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Master Builders revisited

The importance of feedback loops: a case study using salvaged timber and wooden nails only

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Abstract
In the light of today's challenges regarding sustainable solutions for the built environment, our research focuses on building entire structures with timber only. Salvaged timber and wooden nails are selected as starting points to explore the structural and archtiectural possibility by following a timber-only concept. Reminding of the ancient Master Builder idea, the process of our investigations makes clear the importance of all steps and their distinct insights feeding back, following the loops from design to the assembly of the objects, in order to increase the efficiency of material use and optimize the functionality of the final object. In this paper we evaluate the feedback loops performed so far including the lessons learnt from success and failure in design, testing and manufacturing. We also look into the potential of increased structural and architectural quality of outputs and increased diversity of applications by our approach.

Keywords: feedback loops, Master Builder, salvaged timber, wooden nails, timber-only concept, structures and architecture, sustainability, lessons learnt.

Introduction

The Master Builder model

Looking back human's building history, there used to be no clear division of professions like architects and engineers. In ancient time, the person who worked with specific building materials and mastered building skills was responsible for the whole building process from the early design phase to the final realization. This type of profession was referred to Master Builder. The ancient Master Builder normally was passed the knowledge of material, form, and proportions of buildings from his predecessors (Larsen 2003), and developed his building skills with intimate intuitions from nature (Torroja et al. 1958). Based on the lessons learnt from his predecessors and intuitions, the ancient Master Builder developed the building technology from generation to generation.

In Europe, from the Renaissance onwards, the role of the Master Builder began to be divided between liberal thinkers, whose design was based on theoretical, for example mathematical, considerations,and executors (Argan 1969), as first seen in the dome of Florence Cathedral. A further division of liberal thinkers into architects and engineers was triggered mainly by the emergence of architectural methodologies and later by the inventions of new building materials, such as cast iron, steel, and glass, while the executors became mainly responsible for building construction (Saint 2007).

In modern society, the role of the Master Builder has been fragmented into more specialized professions, such as the architect, the structural engineer, the mechanical engineer, and the construction manager, etc. There are several advantages resulting from the fragmentation into individual specialized professions, especially for complex projects. However, the fragmentation may result lack of efficiency due to the difficulty of collaboration between the different professions where different methodologies and different thinking modes are applied. In today’s building design process, architect’s role is limited in conceptualizing the building form, while structural engineer focuses on rationalizing the structure and dimensioning the material (Setareh et al. 2015). Such a separation results in inefficiency in many aspects, such as excessive use of material, inappropriate selection of structural form and high cost (Larsen 2003) consequently. As a possible way to bridge the gaps between architecture and engineering, the Master Builder model was re-mentioned during last decades. Alternative approaches, such as the philosophy of design-build (Nicholas & Oak 2020), architectural engineering or construction engineering as educational programme and profession (Albano et al. 1999; Parasonis & Jodko 2013), the idea of structural arts (Billington 1985), developing robots as the modern Master Builder (Sweet 2016), and graphical methods to design structures and architecture (Markou & Ruan 2022) have been attempted. However, only few exemplary projects can be found in the recent past (Billington & Garlock 2004).

Among the alternatives, integrated design concepts have been identified as beneficial for contemporary architectural design (Moe 2008), where material, structure and architecture (form) and their sequence are essential in the discussion (Oxman & Oxman 2010). Traditionally, a “form-structure-material” sequence was adopted. However, varied sequences of the three elements, have been also explored and practiced. For example, Oxman (2010a; 2010b) proposed a material-based design concept which computationally links the three elements in a “material-structure-form” order. Such order has actually already been practiced by the ancient Master Builder. One example shows in the origin of tectonic expression in vernacular architecture, where the material was selected first and the expression of structure and form was informed subsequently (Oxman 2012).

Nowadays, architectural design allows more aspects to be included in integrated design concepts and more complex combinations of these aspects, because of the increased requirements in efficiency, higher demand for complexity of buildings, increasing wellbeing for users, etc. The setups of combinations and starting points differ due to the varied design tasks, applied technologies and fabrication processes. For example, Liu and Lim (2006) proposed an idea of new tectonics, which includes more elements, such as motion, information, generation and fabrication, compared to traditional tectonics. In Oxman (2012), seven different models of material-based design were presented to show the increased diversity of integrated design concepts in the digital age. Since nowadays it is possible to include more aspects of comtemporary architecture (Moe 2008), more complex Master Builder models are emerging.

