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An integrated architectural and structural design concept by using local, salvaged timber

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Abstract

Our research-based design approach suggests an integrated architectural and structural design concept by using local, salvaged timber in a “material and connection – structure – architecture” sequence, which is in line with Neri Oxman´s discussion of the “Form First, Structure First, Material First: the Designer’s Causality Dilemma”. Following the philosophy of design-build, locally available, salvaged wooden materials connected with wooden nails only is the main design driver. The material, its property, size, and availability, as well as the wooden nail connection are explored separately. The merger of material and the specific connection results in structurally tested prototype-assemblies and previously unnoticed insights respectively. Together with a long-term observation from exposure to the natural environment as well as architectural requirements according to its prototypical use, the findings from the prototype-assemblies are feeding back the design process, as finally showcased by a natural trail project for the city of Kouvola, Finland. The proposed trail meets the requirements of a cheap, fast, replaceable, and sustainable solution, by simultaneously including multiple modular elements for a pedestrian path and a central, partly curved plaza-like area. Future work will focus on smoothening the workflow and on structural and architectural optimization with special focus on the wooden nail connections, and associated assembly geometries.

Keywords: Integrated design concept, salvaged timber, wooden nail connections, sustainability, low-tech, timber-only structures, natural trail.

1. Introduction

Today, three main aspects are guiding the design of buildings, namely architecture (form), structure, and material, making the separation and domains of disciplines obvious. The architect first conceptualizes a form and subsequently structures and materializes in collaboration with the engineer (Oxman and Oxman [20]). The building and construction industry looks back to a historical development of separation, as historical movements have fragmented each aspect in the whole building construction process (design, development, and realization) and resulted various roles (Whitney [29]).

Before the Renaissance, there was no clear division of professions in building constructions and the person who was responsible for the whole process from early design phase to construction, referred as a master builder (AnCor [1]). Although the cathedrals of the Gothic age were designed and built anonymously by the same idea, the term “master builder” has started to be used from the 17th century (Designing Buildings Ltd. [5]). It was Renaissance which brought a division of the roles into two categories: the liberal thinkers (planners) and labors (Argan [2]), and according to Whitney [29], the dome of Florence Cathedral is a good showcase of such division. This division later triggered a further division of liberal thinkers into architects and engineers. Even though Perronet, who founded the Ecole des Ponts et Chaussees which became the first school for Engineering in 1747 (Saint [25]), was intended towards an integration of architecture and engineering. However, the trend of the separation of architecture and engineering was still overwhelming. Whitney [29] concludes on the education and specialization of the architect: "As the profession of the architect has become more expert and distinct from other aspects of building development the distance between these professions becomes a new barricade."

2. Integrated design concepts

During the last few decades, alternative approaches, including the philosophy of design-build or architectural engineering as educational programme and profession (Parasonis and Jodko [21]), have been searched as contemporary forms of the master builder model (Henry [10]), since there were only few in the recent past (Billington and Garlock [4]).

For reasons of increased efficiency, demand for higher (spatial and technical) complexity of buildings, increased wellbeing for users, etc., integrated concepts, where collaborative and inclusive approaches in design and realization are promoted, are identified as beneficial in contemporary architectural design (Moe [14]). Back at the origin of tectonic expression in vernacular building traditions, the integrated design concept was adopted by master builders, where the selection of local materials directly informs the expression of form and structure (Oxman [19]).

In current architectural discourse, new combinations with one or multiple starting points are possible in integrated design concepts. The setup of combinations and starting points is largely dependent on the design task, the applied (material and structural) technologies, and fabrication process. Since it seems difficult to overcome the separation of disciplines and their often-separated education, various combinations and starting points can be identified, in which one specific aspect takes the leading role but is considered simultaneously by the others. Informed tectonics in material-based design by Oxman [19] presents seven representative models to show the diversity of material-based design in the digital age, such as the rationalization model, the evolutionary model, or the flow model - from design to production. In Oxman [18] an inverting turn of the traditional 'form-structure-material' sequence is introduced, where material informs structure and subsequently informs form.

