Timber-only Structures & Architecture

Exploring the Potential of Using Salvaged Timber and Wooden Nails

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Abstract

In light of the serious environmental challenges, it is urgent to ease the current dramatic increase of CO2 emissions. The building sector, as one of the major contributors to global CO2 emissions, is on the move to a more conscious and environmentally compatible thinking. The use of natural resources, short transport, low processing of raw material, and prolonging life cycles of existing building components, are some of the keywords in this context.

In this thesis, a concept of timber-only structures and architecture was proposed to explore possible sustainable solutions for future building construction. Specifically, salvaged timber and wooden nails were used as the only material and connector for building structures. This research consists of three main research phases:

The first phase was initiated by a pedestrian trail project, which searched for a more cost-efficient and more sustainable solution to replace the traditional trail-making in Finland. The solution was mainly based on two individual parts - (i) an investigation on the wooden nails in terms of usage, nailing arrangements, and structural behavior, and (ii) an investigation on salvaged timber in terms of availability, planar arrangements, and resulting patterns. The outputs from the individual investigations were merged in the trail design, where full-scale prototypes were built up and an exhibition was performed.

The second phase rethought the design process of the trail. A systematic review of integrated design concepts was conducted. Inspired by the review, a concept of using feedback loops was proposed to reinterpret the design process of the trail. This feeding-back process also informed a more complex structure to be studied in the following phase.

In the third phase, a planar rectangular slide-in reciprocal frame (RF) system was proposed. A systematic investigation was carried out regarding structural performance, assembly logic, possible layouts, and resulting architectural spaces. As a showcase, a canopy was designed and built by applying the outputs from the investigation, and then exhibited to the public.

According to the overall process of the exploration using salvaged timber and wooden nails, the concept of timber-only structures and architecture showed its potential in various aspects: (i) wooden nails can provide sufficient load-bearing capacity for structural applications, at least for less-loaded structures or structures with low safety requirements; (ii) salvaged timber brings both structural and aesthetic values for new constructions; (iii) using feedback loops to interpret the building design process can bring more holistic solutions compared to the traditional linear design approach; and (iv) the planar rectangular slide-in RF system brings unique architectural features and structural benefits, but they are associated with large deformations and a brittle failure mode in terms of structural behaviour.

Keywords timber-only, structures and architecture, salvaged timber, wooden nails, sustainability, integrated design, feedback loops, pedestrian trail, slide-in system, analytical model

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Preface

In memory of beloved teacher/colleague Dr. Djebar Baroudi.

There are many ways to explore the universe. Some may choose astronomy, some may choose philosophy. I chose to use timber – a building material that has been used throughout human history. This decision stemmed from a fleeting yet profound insight when I saw M.C. Escher's artwork "Stars" in Pisa, Italy, in 2017. “He who wonders discovers that this in itself is wonder”. It has subsequently led me to this PhD journey.

In this academic exploration, my PhD supervisors Prof. Gerhard Fink and Prof. Günther H. Filz are important mentors. Their collective expertise spanning engineering to architecture has paved me a way where rigorous analysis meets radical creativity, offering me invaluable insights that will undoubtedly shape my future career.

I would like to express my sincere gratitude to my thesis pre-examiners Prof. Yves Weinand and Prof. Mariapaola Riggio for their efforts on reviewing this thesis and providing valuable feedback, which have significantly enriched the quality of this work.

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Preface

This thesis is dedicated to my grandfather who is the most important teacher in my life and my parents who unconditionally supported me from the very beginning of this journey. Thanks Jiaxin for everything.

Helsinki, February 8, 2024,

Gengmu Ruan
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List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.


Author’s contributions

Publication I: “Shear capacity of timber-to-timber connections using wooden nails”

Gengmu Ruan conducted the literature review, planned and conducted the experimental tests, analyzed the test results, developed the analytical model, and wrote the manuscript. Günther H. Filz and Gerhard Fink provided feedback for the investigations and the manuscript.

Publication II: “An integrated architectural and structural design concept by using local, salvaged timber”

Gengmu Ruan conducted the literature review, planned and conducted the experimental tests, designed and fabricated the prototypes, and wrote the manuscript. Günther H. Filz and Gerhard Fink provided feedback for the investigations, the design and fabrication of the prototypes, and the manuscript.

Publication III: “Master builders revisited – The importance of feedback loops: a case study using salvaged timber and wooden nails only”

Gengmu Ruan conducted the literature review, conducted the theoretical research, designed and fabricated the prototypes, and wrote the manuscript. Günther H. Filz provided feedback for the theoretical research, the design and fabrication of prototypes, and the manuscript. Gerhard Fink provided feedback for the manuscript.

Publication IV: “Planar rectangular slide-in reciprocal frame system using salvaged timber and wooden nails”

Gengmu Ruan conducted the literature review, planned and conducted the experimental
tests, analyzed the results, developed the analytical model, designed and fabricated the prototypes, and wrote the manuscript. Günther H. Filz provided feedback for the conceptualization. Gerhard Fink provided feedback for the experimental investigations, the analytical model, and the manuscript.
Abbreviations

DfD  design for disassembly
ISAD  integrated structural and architectural design
MID  material-based integrated design
RF  reciprocal frame
1. Introduction

The initiative of this thesis was a collaboration between two disciplines – structural engineering and architecture, for a pedestrian trail project in the city of Kouvola, Finland. The goal of this project was to search for a more cost-efficient and more sustainable design concept as an alternative to the traditional Finnish trail-making solution (see Figure 1.1), which normally requires high-quality timber boards (with large length and large cross-section), use of metal fasteners, possibly high costs for maintenance, and at the same time, lacks aesthetics. This led to an exploration of using only timber to realize the trail, including both structural components and connections. Subsequently, a more general question was raised – what can be built by using this timber-only idea? This question has initiated this thesis.

This is an article-based thesis, which means that it is a summary of the published articles within the topic complemented with additional information. The most important aspects, such as motivation, scope, objective, methodology and results are summarized in the texts, and the publications are referred to and attached.

1.1 Background

In light of the serious environmental challenges, it is urgent to ease the current dramatic increase of global CO₂ emissions [1]. As one of the major contributors – the building sector, which is accounting for around 39% of global CO₂ emissions [2], is on the move to more conscious and environmentally compatible thinking. The use of natural resources, short transport, low processing of raw material, and prolonging the life cycle of existing building components, are just a few keywords in this context.

To achieve a more sustainable built environment, it is crucial to rethink building design process, since it can have a huge impact on carbon reduction at an early (conceptual design) stage [3]. Nowadays, building design process is fragmented into different professions in most of building cases. This may cause high inefficiencies due to the difficulties in collaboration between the different professions. In this regard, integrated design concept has been proposed as a solution [4], where the importance of integrating structural and architectural design has been often highlighted [5, 6].

Another important factor for environmental sustainability can be recognized in the
use of building material, since it contributes nearly 10% to the global CO\textsubscript{2} emissions \cite{7}. As a possible solution, increased demands for timber construction have been proposed, among others, due to the ecological benefits \cite{8}. However, it also brings new challenges regarding sustainability. One is that annual demolitions of timber buildings and cut-offs from timber fabrications and pre-fabrications result in large amounts of timber waste. In fact, this type of waste timber may hold sufficient load-bearing capacity and there exists a great potential to salvage them for structural applications \cite{9}. In the mindset of life-cycle thinking of use and reuse, salvaged material plays an important role. Another issue is that newly built timber structures are mostly connected by metal connectors, which means that relatively large amounts of metal products are still in use. To this end, using natural material, such as wood, for making timber connections may provide a greener solution for future timber construction.