The importance of locally salvaging timber

The building industry is one of the main contributors to greenhouse gas emissions and waste generation (European Commission 2014). In order to reverse the situation, sustainable solutions for future building constructions are urgently needed. Timber construction has been promoted as a possible solution because of timber's capacity of storing carbon and its renewability. In Finland, increasing timber constructions is suggested as an efficient way of reducing the carbon footprint, which is of great importance for the carbon neutral target by 2035 (Finnish Ministry of the Environment 2021).

The revival of timber construction, however, results in significant amounts of timber waste that is mainly used for energy recovery. One example is shown in a local Finnish timber housing company (Figure 1), where the timber waste awaiting for burning is mostly timber cut-offs from standardized products. In fact, this type of material can be characterized by valuable mechanical properties (Cavalli 2016), and it is possible to salvage it for new constructions. For example, Huuhka (2018) and Parigi (2021) showed the possibility of using salvaged timber for non-structural and structural applications when proper design principles are applied, and Niu et al. (2021) demonstrated the environmantal potential of reusing glued laminated timber beams.

Regarding sustainable construction, other means rather than using salvaged materials have been discovered as well. According to Morel et al. (2001), building with local marterials can significantly reduce the environmental impact of building constructions. In addition, low-tech methods in material processing and fabrication have been proved to be beneficial for sustainability (Liliefna et al. 2020). Referred by Filz (2013), the low-tech concept can be also described as a design and construction philosophy for architectural design thinking. Accordingly, large environmental and economic benefits can be recognized by locally salvaging timber-based materials for new constructions with a low-tech design concept. However,in order to achieve economic benefits, a sufficient value chain and a quality control schema is essential.

Figure 1. Timber cut-offs piled up for energy recovery in a local timber housing company in Finland.

Design concept

In the current context of global warming, rethinking building material and its role in architectural design becomes increasingly important. Using locally salvaged timber in constructions, especially without or with low processing, provides possibilities of reducing greenhouse gas emissions. Furthermore, it may create a unique tectonic expression (Frampton 1995, 37), as well as new design spaces where salvaged material and its low processing approach guide the design. On the other hand, limited references are available regarding the design principles of using salvaged material for new constructions (Addis 2012; Kernan 2001). In this regard, new ways of approaching architectural and structural design by using salvaged timber are worth to be explored and exprimented, especially in conceptual design phase.

Inspired by the ancient Master Builder idea, we propose an integrated design concept which considers the key elements regarding architectural and structural design and looks into the relationships between these elements. We apply a concept of feedback loops to interpret the procedure of integrated design as a feeding back process. We evaluate the feedback loops performed so far including the lessons learnt from success and failure in design, testing and manufacturing. We also look into the potential of increased structural and architectural quality of outputs and increased diversity of applications by our approach.

Feedback loops

The concept of feedback loops

In Åström and Murray's introductory book for feedback systems (2008), 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". Accordingly, two main features of feedback – dynamicality and interconnectivity, are characterized.

In a global view, a feedback loop which starts from a simple object (as an element) becomes more complex when more elements are involved. The mechanism of a feeding back process is illustrated in Figure 2. Locally, one feedback loop represents a closed circuit, which consists of one or multiple interconnetions, starting and ending from one specific element. The simplest feedback loop contains n = 2 elements, resulting in one interconnection. Obviously, with increasing number of elements the feedback loop gets more complex. It should be noted that an interconnection between two elements might be related to multiple characteristics.

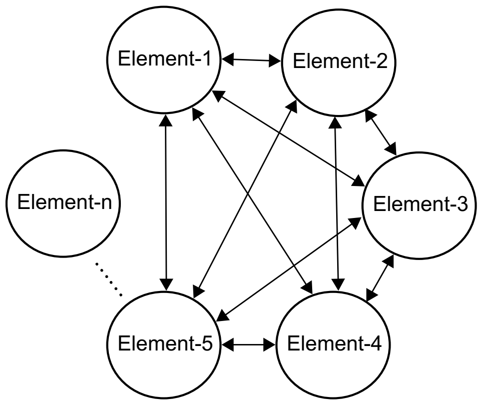


Figure 2. Mechanism of a feeding back process, where *n* means the number of elements.

