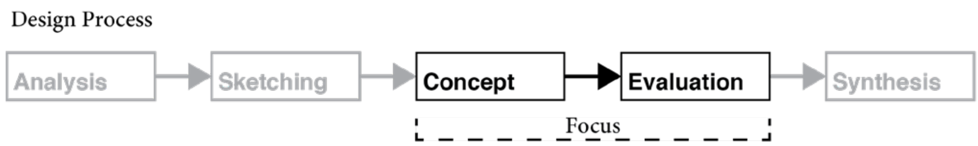


Figure 80: Design Study #2 focuses of the conceptual development of an extravagant structure using The Tool.

The second Design Study serves to still test the tool's core functionality but seeks to test if the tool is a feasible driver for structural evaluation in the fast pace conceptual phase on a structure of larger scale. This is done in a simulated design phase of a large and complex structure. The tool will be stress tested.

The computational load increases with the amount elements in the design, thus also increasing the time needed to get results. As mentioned in Optimizing material efficiency, the tool can utilize the version, a meta-heuristics and heuristics version. This design study will also compare these two versions for computational speed and material waste efficiency.

The design case chosen is Neue Nationalgalerie in Berlin, by Mies van der Rohe.

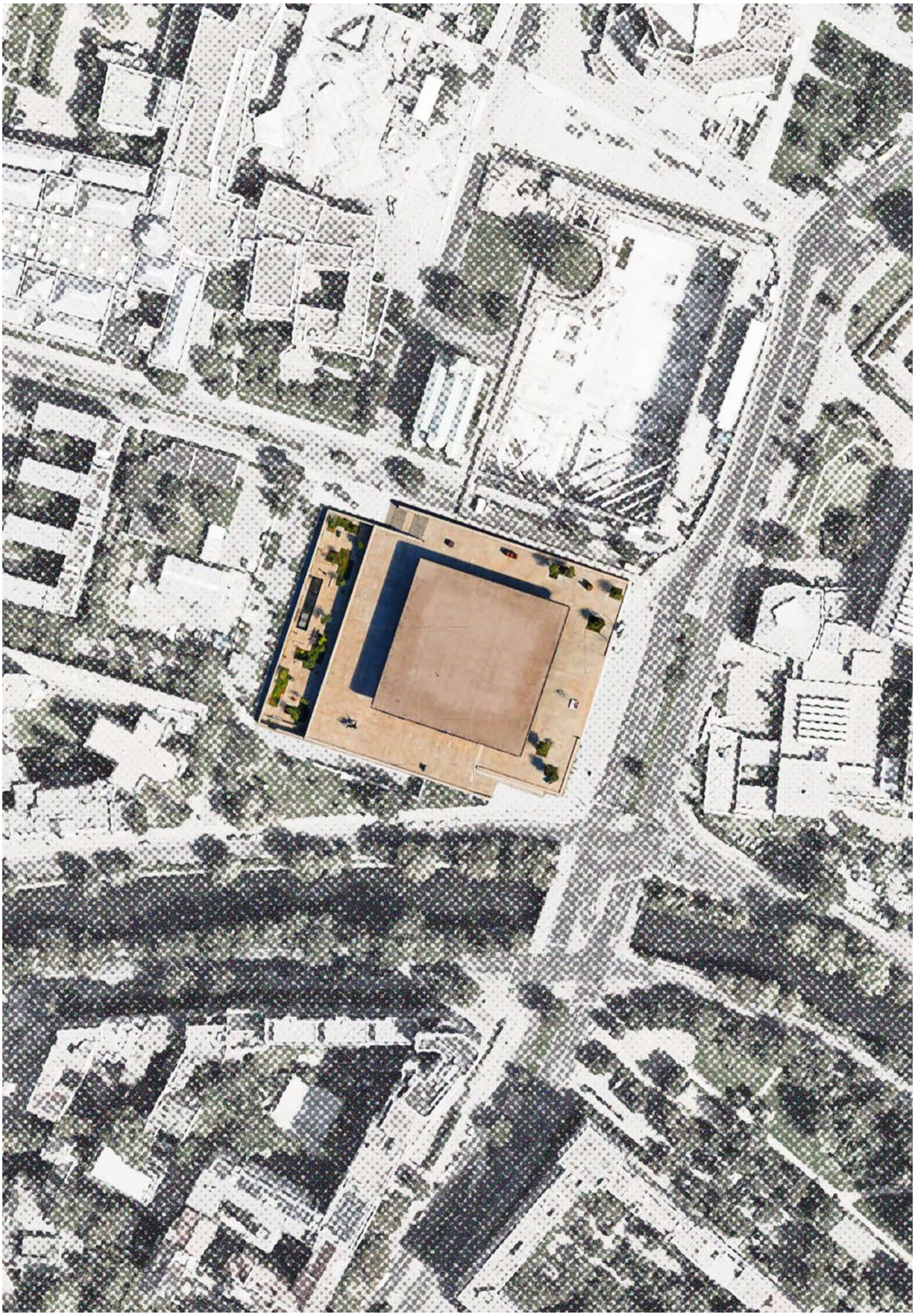


Figure 81: Satellite image of Neue Nationalgalerie. Source: Google Earth (2023, accessed 25 May 2025)

Criteria

- **Only the building's structural system above the ground floor is to be reimagined, the sub-floors will be ignored.**
- **The overall boundary volume must be maintained, only if the structural integrity is compromised new columns can be added.**
- **The structure must seek to maximize span.**

Brief

Neue Nationalgalerie in Berlin, designed by Mies van der Rohe and completed in 1968, is a prime example of modernism ideals and of the potential of the new materials of that time, such as steel and concrete.

The building industry is now fully exploiting these materials to their limits, but as this is pushing the climate to its own limit, how can such modernist architecture be made of reclaimed timber with a mindset rooted in metabolism?

The design will explore two ways of achieving the large span, large trusses similar to Resiplical frames and space frames.