Accordingly, this thesis addresses three main aspects that are related to the challenges mentioned above: (i) structures and architecture, (ii) timber "waste" as new building material, and (iii) wood-only connections – wooden fasteners. Therefore, each of the aspects is briefly introduced to clarify the research background and specific definitions in each field.
Structures and architecture
There was no clear division between professions like engineers and architects in ancient times. Master builder, who was responsible for the entire building process, took the role of liberal thinker (designer) and executor (builder) at the same time [10]. Based on knowledge learned from predecessors and experience gained from working with materials, the master builder was able to apply knowledge from different aspects, including material, form, and proportion of buildings, to making and building process.

In modern society, the role of master builder has become highly fragmented into more specialized professions, such as the architect, the structural engineer, and the construction manager. In this mode, in-depth knowledge from each profession could bring advantages to building projects, especially for complex ones. However, it may also result in inefficiencies due to the difficulty of collaboration between different professions.

In today's building design process, it is often the case that the architect only focuses on conceptualizing the building form, while the structural engineer is only responsible for rationalizing the structure and dimensioning the material [11]. Such separation may lead to a lack of efficiency in many aspects, such as excessive use of material, inappropriate selection of structural form, and high cost [12]. As a consequence, the relationship between structures and architecture has been reconsidered, as some examples have showcased in practice [5, 6].

Learning from the great examples in the past, from Eiffel Tower, Brooklyn Bridge, and Crystal Palace to the works done by Antoni Gaudi, Félix Candela, and Pier Luigi Nervi, it has proven that the design of structures could shape the architecture itself and offer a sense of "elegance", as emphasized by Schlaich [13]. Practice of integrating structures and architecture continues in contemporary architecture, and in some cases, more into specific building materials.

In the context of sustainability, timber has been often selected in such practice. Referring to the experience from ancient skilled carpenters and newly developed techniques of computer science and industrial production, i.e., computer numerical control milling, novel timber structures and architecture were able to be realized. Some representative examples are shown in, for example, the roof structure of Setas de Sevilla, Seville, Spain, which connects six large timber parasols to form a larger spatial lattice structure [14], the Tamedia office, Zürich, Switzerland, which has a highly prefabricated massive timber frame connected with mortise-tenon joints [15], and the Vidy Theatre Pavilion, Lausanne, Switzerland, which employed an idea of Origami for building double-layered plate structures using mortise-tenon connections [16].

Timber "waste" as new building material
"Construction waste" is defined as "debris generated during the construction, renovation and demolition of buildings, roads, and bridges" [17]. The level of recycling or reusing construction waste can vary greatly from different cases. For example in the EU, it can range from 10% to 90% [18]. Particularly in timber construction, long pieces of timber might be also distinguished as waste in some circumstances, such as the cut-offs resulting from prefabrication of timber components, even they have lengths of up to meters and relatively large cross-sections.
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In fact, the not-too-short and not-too-thin timber pieces are able to be reused since they may have sufficient quality for structural applications. However, some barriers of utilizing salvaged timber for structural purposes exist. For example, there are difficulties to separate structural components after their service lives; the durability of salvaged timber needs to be considered; there may have a large variation of mechanical properties; there is a lack of information of loading history; there is a lack of knowledge to use salvaged timber for alternative applications; there are a lack of grading standards for salvaged timber and so on [19, 20].

Different applications using salvaged timber have been explored. There are mainly two categorizations concluded here. The first categorization is to partly or entirely use salvaged timber for fabricating new engineered wood products, such as cross-laminated timber [21, 22] and dowel-laminated timber [23, 24]. The second categorization is to use salvaged timber as the main structural members for building entire structures. Some proposals have been suggested during the last few years. A general guidance of using salvaged timber for structural frames has been suggested by Addis in his design handbook for the use of reclaimed components and materials [25]. Huuhka [26] proposed some principles for reclaimed timber in architectural design, such as to "define ranges instead of fixed properties" and "use efficient forms for long spans from short pieces". Parigi [27] suggested to apply the concept of structural reciprocity to the use of salvaged timber for making load-bearing structures. Pronk et al. [28] conducted a case study by using reclaimed timber formwork for a residential villa in Amsterdam, the Netherlands. Bruun et al. [29] proposed a concept that integrated the removal of existing timber components and their reuse in new assemblies with robotic fabrication. Furthermore, a combination of both categorizations was presented by Klinge et al. [30], where a design concept was proposed by using reused and recycled timber material for reversible multi-story residential buildings.

Wood-only connections – wooden fasteners

Wood-only connections have been used for centuries in timber construction both in eastern and western cultures [31]. In general, there are two basic types of wood-only connections available: (i) carpentry connections, such as mortise-tenon connections, and (ii) connections with wooden fasteners, such as wooden dowels. In practice, a combination of the two types might be used in order to increase strength and stiffness properties of the connection.

Traditionally, the making of wood-only connections has been done by professional carpenters with high mastery of skills, and the process usually took time. For making wooden dowel-type fasteners, hardwood was commonly used [32]. Currently, the developments in fabrication techniques and wood science have made the process easier and the joints stronger, e.g., carpentry connections with complex configurations can be quickly produced by robots [33], and the strength of wooden fasteners can be significantly increased when using wood densification techniques [34].

In 2004, a wooden dowel-type (lateral-loaded) connection was performed by Pizzi et al. [35], which introduced a wood dowel welding technique. The mechanism is to utilize the heats generated during the high-speed rotation welding to melt some polymer materials.
in wood, mainly lignin, which therefore becomes a sort of "glue" that can enhance the bonding of the interface between fastener and wood when temperature drops [35].

In 2013, a wooden nail product was introduced by applying the wood welding technique [36]. However, little research has been conducted related to it. Experimental investigations on the mechanical behaviour of densified wooden nails were carried out by Riggio et al. [37], where applications for modestly loaded and moderately dense timber elements were suggested. The mechanical properties of beech wood nails with different diameters were first reported by Lademann [38], and later approved to be sufficient for load-bearing timber connections [39]. Karte et al. [40] proved that the pull-out strength of the beech wood nails could be doubled when using pneumatic nailer compared to steel nails or hammered wooden nails. Han et al. [41] demonstrated the potential of using wooden nails to replace adhesives and metal nails, but with higher probability of failure.

Few applications of wooden nails have been attempted so far. Inoue et al. [42] explored the possibility of using wooden nails for connecting wooden pallets, and Hasan et al. [43] integrated the use of wooden nails with robotic fabrication of wooden pavilions. A recent building-scale case that used the wooden nails was shown in the BUGA wood pavilion, Heilbronn, Germany, where the pneumatic nailer worked together with a robotic arm for connecting small wooden blocks in the fabrication process [44]. Hudert et al. [45] explored the robotic fabrication of wooden nail connections considering knot detection.

1.2 Scope & Objective

As a consequence of research in the various fields and respective philosophical viewpoints, this thesis pays a special focus on timber-only connections, structure members and/or entire structures with integrated architectural, structural and sustainable design thinking. To explore the potential of this concept, as well as to initiate the process, salvaged timber and wooden nails were selected as the only material and connector (fastener) for building structures. A brief introduction of the related subjects and their specific definitions and scopes is given below.

**Timber-only structures and architecture**

In this thesis, the meaning of timber-only structures and architecture is two-folded: (i) from the perspective of material, all the structural components, e.g., posts, beams and floors, and connections, are made from salvaged timber and wooden nails only, without metal connectors; and (ii) from the perspective of the relationship between structures and architecture, timber as a unique building material works both as load bearing elements of structures and as an expression of aesthetic considerations.