In the context of architecture, the application of feedback loop covers many aspects, such as structural design (Kurilla et al. 2013), robotic manufacturing (Kontovourkis & Tryfonos 2014), building material (Amtsberg et al. 2015) and interior design (El-Ghazouly & El Antably 2021), etc., but it has been mostly used as its meaning in control system (Åström & Murray 2008) and translated as scripts in computational design programs. It is rare to find examples of using feedback loops more conceptually, e.g., as a design methodology (Derix et al. 2012). In this regard, in the present study, we attempt to accosiate the concept of feedback loop with the Master Builder model, searching for a systematic way of thinking in architectural design.

Using the Master Builder model as a feeding back process

Let us assume the Master Builder model as a growing feeding back process, where the newly added aspects can be understood as the new elements involved in the feeding back process. It is obvious that a more holistic design output can be achieved when more aspects are integrated into the Master Builder model. However, there is a premise for using the term "holistic" that all the elements can be effectively feeded back to the design output. Conceptually, a feeding back process explores many aspects related to architecture, which is in line with the definition of the role of architect by Vitruvius – "The architect should be equipped with knowlodge of many branches of study and varied kinds of learning, for it is by his judgement that all work done by the other arts is put to test" (Morgan & Warren 1914, 5).

As an experiment, we apply the idea of feedback loop in the Master Builder model in order to develop an innovative design approach, which continuously improves itself by leaning lessons during the process. This approach is initiated from selected starting points and developed by adding and analyzing more related aspects. To be noticed that, the authors have a common background in structural engineering, the selected starting points are therefore set up from a structural perspective.

Case study – timber-only structures using salvaged timber and wooden nails

Starting points and sequence

This paper presents an exemplary use of feedback loop as the driving force in integrated architectural and structural design. It was experimented in a research-based natural trail project, following a timber-only concept proposed by Fink et al. (2019). As a showcase to explore the potential of using feedback loops, salvaged timber and wooden nails were chosen as the starting points to initiate the process:

- The wooden nail is a fastener made from compressed European beech wood. The wooden nails are used without predrilling. For the fabrication process, a pneumatic nail gun needs to be used.

- The salvaged timber elements used in this propject are mainly timber cut-offs taken from the production (waste) from local suppliers. The present use for these elements is for energy recovery only.

To carry out the feeding back process fluently, we scheduled a preliminary plan by following a small-to-large sequence from the perspective of scale, as well as a simple-to-complex logic from the perspective of design. The initial plan of the

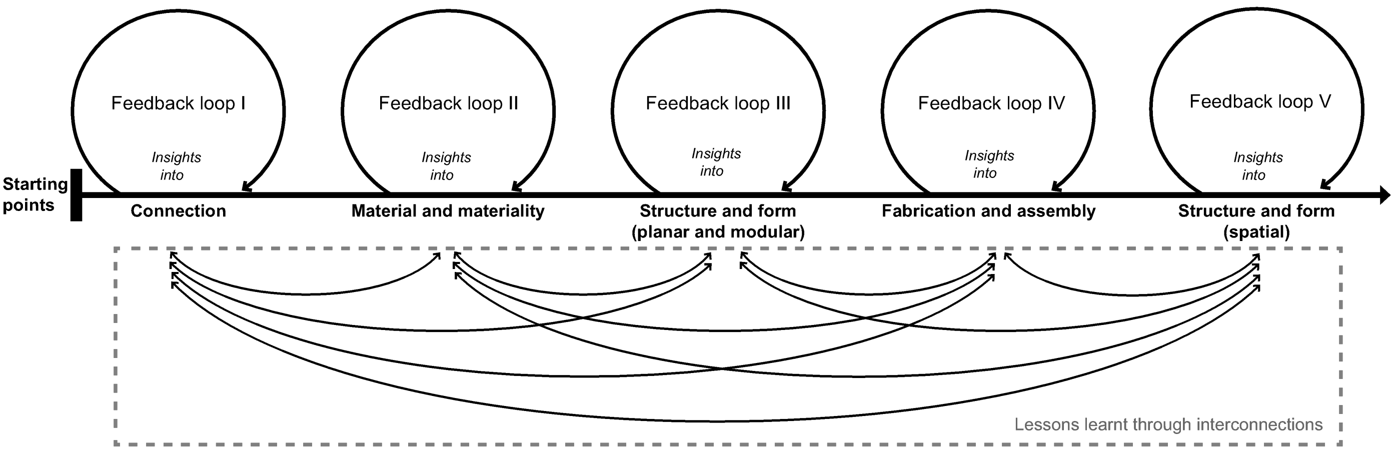


Figure 3. A preliminary plan for the feeding back process, including the starting points, the essential elements, the feedback loops, the insights into individual loops, and the lessons learnt through the interconnections.