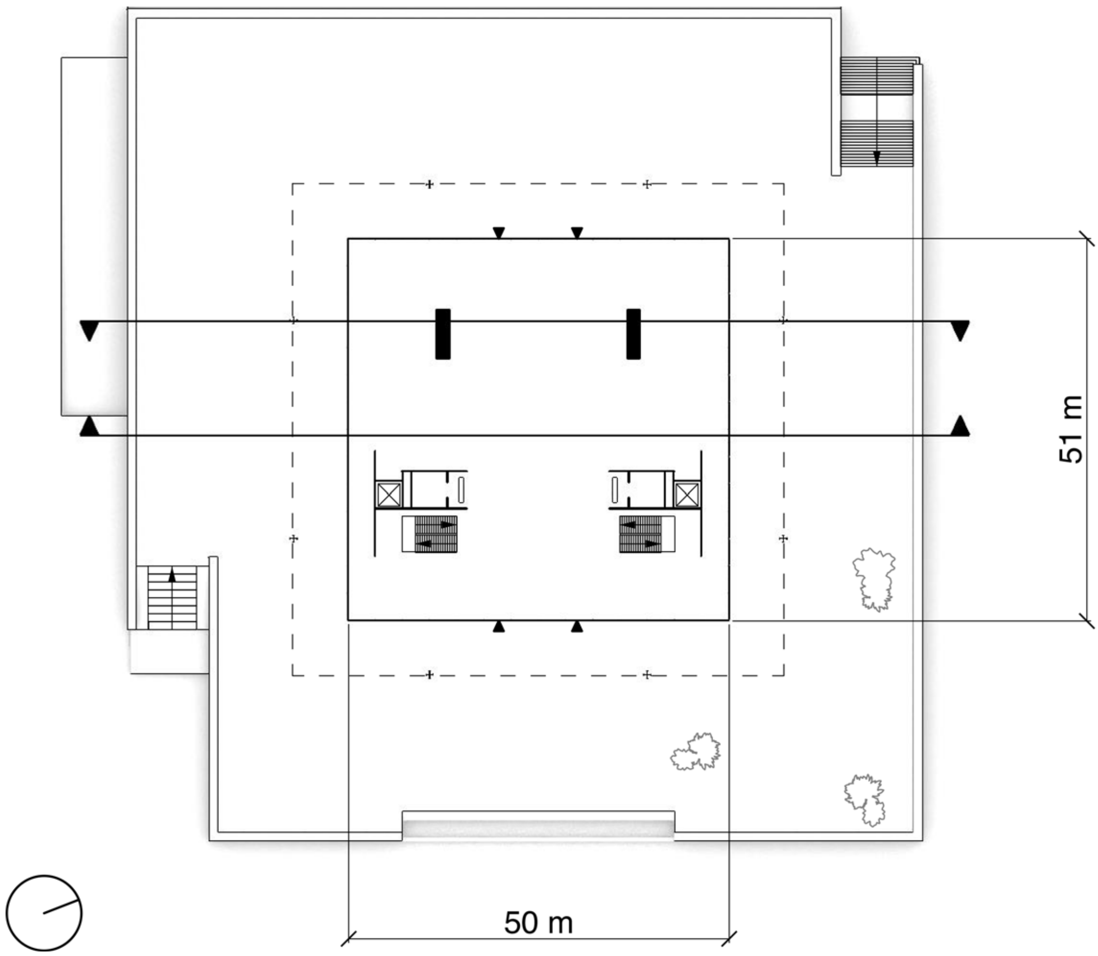


Figure 82: Plan of the existing plan 1:500

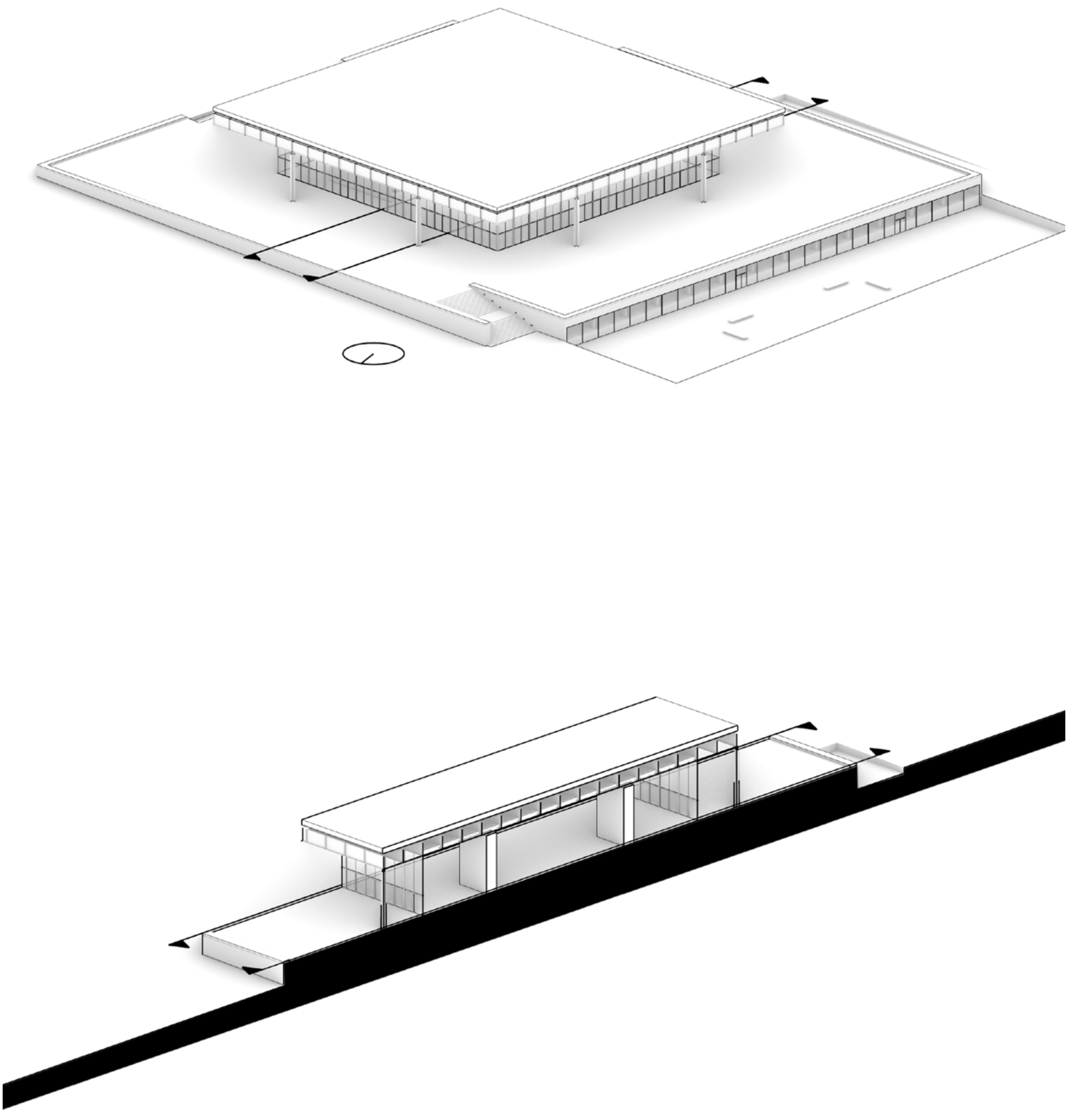


Figure 83: Axonometric (above) of Neue Nationalgalerie and an axonometric section (below) of Neue Nationalgalerie

Structure

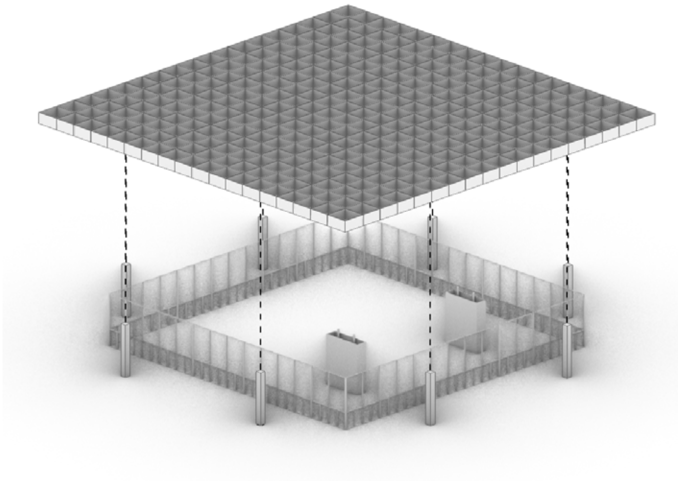


Figure 84: Exploded axonometric of the structure in Neue Nationalgalerie.

The building's defining feature is its monumental steel roof; a flat, seemingly hoverving plane measuring 64 by 64 meters.

This roof is supported by eight slender cruciform columns placed at the perimeter. This configuration creates a column-free exhibition hall, allowing complete spatial flexibility.

The structural system separates the load-bearing structure and the building envelope.

The steel roof and its supporting frame carry the loads, while the glass curtain walls remain non-structural. The roof itself is a deep steel grid, stiffened by box girders, which cantilevers beyond the columns. It acts as a rigid diaphragm that distributes loads uniformly and resisting torsion. This steel grid slab seeks to establish an infinity plane and at night the glass emphasizes this with the disappearance of vanishing points in the glass's reflection.
Columns are placed outside the main gallery space, at a grid of 24 m x 24 m.
These 8 in columns, made of welded steel plates, and made cross-shaped in section to resist buckling and allow symmetrical moment distribution.
Lateral stability is achieved via the underground plinth, not by the columns that support the roof structure.

Structure #1

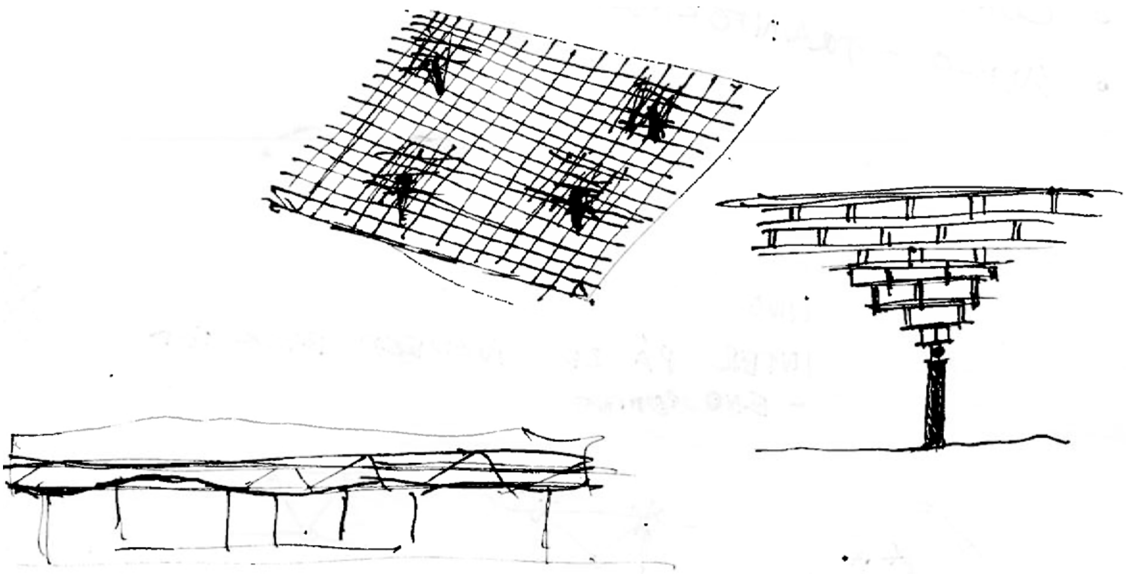


Figure 85: Sketches of a timber structure for neue nationalgalerie maintaining the original concept.