3. An integrated design concept by "material and connection first"

In line with the discussion of "Form First, Structure First, Material First: the Designer's Causality Dilemma" (Oxman [17]), the approach of this research and our below shown case studies propose a novel "material and connection – structure – architecture" sequence. Our starting point is wood as a material, more specifically locally available, salvaged wooden materials which are connected in wood-only manner by wooden nails. Material and connection are chosen as the starting points in the concept, followed by structural testing and application space (architecture) as the second and the third step, respectively.

As a first step the material, its properties, size, and availability as well as the wooden nail connection are explored separately.

In a second step, the two above-mentioned independently investigated aspects are merged into structural elements. However, the marriage of material and specific connection results in previously unnoticed insights, material handling, sequence in assembly and functional aspects such as expected snow and water flow in dependence of the size of wooden boards and the holes of the assembly pattern. Therefore, the structural elements are physically tested in lab- and natural environment as well as in its prototypical use (Figure 6).

In a third step, the architectural diversity of the structure is analyzed. Examples of using the concept in a structural prototype and a natural trail design project are presented. Here, the output from the analysis is subsequently applied in a case study with a variety of forms and configurations. The interconnections of the design concept are illustrated in Figure 1.

The benefits and limits of the integrated concept are concluded in the end of the paper with an outlook of its possible optimizations in future applications.

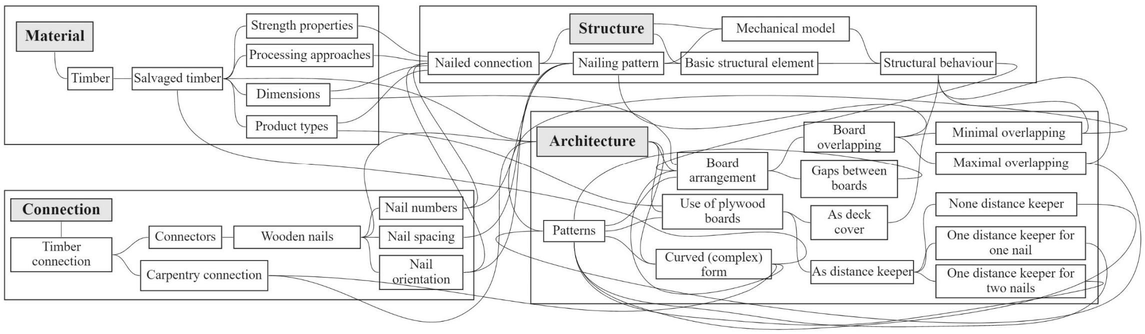


Figure 1: Interconnections of the integrated design concept.

3.1.a Salvaged timber as material

Due to increasing environmental concerns (European Commission [6]), and as announced by the president of the European Commission, Ursula von der Leyen in her 2020 State of the Union address, “the New European Bauhaus is an environmental, economic and cultural project, aiming to combine design, sustainability, accessibility, affordability and investment in order to help deliver the European Green Deal. The core values of the New European Bauhaus are thus sustainability, aesthetics and inclusiveness.” (von der Leyen [28]) As a response to the environmental challenges, prefabrication of timber buildings is encouraged by the building sector (Arup Foresight, Research and Innovation [3]). However, the prefabrication of planar or modular elements for timber buildings results in large amounts of cut-offs. Cut-offs from structural timber and engineered wood products are usually treated as waste wood and in best case it is used for energy recovery. However, cut-offs from standardized products are characterized by valuable mechanical properties. Accordingly, a large environmental and economic potential can be identified by locally salvaging these materials as structural or non-structural members in new applications.

To investigate the properties of salvaged timber locally available in the Helsinki region of Finland, we visited timber housing companies. The average amount of timber wastes from cut-offs from a Finnish medium-size company during a period of 2-3 weeks ready for energy recovery is shown in Figure 2. Some characteristics of the salvaged materials (mainly timber-based cut-offs) can be distinguished:

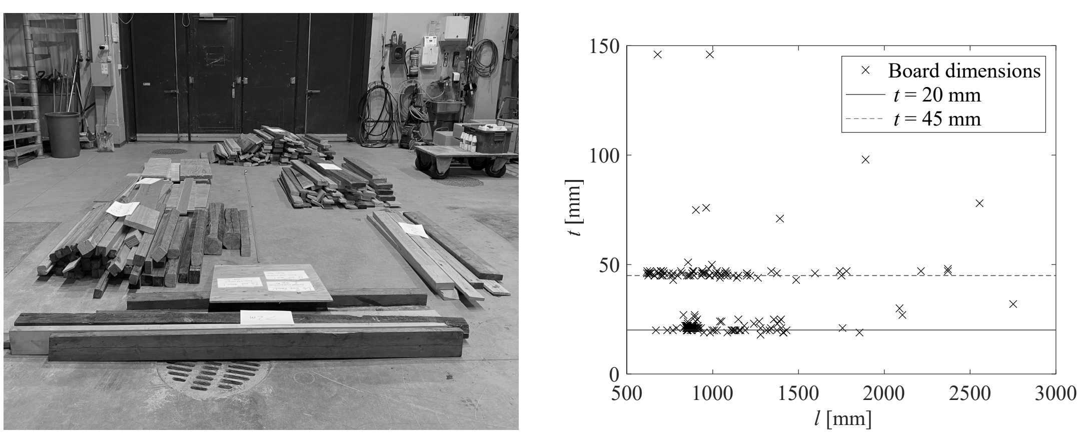
- Product types: mainly sawn timber and plywood; few round timber and laminated veneer lumber (LVL)
- Fabrication process: mostly cut-offs of timber boards due to, e.g., over length; few twisted timber boards
- Dimensions: length – a range of 0.5-1.5 m for cut-offs and more than 1.5 m for twisted boards; cross-section – mostly 100×20 mm^2 and 123×48 mm^2, different dimensions for round timber, plywood and LVL
- Mechanical properties: variable, with known product declarations

For the industry, the incentive of using the materials for energy recovery instead of salvaging is mainly related to economic and structural considerations. However, from an economic perspective, a solution of using salvaged timber for low-cost or low-labor constructions, e.g., robotic constructions, is feasible. From a structural perspective, salvaged timber can still provide considerable load bearing capacity if the use of the materials meets certain design principles, e.g., using efficient structural forms (Huuhka [12]).

In addition, more environmental benefits from timber can be identified when reusing timber (Niu et al. [16]). Therefore, salvaging timber materials for low-tech, low-cost, and short-span timber structures is proposed.

Figure 2: A typical collection of timber wastes for energy recovery in a timber construction company in Finland.

To realize structural prototypes for testing purposes, architectural evaluation, and prototypical use (see Figure 6), salvaging wooden materials from the above-mentioned local timber housing company was carried out. The materials were found in an open-air space of the company, where they had been stored unprotected from weather for 2-3 weeks. After manual, random collection, the salvaged timber was transported from Kouvola to Aalto University (Espoo). The amount and dimensions of the salvaged was restricted by the volume of the transporting vehicle, a Volkswagen Transporter, limiting the timber boards to a maximum length of 2.8 m. The salvaged timber was categorized by dimensions and stored in the laboratory spaces at the Department of Civil Engineering, Aalto University, Finland (Figure 3(a)). The geometries (length l and thickness t) of the salvaged timber are summarized in Figure 3(b). Two main types of thicknesses (t = 20 mm and t = 45 mm) were identified, and most of the boards had a length ranged from 0.5 to 1.5 m.



(a) (b)

Figure 3: Salvaged timber: (a) storage by dimensional categorizations and (b) geometric properties.