**Salvaged timber**

The salvaged timber in this thesis mainly represents timber cut-offs collected from a local timber construction company (see Figure 1.2) and timber wastes from local construction sites. The main concern for the selection of material source was highly related to sustainability issues, that is to reduce material transportation, and to avoid on-site processing, such as de-nailing and cutting.
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**Wooden nail connection**
In this thesis, densified beech wooden nails (Lignoloc®) that work together with a pneumatic nailer (see Figure 1.3) were chosen as the only fastener for making timber structures. Some of the benefits of using wooden nails include: quick and simple processing using the pneumatic nailer without pre-drilling and gluing; no thermal bridge due to its low thermal conductivity; more environmentally friendly compared to metal nails [46]. At the same time, some limitations include: mechanical properties are relatively low; the dimensions of wooden nails are larger than steel nails, which means that there are higher risks for cracks and larger spacing is needed.

In the scope of the three above-mentioned subjects, the main objective of this thesis is defined as to explore the potential of building timber-only structures and architecture merely using salvaged timber and wooden nails.

*Figure 1.2.* Salvaged timber stored at an open area in a Finnish timber construction company.

*Figure 1.3.* Wooden nails (left) and pneumatic nailer (right).
1.3 Structure of this thesis

This thesis contains three main phases and builds upon four publications. An overview of the structure of the thesis, including the individual chapters and their interconnections, is illustrated in Figure 1.4. In general, the entire process starts from searching a specific building solution for the pedestrian trail with a focus on nailing strategy and timber arrangement (Phase I), continues with rethinking the trail design process due to the predefined design constraints, here meaning that only salvaged timber and wooden nails can be used (Phase II), and ends up with an exploration of an informed structural system by the lessons learned from the rethinking process (Phase III). The three main phases are arranged in three main chapters (Chapter 2, Chapter 3, Chapter 4). The developing logic between adjacent phases is highlighted at the end of previous chapter (insights for next phase) and at the beginning of the following chapter (motivation for the current phase). Related details are shown in: (i) Section 2.6 and Section 3.1 for the interconnection between Phase I and II, and (ii) Section 3.4 and Section 4.1 for the interconnection between Phase II and III.

**Figure 1.4.** A graphical overview of the structure of the thesis and the related publications.
Chapter 2 explores a solution for building the trail with a specific focus on the nailing strategy and the patterns resulted by timber arrangements. The solution was mainly based on two individual parts – (i) an investigation on the wooden nail in terms of usage, nailing arrangements and structural behavior, and (ii) an investigation on salvaged timber in terms of availability, planar arrangements and their resulting patterns. Accordingly, the structural potential of wooden nail connection was explored by conducting experimental tests using different types of nails and nail orientations. The availability of locally salvaged timber was examined. Several visits to a local timber construction company and collections of materials were arranged. The collected materials were categorized according to their product types, dimensions and conditions. The salvaged timber were arranged in different ways to visualize the variety of their resulting patterns. To realize the trail, a specific nailing strategy and timber arrangement were chosen based on the two individual investigations. A full-scale prototype that consists of two main integral parts was built to demonstrate the proposed design solution. One part of the prototype was publicly exhibited with an emphasize on its social and artistic values. Furthermore, the trail project also prompted a consideration of integrated design concepts, which initiated a more in-depth discussion in Phase II (Chapter 3).

Chapter 3 provides a review of existing integrated design concepts in the fields of architecture and structural engineering. Since the design process started from salvaged timber (material) and wooden nails (connection), which differs from the traditional design approach that normally starts with the general shape (form), a discussion about architectural design methodology, more specifically, the involved aspects and their sequences in integrated design process, was initiated. Based on the works done in the trail, including all the successes and failures obtained, a systematic approach that uses feedback loops to reinterpret the design process was explored. The feeding-back process (the dashed line in Figure 1.4) resulted in, not only a conclusion of the trail design, but also insights for an informed structural system to be researched in Phase III (Chapter 4).

In Chapter 4 based on the insights from the "rediscovery" of the design of the trail, an informed structural system, which is able to use modular elements in various layouts, was explored. Apart from the resulting patterns of the trail, different nail-patterns and resulting "wood-products", such as panels (trail deck, perforated to closed), horizontal and vertical assembly to linear, planar, or curved elements or structures, were available for the research. In a sense, it brought more flexibility and complexity. A specific structural system was selected based on the insights from the rethinking process in the previous phase. Further investigations on the selected structure were performed regarding assembly logic, possible layouts, structural performance and resulting architectural spaces. Full-scale prototypes were built up as demonstrations. A specific design was physically realized as a showcase, and an exhibition was performed to highlight its social and artistic aspects.

Chapter 5 presents a summary of the thesis, novelty, as well as recommendations for future research.

It should be noted that this thesis includes a summary of four peer-reviewed publications (highlighted in gray in Figure 1.4) as well as supplementary information.
1.4 Scientific contributions

The main scientific contributions of this thesis can be described in four parts:

• By conducting experimental and analytical research on the shear capacity of timber-to-timber connections using wooden nails, the strength and stiffness properties of wooden nail connections were examined. Furthermore, suggestions for their use as load-bearing connections were provided [Publication I].

• Proposals for the use of salvaged timber were suggested, in which the availability, the properties and the idea of less processing of material become the driving force in design [Publication II, Publication III]. This is a contribution to the transition of building industry towards a more circular way of thinking. It also has an impact on beauty, and a future sustainability-based, aesthetic perception of our society.

• A systematic way of understanding building design process was explored based on a review of integrated design concepts. An experiment using the integrated design concept specifically starting from material and connection [Publication II], and interpreted by using feedback loops [Publication III] was performed. This will bring new possibilities for future building design process, and also offer a platform that allows different disciplines to interact in such a process.

• A systematic investigation on a more complex structural system that uses modular elements was performed, including load-bearing capacity, analytical model, assembly logic, and resulting architectural spaces [Publication IV]. This may lead to further developments of the structures towards either more complex architectural geometries or more industrialized and more circular structural solutions.
2. Nails & Patterns

2.1 Starting point & Overview

This thesis started from using only salvaged timber and wooden nails to build simply-supported short-span load-bearing structures as pedestrian trails, which was originally proposed by Fink et al. [47]. The design of the trail applied modular design thinking, which means that the whole trail was assembled from individual short-span (2-4 m) elements. For making the elements, a similar concept with nail-laminated timber was used, which has a layered arrangement of timber boards in perpendicular to the grain direction (see Figure 2.1 (left)) and connected by nails in between layers. In parallel to the grain direction, due to the nature of salvaged timber, which is normally short and random in length and different in height and thickness, an arrangement that consists of several timber boards with possible different heights and/or double thicknesses in individual layers was suggested (see Figure 2.1 (right)). Moreover, a gap between each two longitudinally adjacent timber boards in the grain direction was intended to be left in the same layer, which aimed to avoid water accumulation on the trail surface and visually to create non-repeating patterns. Apart from the flexibility offered by the timber arrangement, the proposed trail design also allows an easy rework process with the assembled elements, such as cutting, and direct incineration without de-nailing, due to the use of wooden nails.

This chapter presents step-by-step investigations on the proposed concept for the trail. Section 2.2 shows an investigation on the shear capacity of wooden nail connections, which was assumed as the main load-bearing part of the trail. Section 2.3 presents an exploration on the availability of locally salvaged timber, the variety of timber arrangements, and the resulting patterns. Section 2.4 describes how the two outcomes were combined and applied for designing the trail, based on which the trail was physically realized. Section 2.5 shows a customized part of the trail that was exhibited to the public as a showcase of the proposed timber-only concept. In Section 2.6, some concluding thoughts from the investigations are summarized in order to inspire the following step.
2.2 Shear capacity of wooden nail connections

Since the trail was planned for public use, safety issues were considered as priority. From a structural point of view, the shear capacity of wooden nail connection is the most dominant part that contributes to the overall load-bearing capacity of the structure, and therefore has been examined.