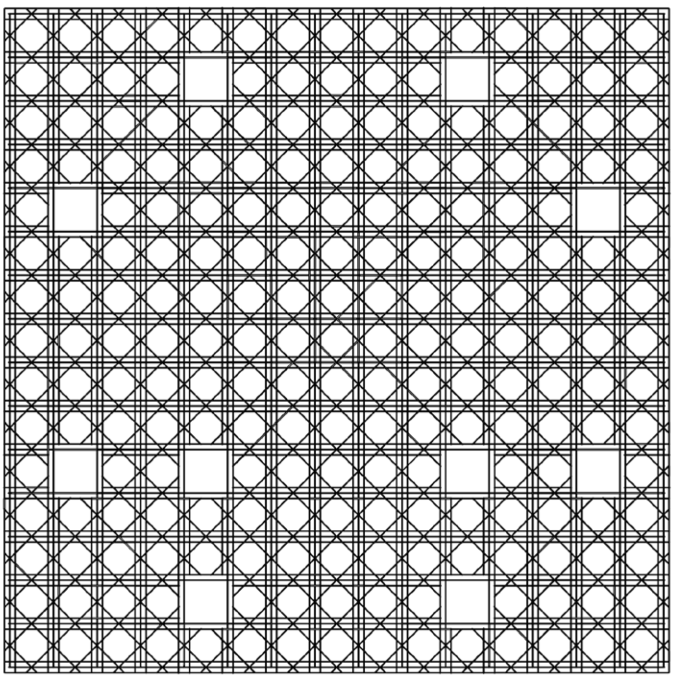


Figure 86: Pattern of the structure seen in plan.

Initial proposals for spanning structures explored the use of space frame systems, drawing inspiration from the Cambridge Central Mosque. The design was based on the visual intent of the infinity plane in the Neue Nationalgalerie, dividing the building into two sets of parallel, orthogonal lines.

These lines were then stretched between columns, which functioned as anchor points, using minimal surface physics simulations.

Structural analysis and form-finding, guided by the design concept, led to the reinforcement of the roof structure by incorporating trusses to distribute loads across the roof and into the space frame system below.

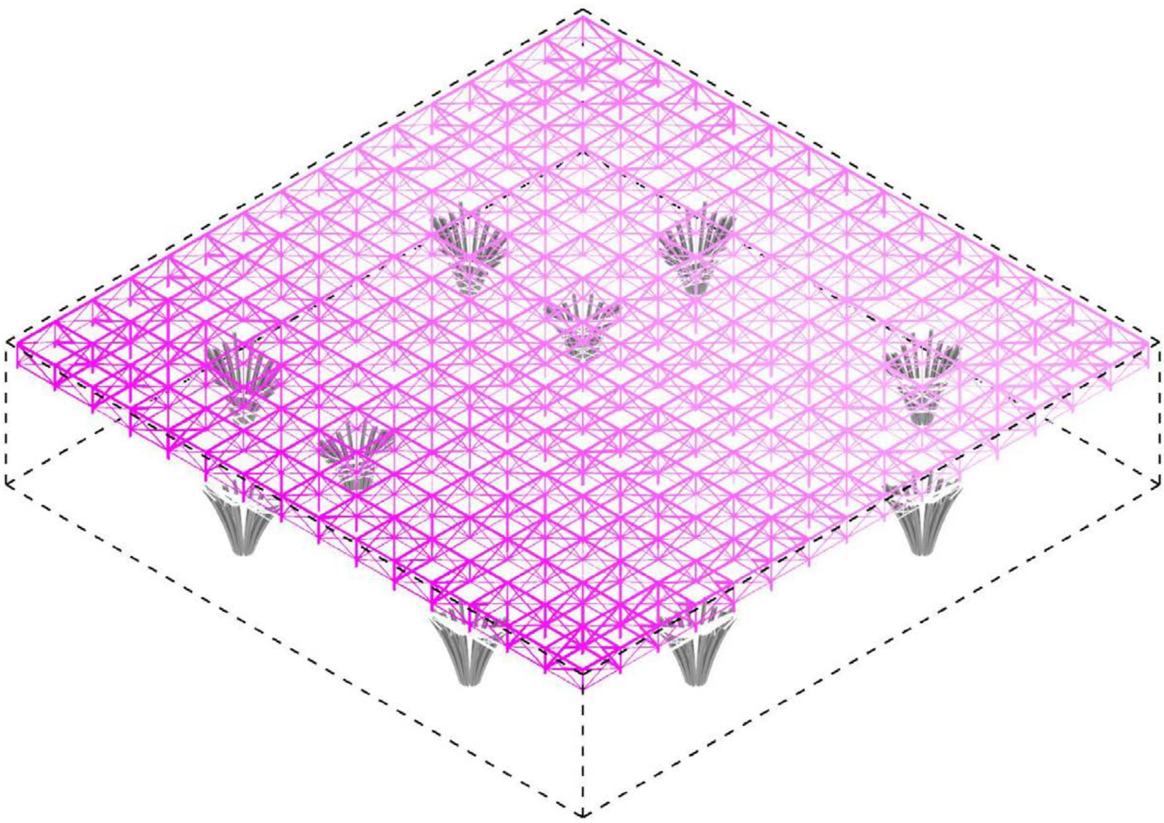


Figure 87: Diagram showing the deformation of a structural analysis performed of the space frame.

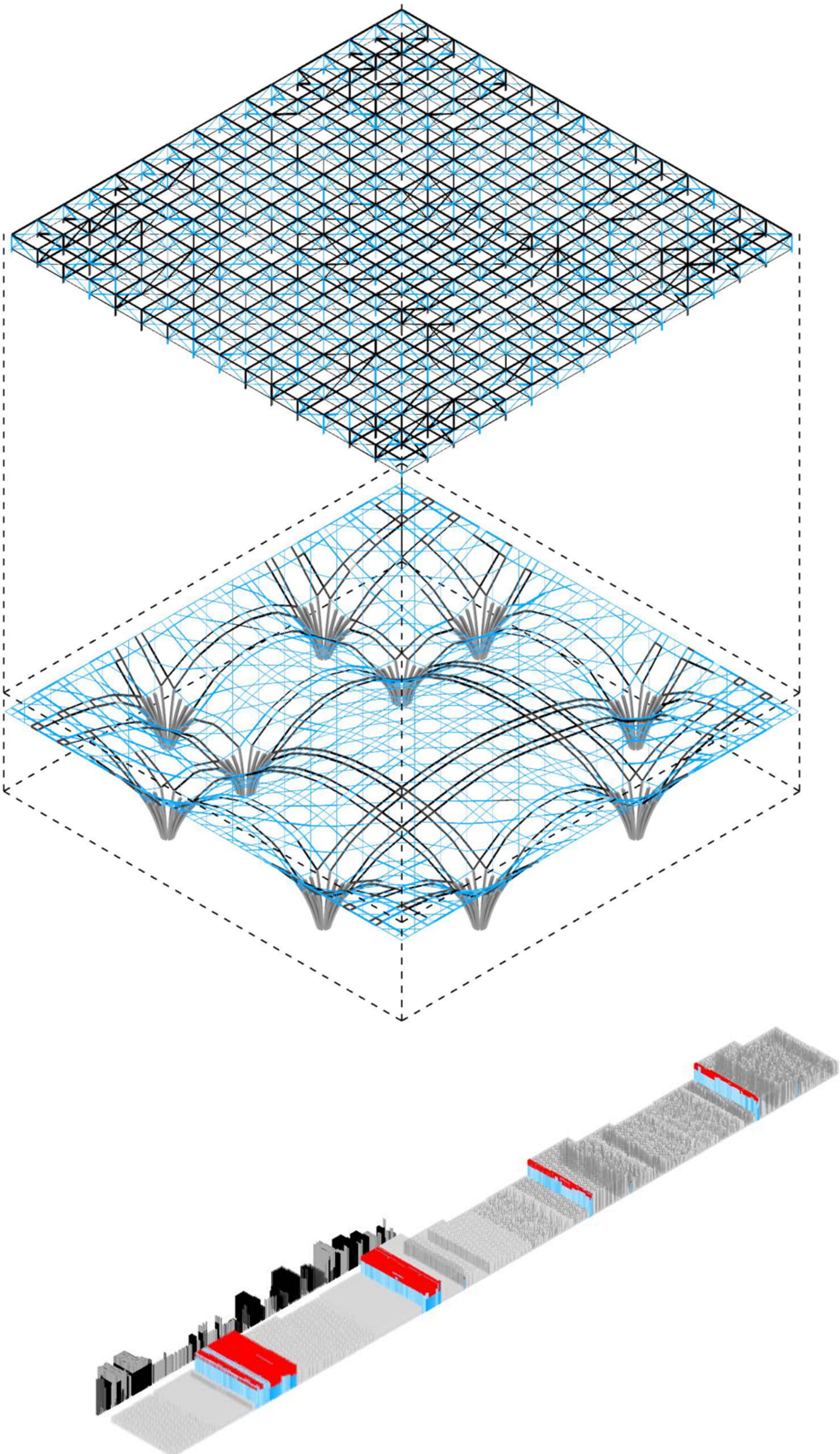


Figure 88: Diagram showing the allocation of mink farm timber to the space frame structure and the stock usage.

The tool was deployed to determine appropriate cross-sections for assigning reclaimed timber elements. Following the structural analysis, a list of demand elements was generated. The matching algorithm then assigned reclaimed timber from a stock of 32,000 elements. The stock was allocated in the structure of approximately 6,000 elements using a meta-heuristic matching algorithm aimed at minimizing cut-off waste. However, this approach proved computationally prohibitive, with processing times reaching up to 40 minutes per iteration.