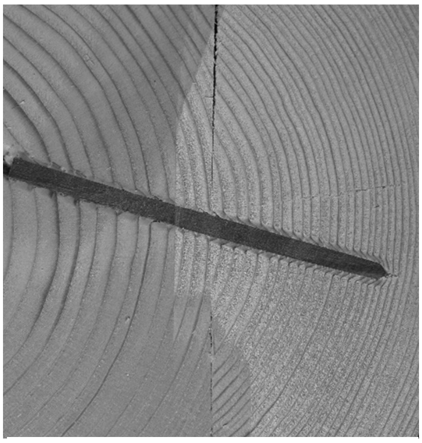


Figure 4. Two timber boards connected with an inclined wooden nail.

feeding back process is illustrated in Figure 3, where connection, material and materiality, structure and form (plannar/modular), fabrication and assembly, structure and form (spatial) have been selected as the five essential elements. In the following the details of each feedback loop are introduced, including the lessons learnt.

Feedback loop I – wooden nail connection

In the first feedback loop, the efficiency of the connection between timber boards using wooden nails was explored. The structural behaviour of wooden nail connections using single and multiple pairs of nails was investigated in the laboratory at the Department of Civil Engineering, Aalto Univeristy, Finland. Three types of wooden nail and two types of cross-section of timber board were used in the experimental investigation. For details about the experimental investigation it is reffered to Ruan et al. (2022a).

Referring to a common way for connections with smooth steel nails (CEN 2014), the wooden nails were used in perpendicular to the wooden surface. To explore other possibilities, we considered assembling with inclined wooden nails (Figure 4). The inclined nail insertion was realized by using an angle reader and a leverer temporarily taped on the nailing gun (Figure 5). The benefit of the inclination is to utilize the tensile capacity of the interface between wooden nail and timber. This tensile capacity contributed by the nail-timber interface is specifically happened in wooden nails due to the “natural” glues generated during the nailing process (Pizzi et al. 2004).

Figure 5. A nail gun (Fasco®), with an angle reader and a leveler temporarily taped on and compressed beech wooden nails (Lignoloc®) loaded.

The load bearing capacity of connections with multiple wooden nails was investigated as well. Simply supported three-member jointed beams connected with mutiple pairs of wooden nails were experimentally investigated under bending. The arrangement of the wooden nails was selelceted mainly based on specific production and for mechanical reasons. Parameters, such as the number of nails and the distance between nails, have been investigated.

Lessons learnt

The nailing pattern and angle were rethought and adjusted according to the experimental test results of wooden nail connections as well as the mode of assembly and practicability. Different from the traditional way of using nails, a cross-arrangement of wooden nail with an inclination of 15° was identified to be more suitable and efficient. For the selection of a specific type and dimension of the wooden nail several aspects were considered. These included not only the load bearing capacity, but also the dimensions of the timber boards and the effect of wood spliting.

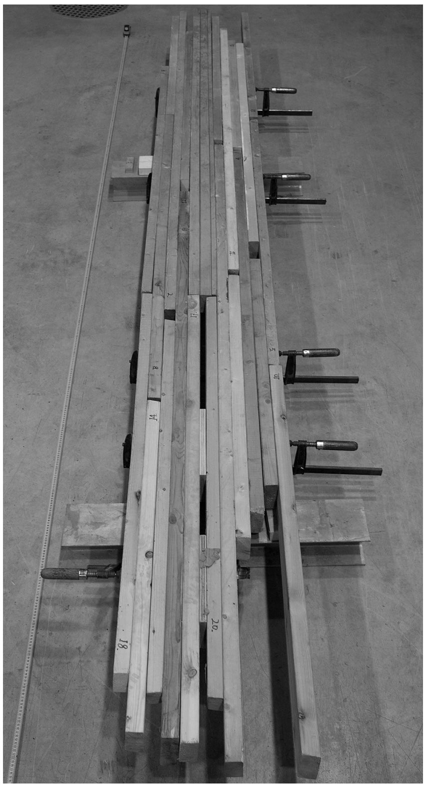
Regarding the bending resistance of the connection with multiple pairs of wooden nails, a simple analytical model has been developed and validated with a high accuracy (Ruan et al. 2022a). This helped for a better understanding of the force flow and also for finding the most efficient way of arranging wooden nails.