Inspired by the inclined arrangement of screws for timber-to-timber connection \[48\] and the research in wood welding \[35\], an inclined arrangement of wooden nails was considered as a possible way to improve the shear capacity of the connection compared to the straight arrangement (same as the shear arrangement in Figure 2.2). Accordingly, experimental investigations were carried out to explore the shear capacity of wooden nail connections. This research has been reported in [Publication 1], where a series of 90 push-out tests (see Figure 2.3 (left)) were performed. This study has examined different nail dimensions, orientations, and arrangements (Figure 2.2) to determine the performance of wooden nail connections. The main finding from this research was that the wooden nails, which result in additional tensile stresses (the shear-tension arrangement in Figure 2.2), showed a higher load-bearing capacity and slip modulus than others, since the wood-nail interface (strengthened by wood welding) could be activated. However, due to the fact that practically different loading conditions on wooden nail connections were possible, a more holistic arrangement was required. Accordingly, the cross arrangement (see Figure 2.2) was selected for the trail, mainly due to specific mechanical and production reasons, such as a comparably high shear resistance, or the smaller required nail spacing compared to the nails with a larger diameter.

Based on the test results of the push-out tests, an analytical model that considers the shear capacity and the geometrical arrangement of wooden nails was developed to predict the load-bearing capacity of multiple wooden nails under bending stresses. In order to validate the model, a series of joint bending tests (in total 18 specimens) using the cross nail arrangement (see Figure 2.3 (right)) were conducted. A good agreement between the predictions from the model and the test results was obtained. The analytical model was then used for finding an efficient nailing strategy for the design of modular elements.
2.3 Salvaged timber: availability, arrangements and patterns

An investigation on the availability of locally salvaged timber was conducted. Material collections at a local timber construction company (Elementit-E Oy) in Kouvola region were organized. The timber-based cut-offs and wastes generated from the production line were originally placed at an outdoor open area and intended to be used for energy recovery (see Figure 1.2). In this project, different types of salvaged timber were collected from the pile and transported to Department of Civil Engineering at Aalto University, Finland.

A comprehensive investigation on the properties of the salvaged timber, the possible arrangements of the timber boards and their resulting patterns was conducted by using the collected salvaged timber. The results have been reported in [Publication II], where the salvaged timber boards were sorted into different categorizations according to their product types and dimensions, assembled with different combinations, and sent to experimental tests, including destructive and non-destructive loading tests. Considering the aspects, such as amount, geometry, structural quality, and durability, solid timber with a specific thickness (48 mm) (see Figure 2.4) proved to be the most suitable material.
for the trail. Using these timber boards as the main load-bearing components, different patterns have been physically tried out as prototypes by following different assembly rules (one example is shown in Figure 2.5). Consequently, their various resulting patterns could be obtained and sometimes more visually pronounced, i.e., in a snowing weather condition (see Figure 2.6).

Figure 2.4. Salvaged timber boards used for making the trail.

Figure 2.5. A prototype for the modular element of the trail (temporarily assembled by using clamps).
2.4 Showcase – Pedestrian trail

The trail was planned in a forest area near Kouvola train station to create a shortcut (roughly 70 m long) between two orthogonally intersecting streets. The design of the trail was divided into two parts – (i) planar modular elements, which were linearly arranged to form a walking path, and (ii) a "plaza", located at the center of the trail for people to stay and sit. A sketch of the preliminary plan of the trail is shown in Figure 2.7.

A detailed design of the trail was finalized based on the preliminary investigations and several site surveys, as reported in [Publication II]. Furthermore, two parts of the trail has been prefabricated and assembled: (i) the planar modular elements, which required a low-cost, fast, replaceable, and industrialized solution, were produced locally in the city of Kouvola; and (ii) the customized plaza area, which explored the spatial potential, the idea of mass customization, and more creative solutions, was realized at Aalto University, Finland. Two workshops were therefore organized for fabricating the two parts [49].

2.4.1 Planar modular elements

The planar modular elements had a width of 0.5 m and a length of either 2 or 4 m (only the elements spanning a ditch are 4 m long, see the sketch in Figure 2.7). The timber arrangement of the planar modular elements followed a similar principle as the prototype structure performed in [Section 2.3]. However, in contrast with the prototype that had a "free" end resulting from the randomness of material length (see Figure 2.5), the planar modular element had a "clean" end that allows easy alignment between elements in the longitudinal direction (see Figure 2.8). The planar modular elements were fabricated in collaboration with Kouvola Vocational Institute Ltd. – Eduko.

1The trail has been partly prefabricated and not been realized on site yet.
2The author's role in the workshop was to: define fabricating principles, collaborate in material collection, and participate in the production of elements.
3Steel nails were used in the fabrication workshop due to the limitation of using wooden nails.
2.4.2 Customized plaza design

The plaza design was finalized by considering the aspects of natural surroundings on site, material availability, and aesthetics etc. The plaza was divided into two main parts and each part has eight modular elements, as seen in Figure 2.9. One part of the structure was chosen to be physically realized (the darker part in Figure 2.9 (top)), as a demonstration of the design concept. The main feature of the structure was a twisted-shape backrest sticking out of the surface (Figure 2.9 (bottom)). Note that the final
realization of the plaza has been modified based on the design proposal in [Publication II], mainly due to the more in-depth understanding of the materials obtained in the process. The realization of this structure has been integrated in a design-build course “Structures and Architecture: Informed Structures” at Aalto University as a hands-on workshop [4].

### 2.5 Exhibition – SALVAŒE

This plaza has been presented as an exhibition with a theme of “SALVAŒE – sustainable use of salvaged timber” [50]. The aim was to showcase the architectural and structural possibilities of using salvaged wood and wooden nails and to promote the mindset of sustainability to the public. The exhibition took place at Väre building in Aalto University, Finland from 8-22 May 2022 [7].

The plaza was placed in an indoor area with its specific designed installations, as seen in Figure 2.10. Right after the indoor exhibition, the plaza was transferred to an outdoor area in Aalto University for everyday use (see Figure 2.11).

### 2.6 Thoughts for next phase

In this particular case, the trail’s design originated from the load-bearing capacity of the wooden nail connections and the availability of salvaged timber, deviating from the conventional design approach typically led by the architect’s focus on the overall shape. As discussed in a preliminary study in [Publication II], the concept of integrated design was introduced. However, integrated design is a broad and somewhat ambiguous concept in the field of architecture, encompassing multiple dimensions [4]. Consequently, in the upcoming phase (Chapter 3), an exploration of integrated design concepts is undertaken in a more general context.

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4 The author contributed to: finalization of the design details, preparation and processing of the materials, fabrication of the modular elements, and assembly of the entire structure.

5 The author contributed to: preparation of the exhibition, including the design of the space and the graphic design of the exhibition, and realization of the exhibition, including the transportation of the structure and the on-site installation of the exhibition.
Figure 2.9. Design sketches of the plaza [Publication III].
Figure 2.10. The plaza in an exhibition space.
Figure 2.11. The plaza as a public space for people’s daily use.
3. Rethinking design process

3.1 Motivation & Overview

Different than the traditional building design approach that normally starts from the general shape (form) of the object [51], the design process of the trail started from the timber arrangement (material) and the nailing strategy (connection). From this perspective, it brought this thesis to a discussion of architectural design methodology, more specifically, the considered aspects and their sequences in design process [52]. This pointed out an important facet in this thesis, which was, beyond the specific material and connection that were used, to provide a more general angle of looking at the integration of architectural and structural design and the role of material in the design process with respect to the society.