This process culminated in a conceptual structural proposal combining reclaimed mink farm timber with new timber. However, due to the high computation times of the meta-heuristic algorithm, the iterative design process was hindered. The resulting structure was not fully optimized, and structural integrity could not be confidently ensured.

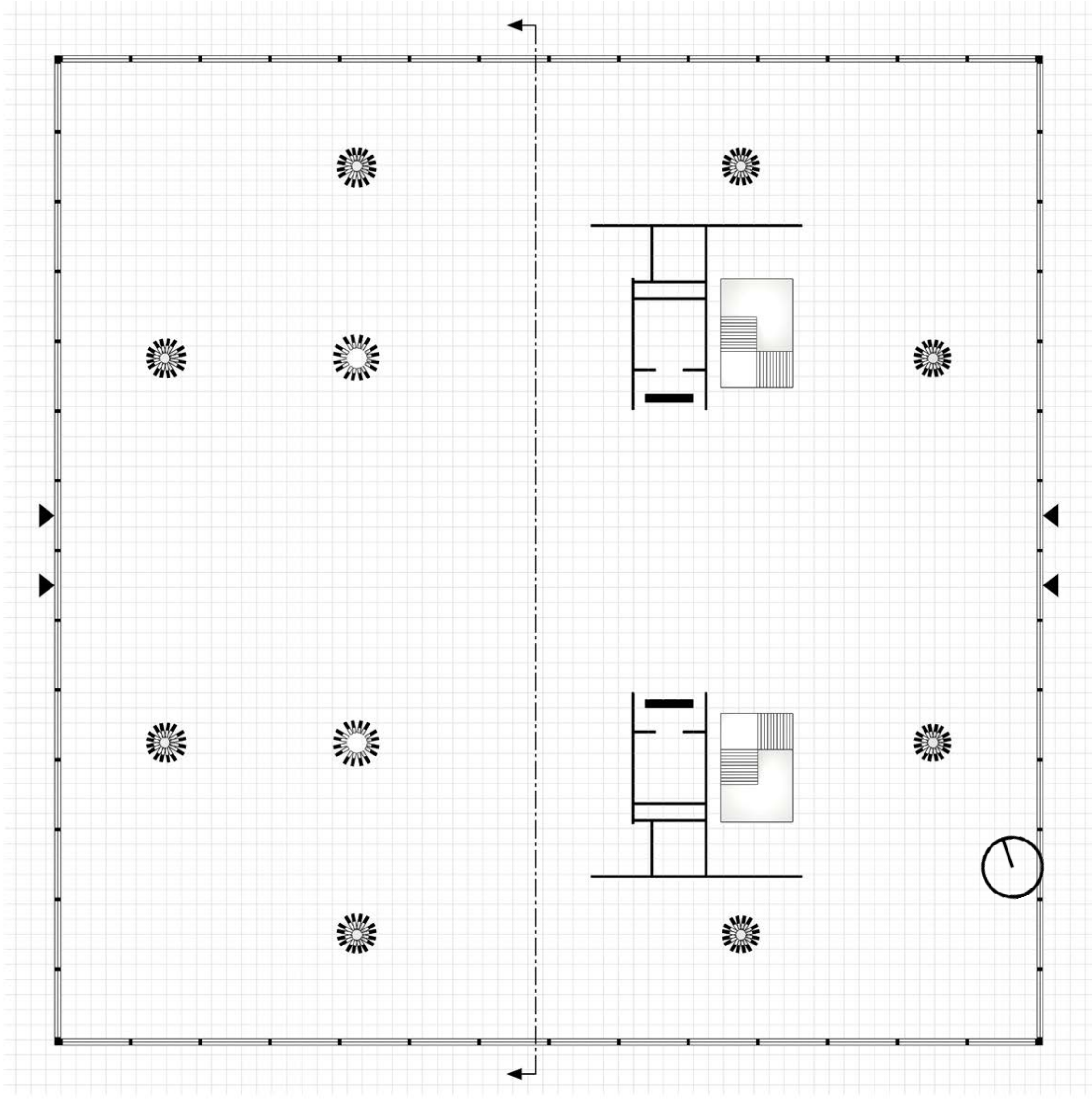


Figure 89: Plan of structure #1 in 1:300.

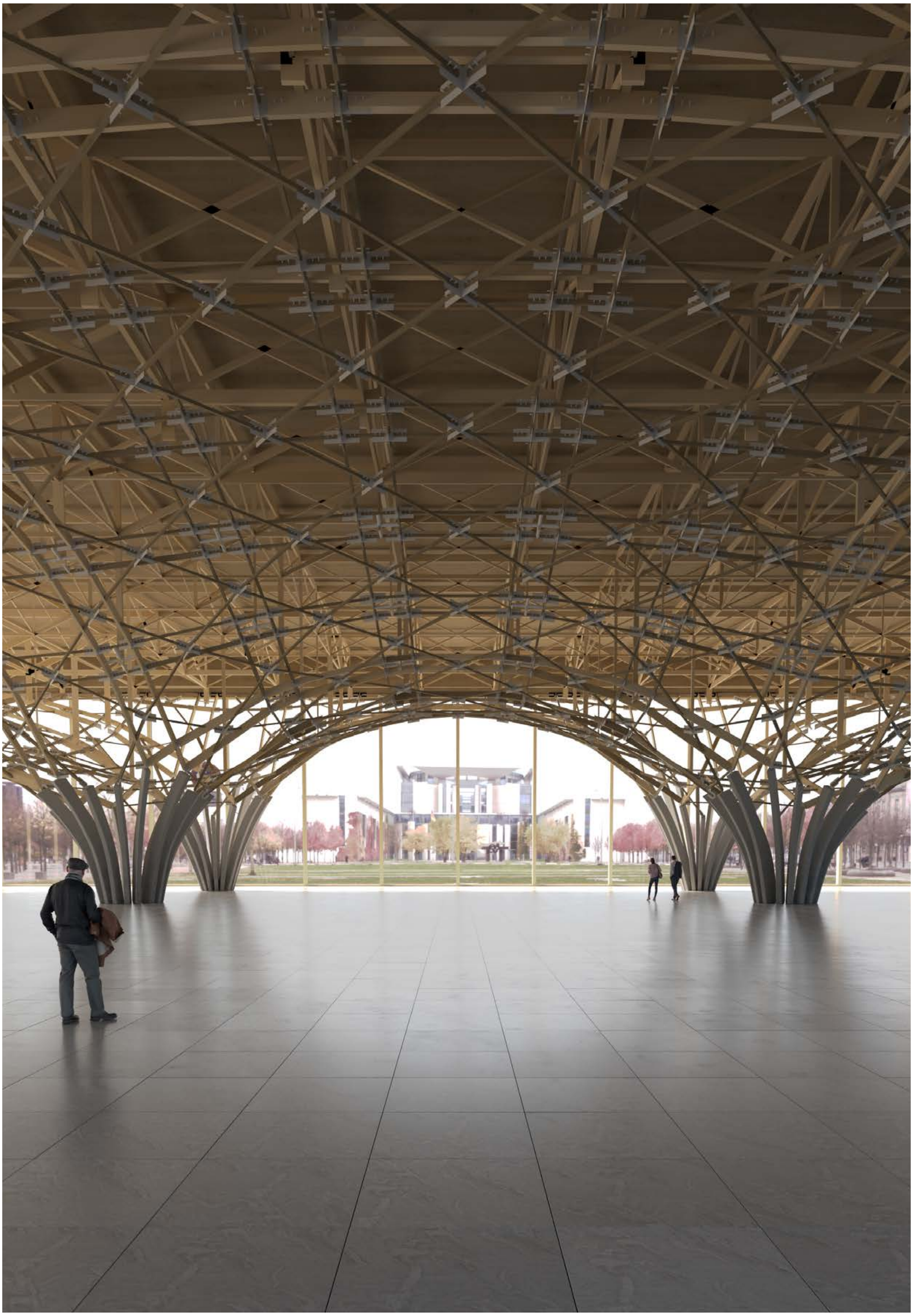


Figure 90: Interior rendering of structure #1

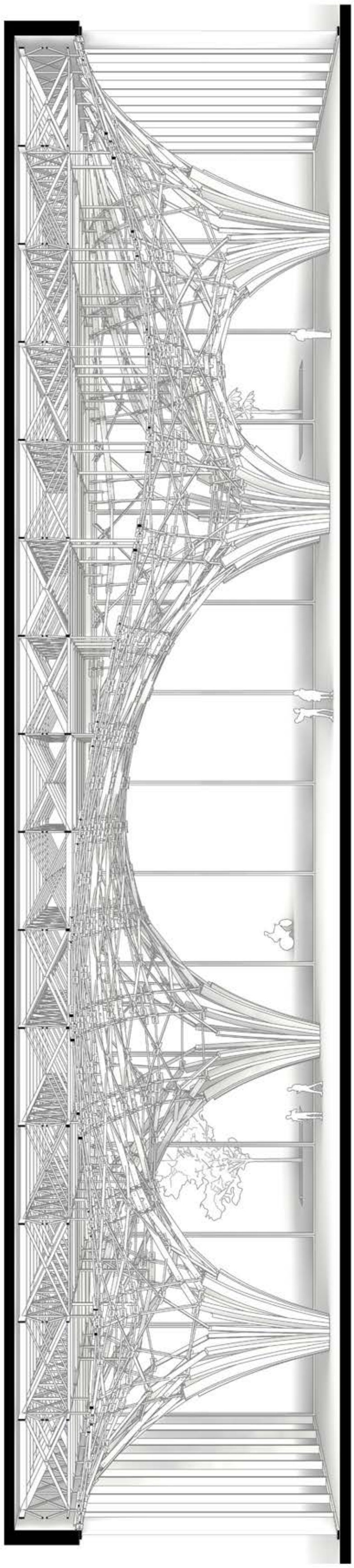


Figure 91: Section of structure #1 in 1:200.