3.1.b Wood-only connection by wooden nails

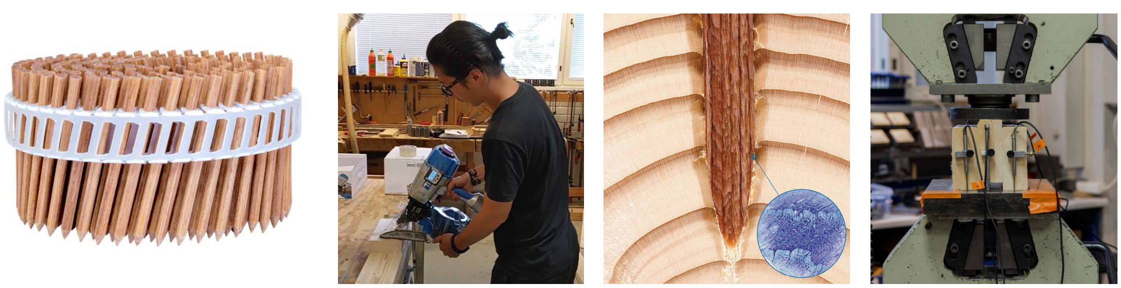
Wood connections are normally realized by wood carpentry or using connectors, e.g. dowel and nails. For wood carpentry, additional processing is needed from wood products to geometrically shaped connections. However, neither man-made nor digital fabrication process is cost-efficient. For connectors, metallic fasteners are often the choice, as an easy, fast connecting process and high strength properties can be achieved. However, the environmental impacts of using metallic materials are higher than from wood materials (Hill and Dibdiakova [11]). A fast, low-tech, and environmentally friendly option is the use of wood-only connections with densified hardwood nails. The benefits of the solution are that no pre- or post-processing (e.g., pre-drilling) is needed and the connection is entirely made from wood. Research about the mechanical properties of wooden nails was performed by Riggio et al. [22], where a moderate load resistance was achieved, and wooden nails were recommended for restoration work in historic timber buildings.

For the intended use of densified hardwood nails, we proposed a design concept of using the shear capacity of wooden nails to carry external loads (Fink et al. [9]). An initial experimental investigation on shear performance of wooden nail connections was carried out by Ruan et al. [24]. Densified wooden nails (Lignoloc®) (see Figure 4(a)) made from European beech (*F. sylvatica L.*) were used. Three nail dimensions (length 75 mm with diameter 4.7 mm; length 75 mm with diameter 5.3 mm; length 90 mm with diameter 4.7 mm) were available for experimental use. The mechanical properties of the wooden nails are available from the technical report of the nail products, for both, the diameter of 4.7 mm (VHT - The German Test Institute for Timber and Drywall Construction [26]) and the diameter of 5.3 mm (VHT - The German Test Institute for Timber and Drywall Construction [27]).

An assembly process of wooden nail connections can be realized by a six-bar air pressure coin nailer (Fasco®), as shown in Figure 4(b). Due to the high-speed rotation created by the nailer, a large amount of heat is generated by friction when the nail is driven, causing the lignin of the wooden nail weld with the surrounding wood (Figure 4(c)). An angle reader and a spirit level were installed on the nailer to shoot with desired inclinations.

The dimensions of timber boards and wooden nails used in this study limited the nailing angle to a maximum of 30˚. During the nailing process, nails may be damaged when meeting wood-knot areas. As a solution, a shift of nailing position was adopted, which resulted in irregular nailing patterns.

The three-member specimens were directly cut from the assembled timber boards into designed sizes. The specimens were tested with a universal testing machine (UTM) with a maximum force of 200 kN (Figure 4(d)). From the results, a considerable load bearing capacity to resist shear forces was distinguished when the nails were arranged with predefined inclinations. The found shear capacity allowed to predict the load bearing capacity of the connections exposed to bending stresses by using a proposed analytical model (Ruan et al. [24]).



(a) (b) (c) (d)

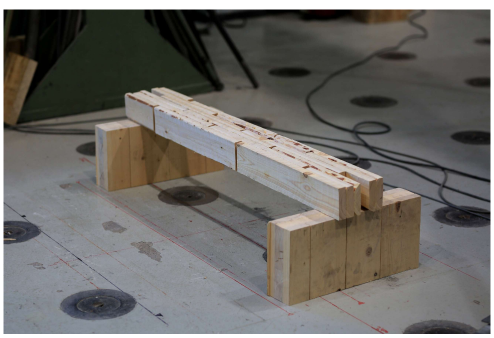
Figure 4: Wooden nail connections: (a) wooden nail (photo Lignoloc©); (b) nailing process; (c) microscopic image of the bond between wooden nails and the surrounding base wood (photo Lignoloc©); (d) testing process.