According to the insights from the trail, three main sections are arranged in this chapter. In Section 3.2 a systematic literature review is presented with a special focus on integrated design concepts. Section 3.3 describes how the design process for the trail was rethought as an integrated design process based on the review. To have a more systematic understanding of the process, a concept of using feedback loops was proposed and experimented, not only to interpret the design process performed so far, but also to inform a following step. In Section 3.4 some concluding thoughts are discussed based on the performed feedback loops, which therefore generated some questions for the next step.

3.2 Integrated design concepts

In today’s design of buildings, there are three main aspects – “architecture (form)”, “structure” and “material” guiding the process (the meaning of “material” here is mainly related to the determination of material usage in terms of structural behaviour). Traditionally, a linear sequential process of “form – structure – material” has been used [51], as seen in Figure 3.1 (left). In such sequence, it is not difficult to distinguish a clear division of two professions (the architect and the structural engineer), where the architect mainly takes
over the "form" part and the structural engineer normally handles the "structure" and "material" parts, in order to realize the "form”. This format has been commonly practiced since the mid-20th century [53], as Neri Oxman has described [54]:

“The image of the architect as form-giver has for centuries dominated the profession. In most cases, structural strategies are addressed by way of post-rationalisation in support of the building’s utility captured by spatial properties. In this light, material selection and application are dependent on structural solutions.”

However, this format may result in a lack of efficiency in many aspects, such as unreasonable selection of structural form, overuse of material and high cost, as described in the relationship of structures and architecture in Section 1.1. One of the main reasons is the increasing gaps between different disciplines, such as architecture and structural engineering, in such hierarchical sequence [55]. To change the situation, alternative design approaches, which welcome different disciplines to interact and collaborate at an early design stage, need to be explored. In this regard, integrated design concepts have been identified as beneficial for contemporary architectural design towards a more sustainable future [4, 53, 56].

Integrated design concepts consider the three main aspects – "form”, “structure” and "material” (sometimes more aspects, such as “fabrication” and “assembly”), and allow them to interact with each other from the beginning of design process (see Figure 3.1 (right)). To form the interactions, interconnections in between different design aspects are built up and examined. By taking as many aspects as possible into considerations through their interactions, integrated design concepts may provide a more holistic design solution compared to the traditional approach, if the decision-making is based on a necessary understanding of the interrelationships of the considered aspects [57].

Various combinations of aspects and their specific ways of integration and sequences have been attempted. Two types of approaches, to the author’s best knowledge, can be identified. One is integrated structural and architectural design (ISAD) approach, which mainly focuses on interactions between disciplines of structural engineering and architecture, while another is material-based integrated design (MID) approach, which initiates design process from material and informs other aspects. An illustration of the design logic of the two approaches is shown in Figure 3.2. Note that there is no clear boundary between the two approaches, for example, ISAD approach can be at the same time MID approach if the process of ISAD is initiated from material.

### 3.2.1 Integration of structures and architecture

The relationship between structures and architecture is a key issue in ISAD. In general, architecture-structure relationship can be very diverse, as described by Macdonald [6]:

"... ranging between the extreme of complete domination of the architecture by the structure to total disregard of structural requirements in the determination of both the form and of its aesthetic treatment."
Building design process is, therefore, a mixture of two types of thinking modes – the engineering, which is "objective deductive", and the architectural, which is "subjective creative" [58]. From this, it is not difficult to distinguish the "difficulties of architect-engineer collaboration in the design process and, paradoxically, the imperative need to foster it" [59].

However, there is still a potential for structure to enrich architecture, if "the structure is given a voice" [5], which means that the structure "contributes architectural meaning and richness, sometimes becoming the most significant of all architectural elements in a building." In such context, to find a form that is at least two-folded – functioning as structure, and at the same time, expressing architecture, becomes essential. In other words, the form-force relationship is in balance and harmony.

This concept has been addressed in the discourse of architecture, where the emphasis has been shifted from "form-making" to "form-finding" [60]. In order to achieve this goal, different approaches have been explored by both architects and engineers [61].

**Form-finding methods**

Form-finding methods have been explored for decades in order to establish a strong connection between form and force. The term "form-finding" has been widely defined and sometimes differs from case to case. A generally accepted definition is given by Lewis [62] (despite some criticisms, as introduced by Veenendaal and Block [63]):

"In general, the process of form-finding should yield optimal structural shapes: shapes that would satisfy the functional requirements and attendant durability and strength at a minimum cost."

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Figure 3.1. Sequence of traditional design approach according to [54] (left) and integrated design approach (right).

Figure 3.2. Two types of integrated design approaches with their specific highlights (in gray color).
Rethinking design process

Form-finding is a design process that results in a specific form of a structure in static equilibrium under a given set of loading and boundary conditions \[64\]. Having originated from the physical explorations by visionary practitioners, such as Antoni Gaudí, Heinz Isler and Frei Otto, the current form-finding process has been made more automated, thanks to the advancement in computational design techniques \[65, 66\] and tools \[67, 68\]. However, it has become more difficult at the same time, mainly due to the diversity and increased complexity of applied theories nowadays. A categorization work of the form-finding methods used for discrete structures (basically the same with compression and/or tension only structures) has been conducted by Veenendaal and Block in \[63\], where three main categorizations, namely, stiffness matrix methods, geometric stiffness methods, and dynamic equilibrium methods, are identified (note that stiffness matrix methods also consider material properties in their processes).

**Structural optimization**

Structural optimization is a mathematics-based way of uniting architecture and structure. Its aim is to “achieve the best feasible design according to a pre-selected measure of effectiveness” according to Kirsch \[69\]. This concept might have some overlap with form-finding methods, however, in some cases, the difference has been clearly clarified. For example, the necessity of deformation in the form-finding methods was highlighted by Bletzinger and Ramm \[65\]:

“The art of form-finding means to find the optimal deflected and finally visual shape due to a given stress distribution acting on the deformed structure. This fact should be clearly pointed out since it is different compared to conventional structural optimization where the undeformed shape is optimized with respect to displacements due to given load cases.”

Structural optimization, including size optimization, shape optimization, and typology optimization \[70\], can be explained as a mathematical programming problem \[71\], where a clear target (a maximum or minimum output) and its affecting parameters are defined. Hence, the form-force relationship can be formulated as a mathematical relationship in all kinds of structural levels (individual components \[72\], joints \[73\], or entire structures \[74\]).

**Graphic statics**

Another way of connecting form and force is graphic statics, which graphically interprets the form-force relationship via two reciprocal diagrams – funicular diagram (form) and force diagram (force). Such visualization allows an easy communication between architects and engineers, since in most of the cases, architects may struggle to understand the structural concerns through the formulas and equations in structural engineering. Using the two diagrams, Graphic statics can be integrated into form-finding \[75\] or structural optimization process \[76\]. The application of graphic statics has been mainly targeted for tension and/or compression structures, where the magnitude of force in each element can be visually identified \[77\]. It also shows a possibility to analyze the structures subjected to more complex loading conditions, such as axial forces with shear and bending \[78\].
3.2.2 Material as starting point

Material is the starting aspect that informs structure and form in MID. This concept is similar with the ancient way of making artifacts, in which "material and form are naturally intertwining into a tradition of making" [52]. However, different from the ancient craftsmen who understood material mainly by their intuitive perceptions [79], modern architecture also adds digital characteristics, which "substantially affect architecture’s physics" [80]. This so-called "digital materiality" brings new possibilities to design, when material is not merely a physical existence, but becomes digitally "informed" (meaning "enriched by information" [80]). Therefore, the way of integrating initial information (data) of material (both physically and digitally) and the logic to generate structure and form are essential in material-based design thinking [81]. In this regard, "tectonics" is of great importance. One definition of tectonics has been given by Oxman [82]:

"Tectonics is a seminal concept that defines the nature of the relationship between architectural design and its structural and material properties."