Structure #2

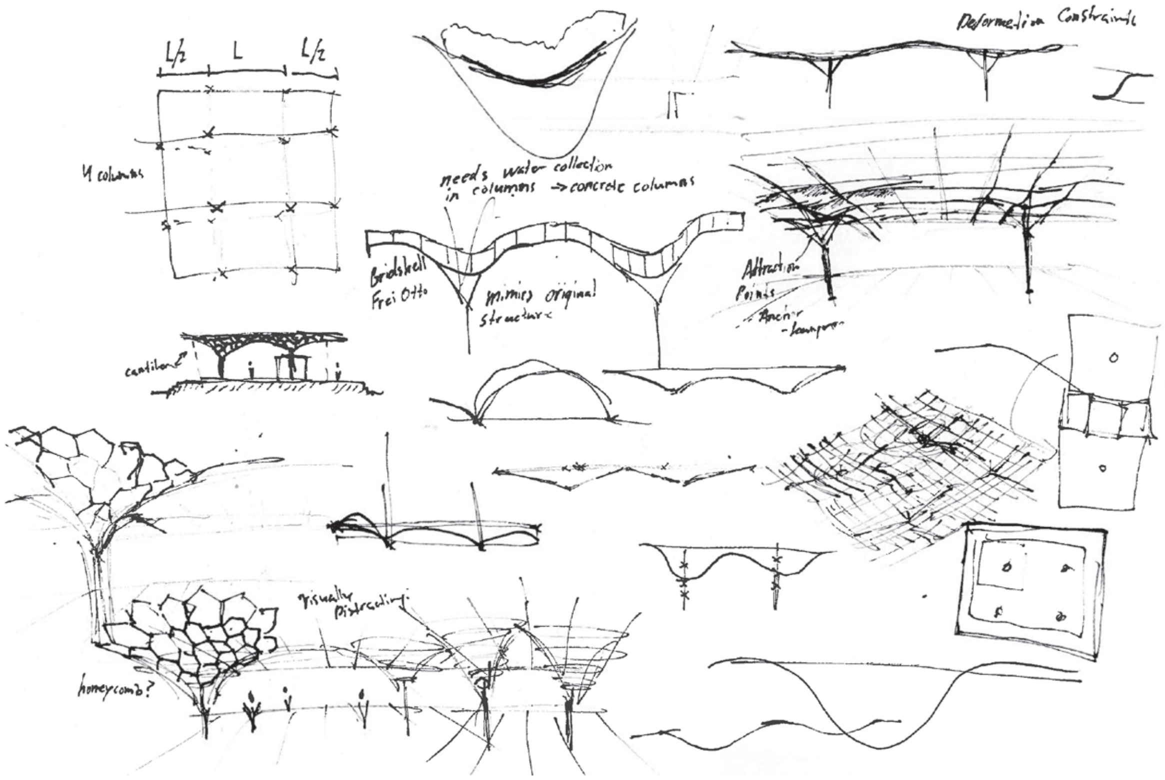


Figure 92: Initial sketches of reciprocal frame structures.

Initial proposals for spanning structures utilized reciprocal frames. This approach was influenced by Apolinarska (2018), who demonstrated the feasibility of robotic construction for such systems. Early studies of reciprocal frames, as seen in figure 93 reveal a predominant use of short, discrete elements. This characteristic aligns well with the selected material stock for this research: reclaimed timber from mink farms.

Through iterative structural analysis and form-finding, the structure depicted in figure 94 was derived. This design evolved from a single layer of reciprocal frames to a stacked, double-layered space frame. The structure also necessitated additional support points, leading to an increased number of columns in the final design.

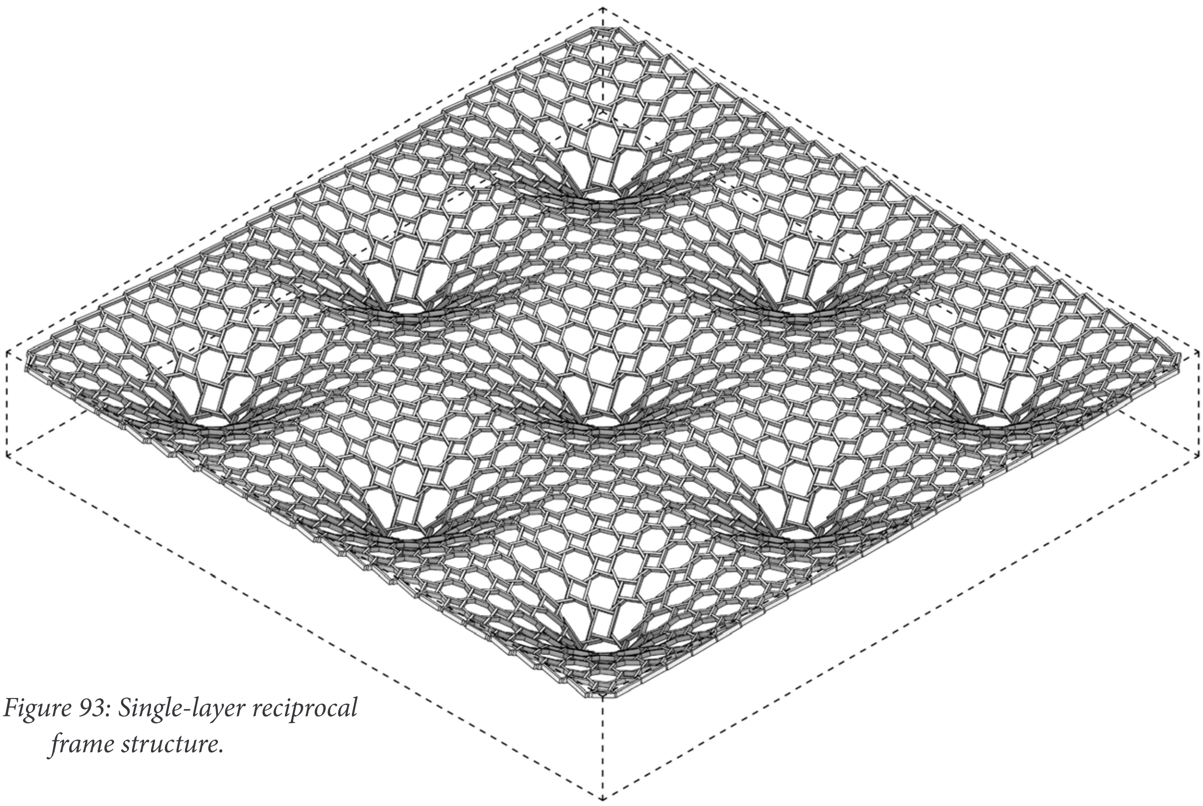


Figure 93: Single-layer reciprocal frame structure.