For an easy and quick fabrication process, we considered to modify the mainly used tool, the nailing gun. To easily assemble the nails with a 15°-inclination, a modification of the angle of the nail gun tip was discussed with the manufacturer, who consequently modified the tool.

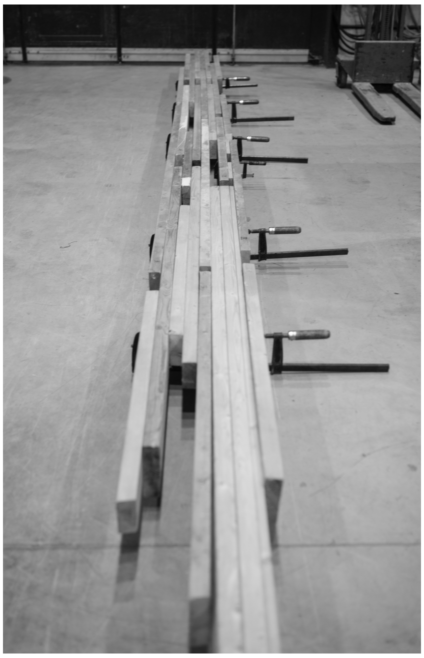
Figure 6. Sorted salvaged timber boards near the waste pile on site.

Feedback loop II – material and materiality

In the second feedback loop, we conducted a preliminary invesitgation on the material properties of salvaged timber and its materiality for architectural expression. The investigation started from searching available local, salvaged timber. To follow the idea of locally salvaging timber, we visited a timber housing



(a)



(b)

Figure 7. Exploring assembly patterns by temporarily clamping the salvaged timber boards: (a) maximizing the overlapping length, and (b) maximizing the gap size.

company in Kouvola, Finland, which stores its timber waste in an open space (see Figure 1).

According to the observation during the visits, some characteristics of the salvaged timber (mainly timber-based cut-offs) can be recognized as follows. The product types were mainly sawn timber and plywood with minority of round timber and laminated veneer lumber (LVL). The lengths of the collected timber boards were mostly in a range of 0.5-1.5 m, while only few longer boards with twisted shapes could be found. From the timber boards, two cross-sections were dominant: 48 × 123 mm^2 and 25 × 100 mm^2.

To realize 1:1 prototypes for testing purpose and architectural evaluation, we organized several material transports from the housing company to the laboratory space at the Department of Civil Engineering, Aalto University, Finland. The salvaged timber was usually collected and stored outside for a few weeks before being sent to energy recovery. We manually collected timber boards from the waste pile on site, sorting them into different categorizations according to their above-mentioned types and dimensions (Figure 6).

To explore the assebly pattern of salvaged timber and its potential in architectural expressions, different timber board arrangements were investigated. Therefore, the timber boards were temporarily attached using clamps. Two examples are shown in Figure 7, where the timber boards were assembled either with the aim of maximizing the overlapping length between adjacent timber boards (Figure 7(a)) or maximizing the gap size (Figure 7(b)). Some features of the assembled structure can be identified – the uneven end and the random pattern resulted by the diverse dimensions of the materials, and the surface color combinations resulting from the nature of the materials.

Lessons learnt

The salvaged timber from a local housing company can be characterized in dimensions and material types. According to these characterizations, on one hand, it is possible to use the materials with certain applied rules, such as setting a limit on material length to provide enough overlapping length, and on the other hand, it results in specific design values, such as the never-repeating patterns because of the randomness of the materials in size and color.

Feedback loop III – structure and form (planar/modular)

In the third feedback loop, we aimed to assemble the salvaged timber with planar or modular arrangements by considering the outputs from the first two feedback loops. Following the ideas of ease-to-build and low-processing, a simply supported, nail-laminated timber (NLT) plate (deck) structure with a span of 2 m was selected as the basic structural form for experimental and prototypical uses.