3.2. Structure second

As an experiment, as well as an example, a nailed-laminated timber (NLT) (Natterer [15]) panel (deck) system by using locally salvaged timber was targeted. The structural system was defined as a simply supported deck structure with a span of 2 m. The overall load-bearing capacity of the prototype was mainly affected by the span and the arrangement of nail connections. The structure was only connected with wooden nails in the board´s overlapping areas. Based on the initial research output from the "material and connection first" stage, salvaged timber and wooden nail connections were intended to be integrated into a prototype-structure. However, some incompatibilities, which were mainly related to material dimensions and the structural properties of the connections occurred during the integration process. As a solution, some limitations were set as follows:

A minimal length of the salvaged timber boards is required to guarantee sufficient overlapping length (longer than 250 mm) for the nail connections. As the nail connections should follow the requirements of minimal spacing and insertion length according to EN-1995-1-1 (European committee for standardization [7]), a minimal width and thickness of the salvaged timber is required.

A series of explorative investigations were conducted, to achieve some pre-knowledge for prototype fabrication. Structures with different nailing patterns and a 1.2 m-span were tested to failure. Two board dimensions ($b \times t = 100 \times 25$ mm^2 and $b \times t = 123 \times 48$ mm^2) were used for sample fabrication (Figure 5(a, b)). The structures mostly failed in the nails when the timber boards reached a large rotational displacement (Figure 5(c, d)). The nailing pattern in the prototype was designed to mainly resist moment loads. In addition, the test results also validated the analytical model proposed in the connection tests. Therefore, the structural behaviour of the prototype can be predicted.


(a)


(b)


(c)


(d)

Figure 5: Explorative bending tests: (a) specimen made from boards with a cross-section $b \times t = 100 \times 25$ mm^2; (b) specimen made from boards with a cross-section $b \times t = 123 \times 48$ mm^2; (c) specimen deformed in the test; and (d) specimen deformation after the test.

The structure for the prototype was realized by following a specific nailing pattern as described by Ruan et al. [24] to connect the selected salvaged timber boards from the material storage. It was supported by two round timber which were also salvaged from the same source (Figure 6(a)). A loading test was carried out by allowing four people to stand, walk and jump on the structure (Figure 6(b)). Without any damages and collapses, a sufficient load bearing capacity for short-term loads was acquired. The structure was exposed to outdoor conditions like sun, UV, rain, and snow for more than half of a year, and no obvious damages were observed.

(a) (b)

Figure 6: Prototype-structure: (a) a simply supported NLT deck realized by salvaged timber and wooden nails; (b) a loading test on the structure including its prototypical use.

3.3. Architecture third

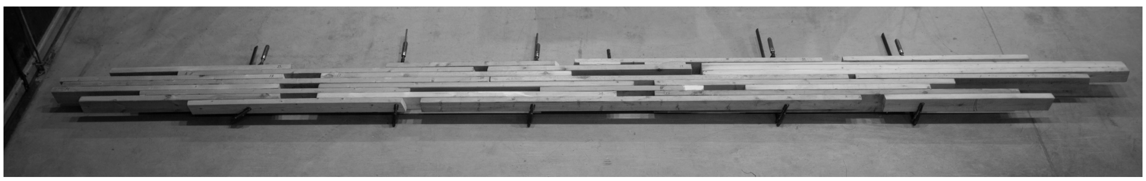
Using salvaged wooden material and wood-only connections is not new. Fink et al. [9] used salvaged timber and wooden nails to build short span timber-only structures for natural trail constructions in Finland. The Recycleshell project by Robeller and Von Haaren [23] is another application of using timber-based cut-offs for the design and realization of a wooden shell structure. The entire structure was made from the door- and window- cut-outs from cross-laminated timber production lines and connected with wood-wood connectors. However, our approach introduces the use of salvaged material without or with minor processing, such as cutting into desired size only, by following low-tech approaches as proposed by Filz [8]. So, we are aiming for structurally sufficient, easy-to-assemble and low-budget solutions with an emphasis on increased sustainability.

3.3.1. Architectural diversity

Looking at the prototype structure as a basic structural form, an exploration of architectural diversity was conducted. Both, the overlapping length of each connection and the use of plywood as distance keeper are guiding parameters for architectural aspects. The change of the parameters may in turn have an influence on the structural behaviour and material selection. Therefore, the minimal load bearing capacity, which is associated to the minimal overlapping length of each connection is an example of a limiting parameter.