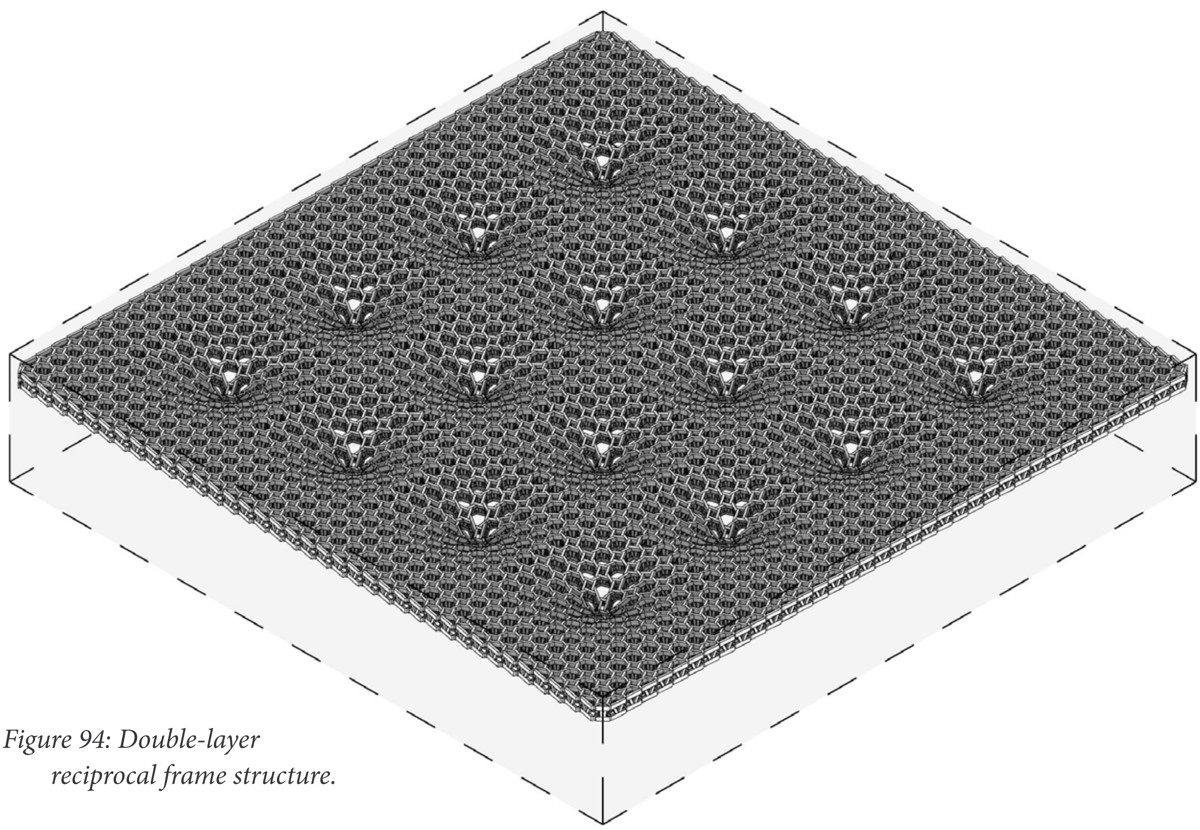


Figure 94: Double-layer reciprocal frame structure.

Iterative structural analysis is an essential component of the tool, enabling the determination of appropriate cross-sections for assigning reclaimed timber elements. The analysis as seen in figure 95, identified cantilever edges and column supports as critical areas requiring larger cross-sections, while most other structural elements were found suitable for smaller dimensions.

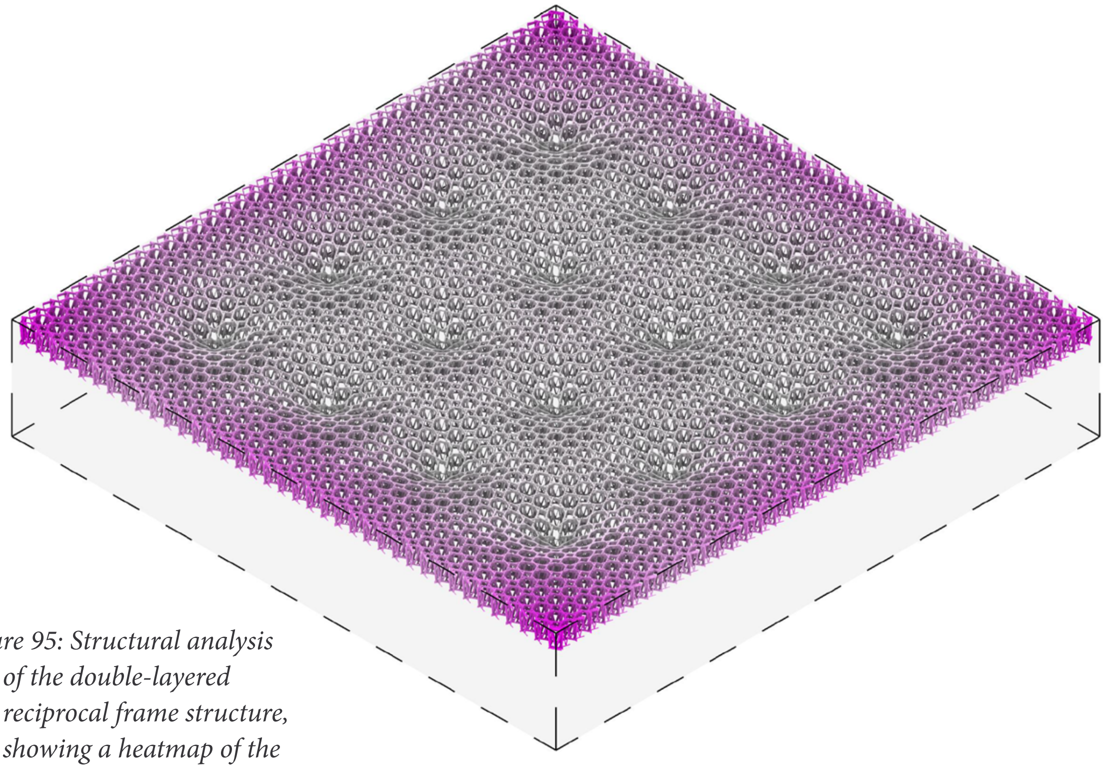


Figure 95: Structural analysis of the double-layered reciprocal frame structure, showing a heatmap of the deformation.

Following the iterative structural analysis, a list of demand elements is generated, to which the matching algorithm assigns reclaimed timber. The algorithm successfully assigns a diverse range of reclaimed timber elements across the structure as seen in figure 96, with the exception of the aforementioned critical areas (cantilever edges and column supports), which often require new timber. Given the structure's scale (approximately 35,000 elements), and the time prohibitive nature of the meta heuristic matching algorithm.

The greedy heuristic algorithm was employed, achieving matching in approximately 30 seconds, a significant improvement over the 40 minutes required by the meta-heuristic approach in Structure #1, making the number of iterations possible increase

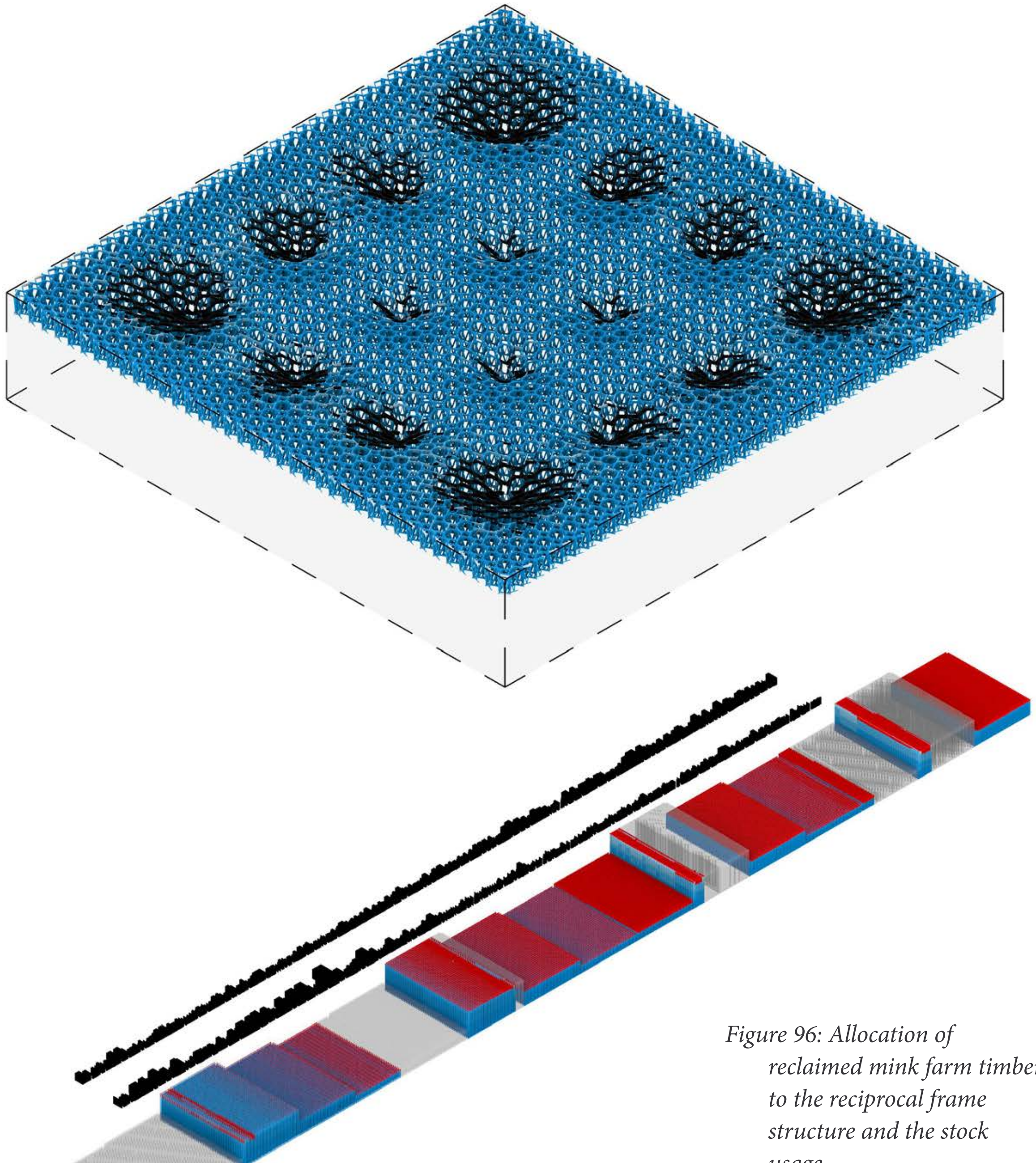


Figure 96: Allocation of reclaimed mink farm timber to the reciprocal frame structure and the stock usage.