Tectonics can be seen as a "mediator" of form, structure and material. The way of mediating might be varied from case to case, and different levels of synthesis are possible in such concept. It can be a relatively simple concept, for example in vernacular architecture, the tectonic expression is straightforward, where "choice of local material results in the expression of form and structure" [82]. It can be also a complex concept, for example in the context of digitally fabricated architecture, both physical and digital materiality are taken into account to inform structure and form, together with considerations of fabrication and construction processes [83]. To tackle such complexity, a term "informed tectonics" was introduced [82], in order to build up a new theoretical framework that allows more aspects to be integrated in the design process and looks at the interrelationships between them. Some built projects in the last two decades have demonstrated the possibility of material-based form generation through a design computation process, such as the series of ICD/ITKE research pavilions [84]. Specifically in timber structures, the expression of tectonics in the digital age was explored and showcased in the works done by the Laboratory for Timber Constructions (IBOIS) at EPFL [85, 86].

To achieve sustainability in building construction, rethinking the use of building material is one of the keys. With this regard, circular design thinking (reuse, repair, refurbish, recycle and recover [87]) has been promoted as one way out. In the framework of MID, the circular economy concept can be integrated at the beginning as input information for material. This integration brings some difficulties for the designers, since it requires a more in-depth material knowledge and the ability of working with flexibility in the design process [88]. However, it is becoming more possible by using the current computational design methods, as some projects have exemplified [89].

In general, sustainability-based MID requires strong and smooth collaborations between different disciplines based on a common understanding of design process. To this end, a theoretical framework that offers a platform where different disciplines can interact has been investigated in this thesis, specifically from a standpoint of timber-only structures and architecture.
3.3 Rethinking the performed process

This section describes how the design process of the trail was rethought. The relationship between "material", "connection", "structure" and "form" was analyzed. Inspired by the rethinking process, a further exploration of integrated design approach was performed, where a concept of using feedback loops to interpret the design process was applied.

3.3.1 As an integrated design process

Learning from the individual investigations on salvaged timber and wooden nails, specific nailing strategy and timber arrangements were applied for designing and fabricating the trail – from the planar modular elements to the customized plaza. In another words, the "form" and the "structure" were informed and integrated by the "material" and the "connection". Consequently, the whole process can be explained as a material- and connection-based integrated design process, which can be also seen as a synthesis of ISAD and MID with an additional starting point "connection", as seen in Figure 3.3. A detailed analysis of the design sequence and the interactions between the four aspects in the trail has been reported in [Publication II].

To be noted that the interaction between each two aspects may contain multiple interconnections. For example, the interaction between material and structure is three-folded – (i) the timber board selection for the main structure, (ii) the timber board arrangement, and (iii) the use of distance keeper, which is a small piece of salvaged timber that keeps a gap in between layers (see more details in [Publication II]).

3.3.2 Feedback loops

In [Publication II], the integration in the trail design was explained by the interconnections between the aspects of "material", "connection", "structure" and "form", which means that if one aspect is adjusted, all the other aspects might be affected at the same time. This feature shows the main difficulty in integrated design concept, which is the resulting complexity when more aspects are involved. Another feature of the trail design is its research-based nature. This implies that many aspects in the trail design needed to be investigated first, because (i) there was no existing guideline for the use of wooden nails; (ii) the material availability was unknown; and (iii) the structural behaviour

![Figure 3.3. Integrated design approach used in the trail.](image-url)
was highly material-based. This may bring more complexity in the integrated design process resulting from the investigation of each aspect separately. Accordingly, a clear theoretical framework that can interpret the complexity of the process is explored in this thesis. [Publication III] has reported an experiment that used a systematic approach to understand the integrated design process, where a concept of using "feedback loops" was employed as a framework to reinterpret the process performed so far, as well as to generate new possibilities for the next step.

The logic of feedback has been applied as a fundamental concept in various fields since its first ever known application as an artificial device (a water valve) in ancient Egypt time [90]. In general, the term "feedback" refers to "a situation in which two (or more) dynamical systems are connected together such that each system influences the other and their dynamics are thus strongly coupled" [91]. The feedback between the individual systems consequently forms a circuit or loop(s), resulting in a complex larger system. Feedback loops offer several benefits when properly designed and utilized, such as the dynamics of design and possibly higher levels of automation [91].

In the range of architectural and structural design, the application of feedback loops is mainly related to (structural) performance analysis and optimization. Current parametric design tools allow the formation of feedback loops to have fast feedback between structural performance and architectural form, mostly using the form-finding approaches mentioned in [Section 3.2]. Some examples that have showcased this process are: Fivet [92] highlighted that in the conceptual design stage when a new structural concept is formed or an existing one is transformed, its performance needs to be understand as a fast feedback to the concept, where graphic statics could be used for this purpose; Kurilla et al. [93] used optimization method to integrate architectural design and structural design through forming feedback loops between structural solver and geometry modeler; Bao et al. [94] attempted to integrate architectural complexity with structural efficiency using typology optimization and generative design algorithms, where a structural behaviour feedback loop was established and used in form-finding. Besides, feedback loops were also often applied when designing for robotic fabrication, e.g., using sensors to receive information about material location and characteristics and therefore to support design decision-making [95]. In timber construction, this technique has been used in both additive manufacturing [96] and subtractive manufacturing [97].

Using the above-mentioned definition of feedback by [91]: if we see each involved aspect as the "system", and the interconnections between the aspects as the "coupled dynamics", the integrated design concept will show an almost identical characteristic with the concept of feedback. However, it is in general not common to use feedback loops as a pure design framework that integrates the aspects involved in the design process, as only few cases exemplified such concept [98, 99]. The main obstacles are shown in: (i) required comprehensive understanding of various aspects involved in the process by individual, (ii) need of enhanced collaborations between multiple disciplines, and (iii) the increased difficulty and complexity to integrate the involved aspects when the number of feedback loops increases. However, if the involved aspects are well-defined, and if interdisciplinary collaboration goes efficiently and seamlessly, a comprehensive solution might be attained.
Rethinking design process

Following this idea, an experiment of using feedback loops to interpret the integrated design process has been carried out, where five aspects – "connection", "material & materiality", "structure & form (planar and modular)", "fabrication & assembly", and "structure & form (spatial)" – were defined and analyzed. The feeding-back process was a continuous learning process that might result in a reconsideration of an individual aspect, but from a different perspective. Particularly, this reconsideration was shown in the aspect of "structure & form", which had two versions in the performed process: (i) a planar and modular version that provided a simple, quick and sustainable solution for the trail, and (ii) a spatial version that aimed to propose spatial solutions for the use of salvaged timber and wooden nails in a larger scale. The former version has been studied and physically realized (see Chapter 2), while the latter version has been primarily explored in [Publication III].

Interconnections were built up based on the five aspects to form feedback loops, where lessons were learned through the process. This idea of lessons learned was inspired by the ancient master builders, who normally learned the knowledge of material, form, and proportion of buildings from their predecessors [12] and developed their skills from the intimate intuitions from nature [100]. In the feeding-back process, all the lessons were learned through the interconnections between the involved aspects. A detailed feeding-back process is illustrated in Figure 3.4, where the number of interconnections between different aspects are proportional to the line thicknesses of the curves.

Through the performed feeding-back process, an integral design concept has emerged. Nevertheless, it is important to acknowledge the limitations:

- Due to the predefined scope of the thesis, other aspects, such as long-term behaviour of the structure, economic benefits or automated construction workflow, were not considered.

- The selection of the aspects considered in the design process was highly dependent on the backgrounds of the involved people, i.e., the starting points were set up from a structural perspective.