The first parameter is the overlapping length of each connection. Two resulting patterns by arranging different overlapping lengths were analyzed, namely a maximal overlapping (minimal gap) pattern and a minimal overlapping (maximal gap) pattern. To achieve a maximal overlapping pattern, an approach to align the end of the long board to the middle of the short board in each connection was adopted. The formed pattern is shown in Figure 7(a). In contrast, to achieve the minimal overlapping pattern, an approach to arrange as much as connections with the required overlapping length was used. The formed pattern is shown in Figure 7(b).

(a)



(b)

Figure 7: Patterns resulted by: (a) maximal overlapping arrangement and (b) minimal overlapping arrangement.

The second parameter is the use of plywood as distance keepers. For this design alternatives conventional nails have been used. Here, the distance keeper is a small piece cut from the salvaged plywood boards. The main reason of using distance keepers is to create small gaps between the timber boards in the lateral direction. It helps reduce the accumulations of tree leaves and small branches for the structure in outdoor use. From an architectural perspective, this also modifies the resulting patterns. Board arrangements without distance keepers (Figure 8(left)), board arrangements with one distance keeper for each two nails (Figure 8(center)) and board arrangements with one distance keeper for each nail (Figure 8(right)) were arranged and performed. Accordingly, the three arrangements created varying patterns – short rectangular shape, long lined shape, and 'H' shape, respectively.

From the exploration of the parameters, a structure with maximal overlapping pattern and the use of distance keepers was recommended. The recommendation is mainly based on a comprehensive consideration of architectural expression, load bearing capacity and environmental resistance.

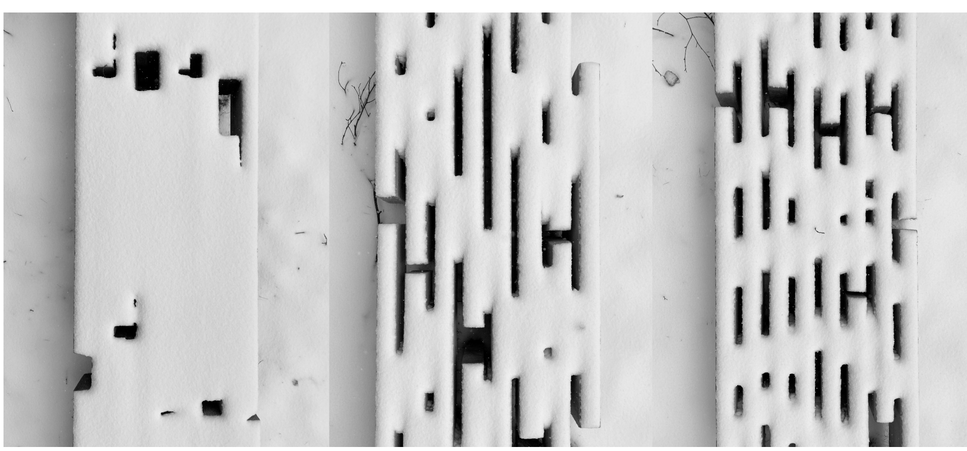


Figure 8: Patterns (covered by snow) resulted from different arrangements of distance keepers: (left) without distance keeper; (center) one distance keeper for each two nails; (right) one distance keeper for each nail.

3.3.2. Case study – a natural trail design

The design concept was proposed for a natural trail project in Kouvola, Finland, which required a cheap, fast, replaceable, and sustainable construction solution. The trail project was planned in a forest area near the Kouvola railway station, to create a shortcut between two orthogonally intersecting roads as well as a future connection to a planned residential area. An initial design of a 70 m-long, prefabricated structural system composed from multiple flat modular elements and a partly curved central plaza-like elements was proposed according to a preliminary site survey (Figure 9(left)).

The modular part of the trail was divided into multiple segments for modular fabrication. The lengths of the segments ranged from 1.5 m to 3 m. For each segment, one module was planned. As the salvaged materials used for the natural trail was planned to be collected from the mentioned timber housing company, material properties similar to the prototype design was assumed. The design of modular elements followed the recommendation from the analysis of architectural diversity. As the lengths of the modules differ, the salvaged timber boards were planned to be categorized by dimensions and to be use according to the needed module length.