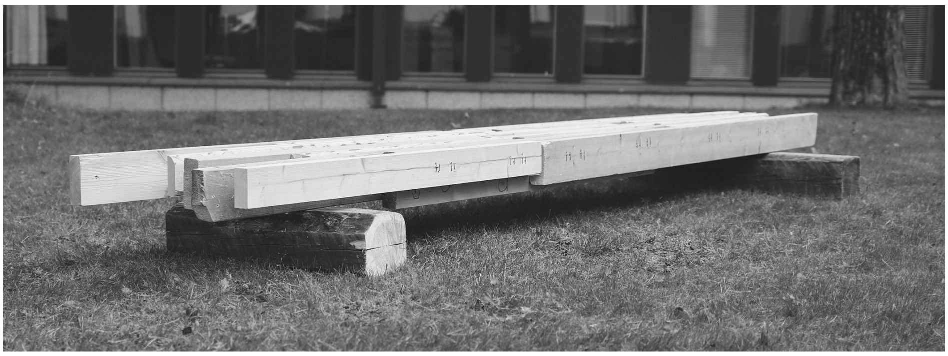


Figure 8. A prototype fabricated for a natural exposure test (before aging).

Figure 9. Dirt accumulation on the surface of the pototype structure during the natural exposure test.

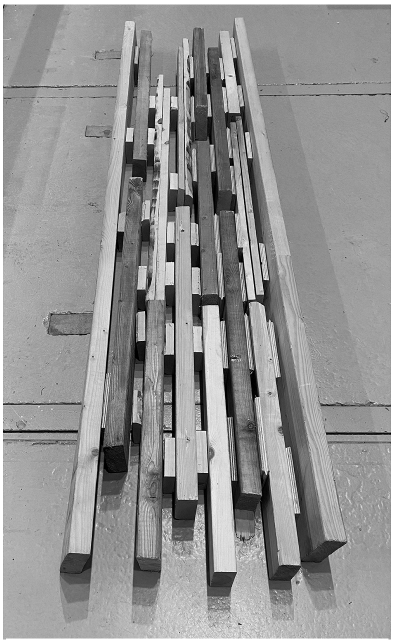


Figure 10. A board arrangement using distance keepers.

Since the application of the modular structure (the natural trail project) is for outdoor use, long-term performance of the structure needs to be considered. In the light of environmental conditions and exposure to users, rain, snow, dirt, and maintenance, the modular structure was prototyped by the salvaged timber with the two main cross-sections and tested under a long-term exposure to natural environment (Figure 8). After a one-year exposure period, no obvious damages were observed in the structure. A sufficient load bearing capacity for pedestrian loads remained, validated by the result of a non-destructuve loading test. However, water and dirt accumulation was visible on the surface of the timber boards all over the year, mainly due to the presence of wane, which is untrimmed bark or wood that is missing along the edge or corner (Figure 9). Due to the water and dirt accumulation the timber boards are expected to absorb more moisture.

To avoid water and dirt cumulation, we inserted small pieces of sawn timber or plywood boards in-between each two layers as distance keepers, which would allow dirt and water dropping down through the gaps (see Figure 10). However, with the additional layer, the connection stiffness was significantly reduced, which may easily result in local failure of the structure, especially in the corner areas.

In parallel, the aesthetic expression of the assembled, salvaged timber was explored in an unintentional way, which means that the assembly patterns of the modules were not designed to large extent, but the used look and the resulted patterns came as an emerging aspect of aesthetic value. An exmple is shown during the long-term exposure to the nature, when the structures, including the prototypes with distance keepers, were covered with snow (see Figure 11).

Lessons learnt

Distance keepers that we proposed for avoiding dirt cumulations reduced the local strength of the structure, which was therefore not adopted. The water and dirt cumulation, was mainly observed at timber boards with wanes. The timber boards with larger cross-section (48 × 123 mm^2) and without wane in the cross-section were therefore selected as the main material for the main (deck) structure. Beside the dirt accumulation also the general durability of these timber boards is expected to be longer.

Unintentionally, the structure with planar arrangements showed emerging aesthetics in patterns created by the randomness of the material and the natural environment. This aspect needs to be consdidred in the design process, since it architecturally leads to rethinking about the people's perception of waste material, in our case, the salvaged timber, which consequently may propose a new type of aesthetics.