- The selection of the involved aspects also resulted in limitations regarding the scope of applications, e.g., it was tailored for the project's unique needs so that it might be difficult to apply all the lessons learned directly to other applications.

3.4 Thoughts for next phase

The performed feeding-back process has served as an inspiration for the subsequent step, which involved a proposal of a specific structural system (details introduced in [Chapter 4]). The structural system was a result of utilizing the key insights from the lessons learned in the process. In brief, these insights encompass the following considerations and improvements:

- The load-bearing capacity of the wooden nail connection was beneficial from an
inclined arrangement when the tensile capacity of the connection was used. How to further utilize this benefit?

• The collected salvaged timber has shown some dimensional characteristics: few types of standardized cross-sections, random and short in length. What kind of form can give the flexibility of using these materials requiring less further processing?

• Architecturally, the salvaged timber brought an emerging aesthetics in the trail, since the timber was arranged in a way that the material characteristics (random in length and colors) were highlighted, but mainly in two dimensions. How to bring this sense of aesthetics in a more spatial structure (three-dimensional)?

• Structurally, the failure of wooden nails was dominant in most of the cases compared to the failure of timber boards. How to make it possible to predict the load-bearing capacity of the entire structure from wooden nail connections?

• The idea of using salvaged timber and wooden nails for building structures was supposed to be in line with a low-tech approach [101] and design for disassembly (DfD) concept [102]. Which form can allow easy modular fabrication and a simple assembly process?
Rethinking design process

To the next step

Figure 3.4. The feeding-back process with its resulting lessons learned through the interconnections.
4. Structures & Layouts

4.1 Motivation & Overview

This chapter explores a structural system that allows use of modular elements for various layouts. Inspired by the questions asked in Section 3.4, the feedback loops led to an exploration of a traditional structural system called reciprocal frame (RF). Following the low-tech approach and DfD concept, a planar rectangular slide-in RF system (referred to as the term ”slide-in system” for the rest of this thesis) was proposed. Compared to the trail, the slide-in system used the timber boards with a 90°-rotation along the longitudinal axis of the boards, so that the flat surfaces of timber boards become horizontal. It also applied the idea of leaving a gap in between the timber boards in the same layer, but in this case, serving as structural connections instead of non-structural purposes.

Accordingly, in Section 4.2, the concept of RF is introduced and the reasons why it fits the use of salvaged timber and wooden nails are stated. Section 4.3 introduces the slide-in system and describes how it was developed, where its structural and architectural qualities were examined, including the structural behaviour of the basic element and the entire structure, the assembly logic, the possible generated layouts and the resulting architectural spaces. Section 4.4 presents a canopy structure that was designed and built by using the output from the investigations on the slide-in system. Section 4.5 describes the exhibition of the canopy, which also served for public use.

4.2 Reciprocal frame

In RF structures, all elements, usually linear, mutually support each other to form a closed load-bearing system. RFs provide an intriguing approach of using short elements, which creates a span longer than the elements themselves by self-interlocking. This concept has been applied for centuries, such as in the neolithic pit dwelling, the Eskimo tent, the Indian tepee, and the Hogan dwellings [103]. Historically, timber has been the preferred material for making RFs. Planar RFs can be simply realized by notched connections, as proposed by Sebastiano Serlio for the construction of planar floor structures.
A typical notched element in a planar four-element RF is shown in Figure 4.1 (left).

Within the contexts of this thesis, especially because the connecting fastener was limited in wooden nails, the traditional planar notched RF was not the most suitable solution. However, the structural system itself brought some insights that may help to discover a more appropriate solution. In light of the questions given in Section 3.4, some examples of specific solutions in terms of using salvaged timber and wooden nails to make RF system are described here:

- Instead of making notches (reducing cross-section), it is possible to fabricate individual RF elements in an additive manufacturing way of thinking – arranging salvaged timber in a layered configuration and connected with wooden nails across the layers. To do so, a more efficient use of wooden nails can be realized if they are arranged in a way that their tensile capacity is fully activated;

- RF provides flexibility in layout, which means that different sizes of salvaged timber could be used if the layout is designed based on material availability. Low material processing can be therefore achieved;

- The over-length of material (see Figure 4.1) can be utilized in connections in an RF system, and if the design is smart, the randomness of material can enrich architectural space;

- The structural system of RF can be simplified according to existing literature [105]. It is possible to build a mechanical relationship between the connection (here meaning the wooden nail connection between the layers in an element) and the entire structure system if the connection is the governing factor;

- RF can be fabricated as modular elements and assembled if feasible assembly logic can be discovered and considered carefully in the design process.

![Figure 4.1. Planar four-member RFs and their basic consisting elements: traditional notched RF (left) and slide-in system (right).](image-url)
4.3 Planar rectangular slide-in reciprocal frame system

Basic planar rectangular layout of the slide-in system consists of several short, salvaged timber boards that are joined together with wooden nails. Timber boards are arranged in a way to create an opening for the slide-in connection (see Figure 4.1 (right)). The opening serves in many ways, including offering an easy assembly and disassembly process (possibly tool-free), and modular prefabrication of the elements. The following terminology was used here. Element represents the individual member (here an assembly of short timber boards) that the slide-in system is assembled of. Unit is defined as the structure composed of a minimal number of basic elements, which can be expanded into larger systems or nested with one or several smaller units in a fractal way. In a rectangular layout, the simplest unit has four elements.

The system was intended to be studied in planar rectangular layouts. The reason was mainly related to the idea of low material processing: since most of the salvaged timber boards have standardized cross-sections and straight ends, a 90°-insertion between each two elements requires no cutting and at the same time forms tight connections. A preliminary study on the slide-in system has been reported in [106], based on which, an extended and more in-depth study was conducted in [Publication IV]. Below is an overview of the research output from the proposed slide-in system.

The structural behaviour of the slide-in system was investigated. Individual elements with different arrangements (both symmetrical and asymmetrical arrangements) were experimentally tested (see Figure 4.2). The results showed that the failure of wooden nails was dominant in general, but the bending failure of the timber board can be reached in the symmetrical arrangement. Based on the results, an analytical model was developed in order to associate the load-bearing capacity of the individual element to the entire system. The model was developed based on two main assumptions: (i) all the slide-in connections are pin connections so that the entire structural system is structurally determinate, and (ii) the load-bearing capacity of the system is dependent on the bending and shear capacity of individual elements, which are correspond to the bending strength of the timber and the load-bearing capacity of the wooden nail connection, respectively. This model was validated by the test results. Note that the model might be associated to large uncertainties, resulting from the use of salvaged timber (see e.g., [107, 108, 109]). Using this model, it is possible to generate an efficient layout according to a clear target in a specific set of loading and boundary conditions.

The assembly logic of the slide-in system was investigated, where the feasible assembly process and the resulting layouts were performed. Examples and their assembly sequences are illustrated in Figure 4.3. Example 1 showcases the vertical and horizontal approach to form a slide-in connection. Example 2 highlights the use of a nested fill-in unit, which is fully supported by another unit. Example 3 is a showcase to form a larger structure using the basic unit. Following such assembly logic, the slide-in system was exemplified in different layouts and built in full-scale. One was a street furniture, which used the salvaged timber originally for concrete formwork on a local construction site, as seen in Figure 4.4. Another case was a frame structure, which was built for testing purposes, as seen in Figure 4.5. Note that the design of the frame structure was realized
by using the developed analytical model, which was aimed to find a material-efficient layout according to a fixed amount of material, a fixed size of structure, and a pre-defined boundary condition. The frame structure was loaded until failure. However, most part of the structure remained and therefore was able to be reused. Accordingly, a smaller frame structure that used the remaining elements was built and sent to a loading test. The test results from both frame structures were used for validating the analytical model. More detailed information is given in [Publication IV].