Figure 97: Interior rendering of structure #2.

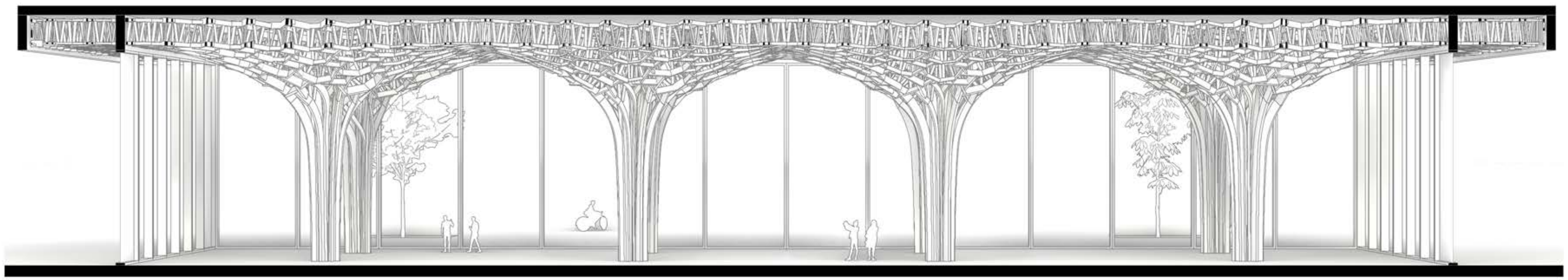


Figure 98: Section of structure #2 in 1:200.

Conclusion

The aim of Design Study #2 was to test the tool's performance on complex structures by redesigning the Neue Nationalgalerie in Berlin, originally designed by Mies van der Rohe, with reclaimed timber as a guiding constraint. The criteria for the experiment allowed for modifications only to the upper building volume and emphasized maximizing the span. While the resulting structure fulfilled these criteria, the tool's performance and its integration into the design process proved suboptimal.

As outlined in the experiment description, the computational load increases with the number of elements in the model, directly affecting the time required to generate results. By comparing the two versions of the matching algorithm, meta-heurstic and heuristic versions, it became evident that they serve two different purposes.

The meta-heuristic version, while far more effective in reducing cut-off waste, performs the matching too slowly for the iterative design process. On the other hand, the heuristic version can perform the matching in an appropriate time frame for such a complex structure, but produces far more waste than the meta-heuristic version.

Epilogue

Conclusion

This thesis addressed the imperative of Designing with Scarcity by developing and evaluating algorithmic workflows for the structural optimization of buildings using reclaimed timber. As demonstrated through the parallel approach of tool development and the design studies, the presented tool offers a pathway to integrate principles of circularity and material-flow-first thinking into the architectural design process.

The tool provides feedback on the material utilization of available reclaimed timber stock, transforming it from a passive constraint into an active design factor in form-finding. Contemporary structural analysis frequently sizes elements by referencing a critical member. In contrast, this tool provides a complementary optimization strategy by discretely assessing each structural element and assigning available reclaimed material specifically suited to its individual performance requirements, a crucial method when dealing with the material heterogeneity of a stock of reclaimed timber. Its adaptability to varied structural typologies and design constraints, as explored in the Design Studies, underscores its potential.

Design Study #1 (the house renovation) successfully showcased the tool's potential of guiding design towards reduced virgin timber use, achieving 100% reclaimed timber utilization in the optimized structure. This was achieved by leveraging the meta-heuristic optimization (via Wallacei) to refine geometry based on architectural intent and material availability, effectively demonstrating how scarcity can drive resource-efficient design. This aligns with the conceptual frameworks of Metabolism and the built environment acting as a Safe Sink.

Design Study #2 (the Neue Nationalgalerie reimagining) highlighted a key challenge: the computational load associated with analyzing highly complex structures with a large element count can become prohibitive, impacting the practicality of developing iterations.

In directly addressing the research question—how algorithmic workflows can adaptively allocate reclaimed timber, leveraging material scarcity as a driver of form—this thesis demonstrates a viable, albeit evolving, solution. The tool successfully bridges the tectonic mindset with the realities of finite resources, offering an architectural methodology for the mitigation of timber overconsumption. Future development should focus on enhancing computational efficiency, simplifying user interaction, integrating more comprehensive structural detailing and delivery to robotic fabrication.

Discussion

This thesis explored how algorithmic workflows could reshape the architectural design process, particularly with a mindset of form following availability. The ambition was to develop a tool that not only facilitates the structural use of such materials but also actively leverages material limitations as a driver of form. Developing this tool and testing it through design studies has highlighted both its potential and shortcomings, which warrants a deeper reflection.

From conceptual design to feasible structures

At its core, the developed tool seeks to operationalize vital sustainability concepts. It engages with the principles of Metabolism by tracking and managing the flow of reclaimed timber elements, aiming to slow virgin material consumption. In doing so, it supports the vision of buildings as Safe Sinks – active repositories of material value that significantly extends the life cycle of timber, transforming potential waste streams into valuable assets for future construction. The embedded documentation features, designed to save geometric and material data, are foundational to this long-term perspective. Furthermore, the challenge of working with reclaimed timber, with its inherent variability in size, quality, and history, necessitates a reimagining of the tools necessary in the design process.

While the direct implementation of robotics and fabrication was beyond this project's scope, the research into advanced manufacturing was critical in understanding the contexts where such a tool would be feasible. As evident in the research in Robotic Fabrication of discrete elements, through the cases of The Sequential Roof and Woodstock Robotics, there is a potential in using robotics for variable reclaimed elements, even for highly complex structures.
Further development could improve the tool to prepare construction-ready drawings for robotics to cut the reclaimed stock elements, as well as assemble them, effectively providing a proof-of-concept for a streamlined approach from design to construction. By providing near-instant feedback, the designer would be informed of both the structural expression and detailing of joints possible for the designed structure. These points highlight the need for robust feedback loops between digital design, fabrication processes and on-site execution, fostering a closer collaboration between designers, engineers, manufacturers and contractors than is often typical today. While the economic aspect of reclaimed timber was not a central research parameter, the cost-benefit analysis of sourcing, processing, and integrating reclaimed timber through such advanced workflows is an undeniable factor in its broader adoption.

Navigating computational complexity and architectural design

The design studies, particularly the renovation case, demonstrated the tool's capacity to act as an effective design companion, providing feedback on reclaimed timber utilization. It successfully guided the design process from an initial 75% reuse potential to a fully reclaimed timber structure through iterative optimization. This ability to identify and prioritize members under lower stress for replacement with reclaimed timber, offers a significant advantage in maximizing reuse. However, this interaction is not without its nuances.

The visualizations from Design Study #1 revealed a key challenge: one optimal solution, driven by the input parameters for the meta-heuristic search, unexpectedly resulted in concealing a spatially significant joint. This outcome highlights the complexity of integrating optimization and balancing geometric variables with both architectural expression and material reuse efficiency. As specifically crafted hierarchies of criteria are needed, it increases the designer's cognitive engagement and load specifically in the area of evaluation. However, this nuanced demand should be contextualized; if the contemporary architectural design process is to consider material reuse beyond a conceptual level, the tool would decrease the overall cognitive load for architects pursuing practical solutions by heavily simplifying many complex tasks.

Bridging the Digital and Physical

The effective transition of this tool from a research prototype to a practical solution hinges on navigating several real-world complexities. The tool's current reliance on simplified structural analysis, while adequate for early-stage design exploration, necessitates further structural verification for construction-ready outcomes. Critically, its performance is intrinsically linked to the quality and availability of data regarding the reclaimed materials. Currently, this data is often incomplete, inconsistent, or difficult to obtain. Without reliable stock databases, standardized grading protocols, and traceable material histories, the tool's outputs remain somewhat speculative.

There is also the consideration that changes made in the digital environment affect the constructability of the proposed structure. For example, while using shorter elements may reduce the amount of new timber required, it also increases the number of joints, making the structure more difficult to assemble. Therefore, an evaluation that does not include metrics for the time required for the fabrication and assembly of elements and joints would not provide a satisfactory feasibility analysis, particularly in bridging the gap between the digital and the physical.

From this, the question of joint design becomes critical: which joint type should be selected, and when? For future development of the tool, a joint library could be implemented, enabling automated allocation of joint types based on the angle between elements and the number of elements converging at a given node.

Accessibility and the path to broader Impact

The practical utility of any new tool is significantly influenced by its accessibility and ease of integration into existing workflows. The current iteration, built within the Rhino Grasshopper environment and leveraging Karamba3D, anticipates a degree of familiarity with parametric modeling and computational design. This barrier to entry could limit its use by most architects in the building industry.