Figure 9: Plan view of the natural trail (as provided by Kouvola city©) (left); a big rock (right-bottom) and a small ditch (right-top) in the area.

The plaza area was planned in the central area of the trail. The area is located at the intersection between the trail route and a future planned link to the nearby residential buildings. In this area, a big rock next to a tree (location 1 in Figure 9) is of importance for the client. A ditch, which goes cross the routine is close to the eastern end (location 2 in Figure 9) of the trail. An initial design of the plaza area considers and reflects the atmosphere of the natural surroundings (Figure 10). Curved arrangements of timber boards with both upward and downward curvatures were guiding in architectural design. The connecting approach followed the same approach in the prototype (see also Figure 10). The board arrangements with a downward curvature were forming seating, while the board arrangement with a downward curvature set the big rock into scene.

Some technical and architectural limitations emerged from applying the assembly patterns to the more complex, curved shapes. For example, the nailing angle is limited to smaller values as the overlapping area becomes less than the flat form. Additionally, the loading condition of the curved form is different from the flat form, so the structural efficiency of the wooden nail connections needed to be reconsidered. However, the design concept and methodology for assembly has been accepted and is about to be realized.

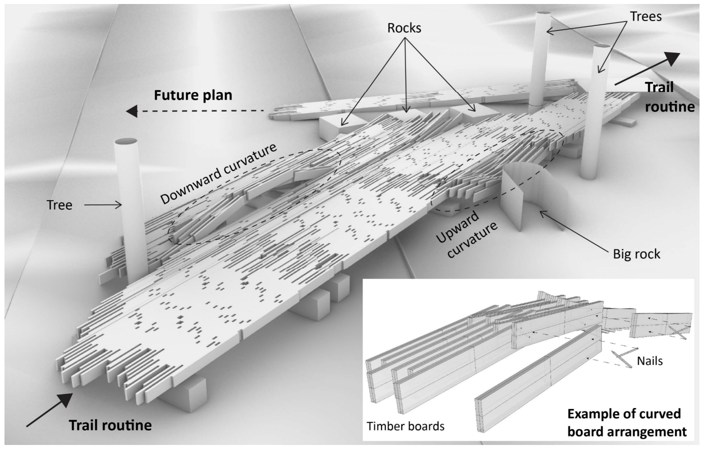


Figure 10: An initial design for the plaza area in the natural trail project.

4. Conclusion

With this paper, an innovative integrated design concept which follows a sequence of 'material and connection-structure-architecture' is introduced. Our integrated design concept is based on the idea of "material and connection first" as introduced by Oxman [17] and proposes a novel "material and connection – structure – architecture" sequence. Initially explored separately, the salvaged timber material and the wooden nail connection are merged into a prototype-structure.

Limitations related to material dimensions and properties of the connections were identified by combining the afore-mentioned aspects and leading to a series of explorative bending tests and an experimental prototype design of the structure. Sufficient load bearing capacity and environmental resistance of the structure were proven by lab-tests and long-term exposure to environmental conditions. The application space in architecture and the architectural diversity of the prototype-structure was analyzed by comparing the resulting assembly-patterns through changing the overlapping length between timber boards and the use of salvaged plywood boards.

A proposal for a natural trail project, which required a cheap, fast, replaceable, and sustainable construction solution was presented as a case study. Our design proposal includes multiple modular elements for the path and a central, partly curved plaza-like structure.

From the experimental sequence of using the proposed integrated design concept for a real construction project, following aspects can be identified: The "bottom-up" design process starts from individually investigated sub-aspects, namely the material and the connection. Their merger into an integration process creates a design space where architectural diversity can be explored.

The holistic approach considers material aspects, structural behaviour of connection and structural elements as well as architectural features and expression in an iterative way and by feedback loops. Future work will focus on the smoothening of the workflow and flow of information, on realizing limitations as potential for creatively triggering solutions in the multidisciplinary setting of material-connection, structure, and architecture. The structural and architectural potential for optimizations regarding the wooden nail connections, and associated assembly geometries are subject to ongoing investigation. The potential of structural/architectural applications for indoor use will be another aspect worth exploring.

Acknowledgements

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