Figure 4.2. Experimental test of the individual elements of the slide-in system: symmetrical arrangement (left) and asymmetrical arrangement (right).

Figure 4.3. Examples of slide-in system and their assembly sequences [Publication IV].
Figure 4.4. Street furniture made from salvaged timber and wooden nails [106].

Figure 4.5. Frame structure made from salvaged timber and wooden nails.
4.4 Showcase – Canopy

A full-scale canopy was designed and built to demonstrate the structural and architectural qualities of the slide-in system, and its advantages in assembly and disassembly.

The canopy has two parts – a superstructure using the concept of slide-in system and four supporting columns (see Figure 4.6). The superstructure has four individual substructures and each substructure has three different sizes of units with a column inserted into the inner hole of the smallest unit. The principle of slide-in was applied for both between and inside of the substructures. In total, 48 elements (see Figure 4.7) were designed and prefabricated with a consideration of zero-waste of raw material. It means that each timber board used in the elements was designed with varying lengths instead of a fixed length, so that the original length of the timber board (roughly 4.8 m) can be fully utilized with well-designed cuttings. This ability was enabled by the flexibility of the slide-in system, which allows over-length in the slide-in connection. The four columns were constructed first on site, which located at the campus of University of Innsbruck, Austria. Considering that only man power was available in this case, it was difficult to assemble the superstructure as a whole before placing on the columns due to its self-weight (approximately 500 kg). Accordingly, the elements were assembled as individual superstructures (following the assembly process of Example 2 in Figure 4.3) and installed on the columns. In order to achieve the final shape, final in-plane rotational sliding between the substructures was required. This was realized by rotating the outer units through the pre-reserved gaps in the outer elements (highlighted in Figure 4.6 and Figure 4.8). The detailed assembly process is illustrated in Figure 4.6.

Figure 4.6. Assembly process of the canopy structure.
The canopy was realized in the framework of a design-build course "Design of Structures" at Faculty of Architecture, University of Innsbruck. In total, 12 students were involved. The entire fabrication and assembly process was realized in three days. The realized canopy is shown in Figure 4.9.

![Figure 4.7. Prefabricated elements for the canopy structure.](image)

![Figure 4.8. Details of the slide-in connection.](image)

The author organized a hands-on workshop as a part of the course. In the workshop, the author contributed to: conceptualization of the structural system, finalization of the detailed design of the canopy, planing and processing of the salvaged timber boards, fabrication of the modular elements and the column supports, and assembly of the entire structure on site.
Figure 4.9. The canopy structure on site.
4.5 Exhibition – Reincarnation

The superstructure of the canopy was disassembled and reassembled for an exhibition with a theme of "Reincarnation" from 13-26 June 2023 at the south foyer of the Faculty of Architecture at University of Innsbruck. It was arranged in a green area so that a tree could be located inside the structure. The layout of structure created a pattern on the ground, which could be seen from the faculty building (see Figure 4.10 (top)). The structure was also opened to the public, which allowed people to use and to socialize in the space (see Figure 4.10 (bottom)).

Figure 4.10. The superstructure of the canopy in the exhibition and for people's daily use.
5. Conclusions & Outlook

5.1 Conclusions

In this thesis, a concept of timber-only structures and architecture was explored by using only salvaged timber and wooden nails. Initiated by a pedestrian trail project, which required a low-cost, fast and sustainable solution, salvaged timber and wooden nails were investigated individually and the outputs were subsequently merged and applied in the design of the trail. The merging process has resulted in rethinking of the design process of the trail, mainly regarding the considered aspects and their sequence in the process. It associated this thesis to a discussion of architectural design methodology, more specifically, integrated design concepts in architecture. To have a more systematic understanding of the design process, a concept of using feedback loops was proposed and practiced. By using this concept to reinterpret the performed design process of the trail, new thoughts were generated, which led to an exploration of RF structures. Consequently, a slide-in RF system was proposed and therefore systematically studied. Through the entire process of the exploration performed so far, the main conclusions are drawn here:

- Wooden nails can provide sufficient load-bearing capacity for structural applications, at least for less-loaded structures or structures with low safety requirements. With an inclined nail arrangement that results in additional tensile forces on the nails, the shear capacity of wooden nail connection can be significantly improved compared to a straight arrangement. Based on the shear capacity, the load-bearing capacity of wooden nail connections under bending stresses can be predicted using an analytical model developed in this thesis.

- Salvaged timber brings specific values to new constructions: (i) the structural value, which means that the mechanical properties of salvaged timber are sufficient for structural applications, and (ii) the aesthetic value, which means that the nature of salvaged timber, such as the difference in color and the randomness in dimension, could become the driving force in design and bring new sense of beauty to the society.
Conclusions & Outlook

• Instead of the linear sequence in traditional building design process, a material-based integrated design process, which requires interactions between the involved aspects in the design, is considered more suitable for this thesis. Inspired by the ancient master builders, a concept of using feedback loops to interpret the integrated design process is used. Through the lessons learned from each aspect feeding back to the overall design, a more holistic design solution could be obtained. However, it may have difficulties for large building projects, mainly due to the increased difficulty of collaboration between the increased disciplines, and the need for comprehensive understanding of all the involved aspects and parameters.

• The proposed slide-in system allows the use of short and non-standard salvaged timber using the low-tech approach and DfD concept. The slide-in system can be used as load-bearing structure, but it is associated with large deformations and a brittle failure behaviour. The load-bearing capacity of the system could be predicted from its individual element by using an analytical model developed in this thesis, but possibly with large variations, especially when using unclassified timber. Following the specific assembly logic, the slide-in system can provide flexibility in planar layouts. By increasing the number of layers and shifting between elements, the spatial possibility of the system can be also uncovered.

5.2 Novelty of this thesis

In this thesis, multiple aspects, including structural efficiency, material availability, low material processing and transportation, modular prefabrication, and easy assembly and disassembly process, were attempted to be addressed and integrated into specific building solutions. The novelty of this thesis is highlighted in:

• The experimental investigations on the shear capacity of wooden nail connections aimed to explore the structural potential of wooden nails, which was not systematically studied in the past literature. An efficient use of wooden nail connection under shear stress was discovered, which was available for future practical applications.

• The concept of integrated architectural and structural design was applied. A specific integrated design path that started from "material" and "connection" was performed and demonstrated in the trail project.

• The concept of RF is known in timber construction, but mainly realized by subtractive manufacturing approach, i.e., making notched connections by reducing cross-section. Differently, an additive manufacturing approach was applied in this thesis for making the slide-in system, i.e. using the wooden nails to connect short timber boards and arranging timber boards in a way that slide-in connections could be formed.
5.3 Outlook

- The feeding-back process performed in this thesis is a continuous process. A more holistic solution might be generated by considering all the involved aspects and the lessons learned through the feedback loops. Future work will be interested in informed next steps that consider more aspects in the process.

- The design concept proposed in this thesis has been influenced by the ancient master builders who have acquired knowledge through the process of making. Their craftsmanship, their spirit of making, and their understanding of materials are still inspiring modern architecture and engineering practices. Future work will be interested in the construction history of timber structures built by the master builders. By learning from historical examples, inspirations will be obtained in terms of developing innovative timber structures and joints.

- Sustainability has become increasingly important not only in the building design process, but also in the entire life-span of the structure. Future work will focus on an in-depth life-cycle assessment of the structures proposed in this thesis, exploring their sustainable potentials in a longer time frame.

- There is a potential of using robots to realize the construction process performed in this thesis, including the fabrication of modular elements, and the assembly and disassembly of structures. Future work will explore the possibility of integrating robotic fabrication to the process.
References


References


References