Methodology framework

Referring back to Oxman's models and the varying levels of familiarity with the parametric and computational design space, one could argue that "experts", in this case, the tool's developers, can fully utilize the tool, situating it within the compound model. For architects with less experience in this domain, the tool would be used more in line with an augmented Performance-Based Generative model. While it draws conceptual inspiration from Oxman's compound model, the tool does not support multidirectional

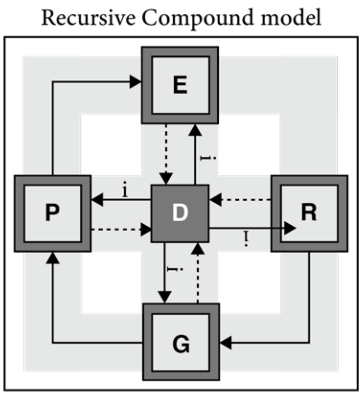


Figure 99: Recursive Compound Model, inspired by Oxman (2006).

data flow across all modules. Instead, the process remains linear: data flows from the digital representation, through generation and performance evaluation, and ends at the evaluation node, where it awaits new input via the representation module before continuing. Meaning that direct tampering with the tool becomes locked.

For the tool to achieve wider impact, future development must prioritize a more intuitive user interface, as it is perceived that only few in the industry have computational design experience. It could also be imagined that future advancements in Artificial Intelligence and its incorporation with tools such as Rhino Grasshopper, could function as an expert by translating architectural sketches to Karamba3D-ready Rhino Grasshopper models. This could effectively provide a streamlined process that transforms sketches into structurally viable designs optimized for material reuse.

The computational demands observed in Design Study #2, where processing times increased with model complexity, questions the practicality of the tool when addressing complex structures. As the number of elements in a structure increases, the computational time increases drastically, as discussed in the Algorithms chapter. The chapter Tool Development concludes with a suggestion of two algorithms, a fast version using heuristics, and a slow version using meta-heuristics. The heuristics version of the tool produces a significant increase in cut-off waste, but is much faster when handling large data sets. This ultimately questions the use of such a tool in complex structures.

In practice, the design phase for more complex structures may benefit from the faster, materially inefficient heuristic algorithms, accepting a degree of waste for the sake of processing speed. In contrast, less complex cases such as in Design Study #1, could use the slower, meta-heuristic algorithms to provide more precise feedback and optimized solutions.

Towards a materially intelligent future

Despite these challenges, the algorithmic workflow developed in this thesis offers a compelling vision for a more materially intelligent architectural design practice. It provides a tangible means to engage with the principles of circularity and resource management, transforming the constraints of scarcity into opportunities for design innovation. The tool serves not as an autonomous decision-maker, but as a collaborator, empowering architects to make more informed choices about material use, structural form, and spatial expression. This thesis affirms that by thoughtfully embracing digital tools and critically engaging with their outputs, architecture can design more sustainable, and expressive ways of building with the resources already at our disposal.

List of figures

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Appendix

A

The following scripts account for the main scripts used in The Tool developed in the thesis:

Eurocode 5 Cross Section Optimizer

This script accounts for the structural analysis performed by The Tool, iteratively performing structural analysis going from the first to the last cross section used as input, the FE-analysis is performed with the Karamba3D library (Preisinger, 2013).

Matching Algorithm - Heuristic

This script performs the allocation of a list of demand elements to a list of reclaimed stock elements. The strategy used is a heuristics one, meaning it greedily applies the best matches it first finds.

Matching Algorithm - Meta-heuristic

This script performs the same allocation of a list of demand elements to a list of reclaimed stock elements. The strategy used in this one, is meta-heuristic, meaning it simulates different packing arrangements in order to find a global optima.

All of these can be found in the following github repository, along with a template Rhino Grasshopper file.

https://github.com/OKlejs/Designing-with-Scarcity

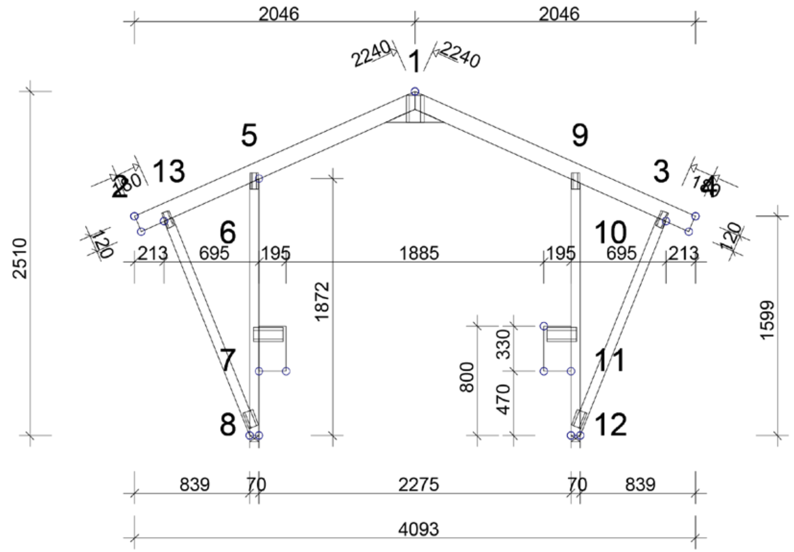
B

Mink specfications can be seen on the following page

S1 - 59 stk.

Vægt: 25 kg/stk

59 stk. 2-rk
max. c/c 206cm



GENERELLE OPLYSNINGER

SPÆRET ER KONSTRUERET OG BEREGNET MED EDB-PROGRAMMET "TRUSSCON". LIC.NR: 8269
SNITKRÆFTER ER BEREGNET SVARENDE TIL 1.ORDENS DEFORMATIONSTEORI.
TRÆNORM : EN 1995-1-1 + DS-NA + DS/INF 175:2009
BEREGNINGSMETODE 2 iht. EN14250 pkt. 5.1
TANDPLADER: EN-GODKENDELSE

MAX. LÆGTEAFSTAND 400 mm.

BEREGNINGSFORUDSÆTNINGER:

TRÆTYKKELSER: (mm)	45
SPÆRAFSTAND c/c (mm):	2060
ANVENDELSESKLASSE (1=I, 2=IU, 3=U):	2
KONSEKVENSKLASSE (1=CC1, 2=CC2, 3=CC3):	1

BRAND - KLASSE: D-s2, d0 (Ikke brandimprægneret)
SPÆRFABRIKKEN OVERVÅGES AF DS CERTIFICERING A/S
PRODUKTCERTIFIKAT 0527-CPD-2215

BELASTNINGER (N/m²):

SNELAST (GRUNDVÆRDI):	900
VINDLAST (GRUNDVÆRDI):	540
NYTTE LAST:	NR

EGENLASTE: SE TRÆTABEL.
ØVRIGE LASTE: SE BEREGNINGSUDSKRIFT.

VEDERLAGSREAKTIONER BRUDGR. (N):

NR	RETN.	LK P MAX	LK M MAX	LK K MAX	LK Ø MAX	LK Ø MIN	V-BR MM
8	Horiz	-29	-24	-289	1507	-200	
8	Vert	1214	1012	5109	3166	-917	9
12	Horiz	29	24	289	-2239	1332	
12	Vert	1229	1024	5122	3029	-1054	10

TOLERANCE FOR FORBINDELSEMIDLET: 10 mm

TRÆ:

TYKKELSE 45 mm

TRÆ-DEL	HØJDE mm	KVAL.	AFSTIVN. mm	LAST N/m²	UDN. %
4-1	120	C24	400	220	93
1-2	120	C24	400	220	96
5-8	70	C18	Nej		95
9-12	70	C18	Nej		96
3-12	70	C18	Nej		53
8-13	70	C18	Nej		41
Kile 1	95	C24			1
6-7	195	C24			
10-11	195	C24			

TANDPLADER: EXCL. STØDSAMLING

KNUDE NR	PLADE-TYPE	BREDDE mm	LÆNGDE mm	UDN. %
1	GNT100S	130	198	63
3	GNT100S	55	119	60
5	GNT100S	55	119	67
8	GNT100S	76	119	61
9	GNT100S	55	119	84
12	GNT100S	76	119	80
13	GNT100S	55	119	60
7	GNT100S	103	218	
11	GNT100S	103	218	

TANDPLADER - STØDSAMLING:

KNUDE NR	PLADE-TYPE	BREDDE mm	LÆNGDE mm	UDN. %

MAX DEFORMATION FOR KARR. LAST (mm):

KNUDE NR	VERT.	HORIZ.	LK NR.
4	-15.9	-28.3	26
2	15.6	-27.6	26
1-9	1.8	-36.1	26

FOR DEFORMATION I FLERE PUNKTER: SE BER.UDSKRIFT

VERSION: 2019d
TID: 14.26

TrussCon

TEGNET KONSTR.AF	GODK.	ORDRE NR.
, den 11.12.2013		40022

Brian, Tårs

Projektleder: kaj
Kontrol. af: sap

SKALA 1:45(A4)

TYPE	TEGNINGS NR.	REG.
S1