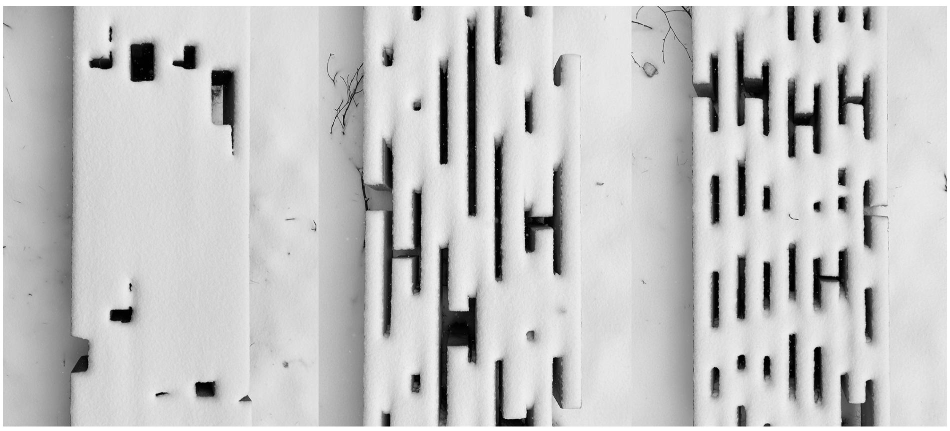


Figure 11. Patterns on prototypes resulted by snow (Ruan et al. 2021).

Figure 12. Modular elements assembled in a linear shape in Kouvola, Finland.

Feedback loop IV – fabrication and assembly

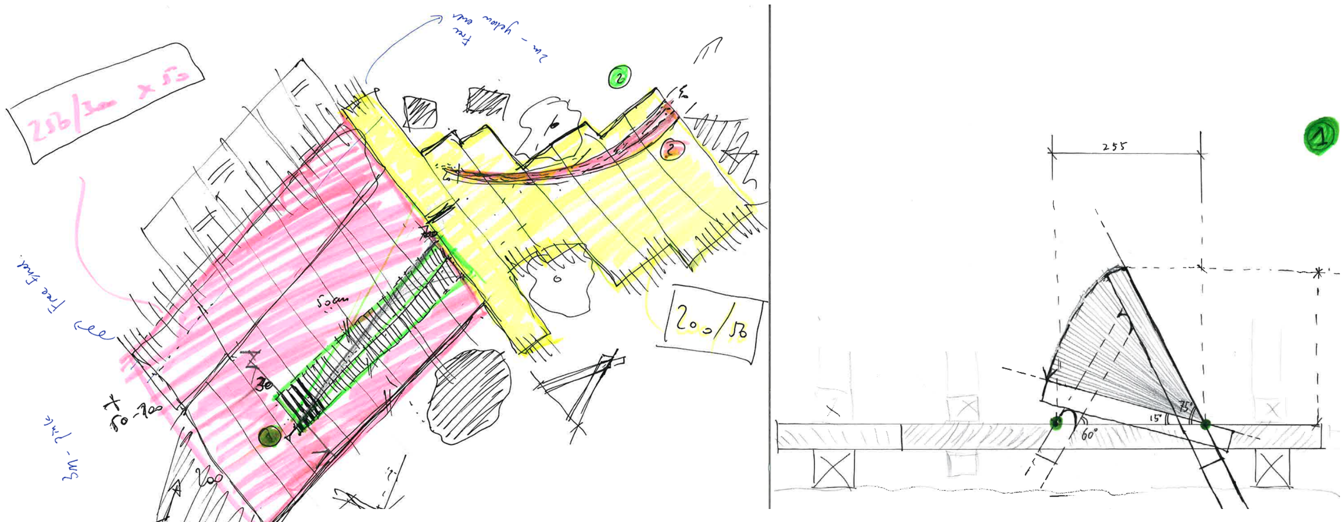
In the fourth feedback loop, we applied our prototype structure as the modular element for the natural trail project in Kouvola, Finland. The trail was planned for a forest area near the Kouvola train station, in order to create a shortcut between two orthogonally intersecting streets. The design of the trail project has two main parts – multiple flat modular elements and a customized central plaza-like area. The two parts were planned to be fabricated in two different places for different reasons. The flat modular elelments which require a cheap, fast, replaceable and industrialized solution were produced locally in Kouvola. The customized plaza area, which explores the spatial potential, the idea of mass customization and more creative solutions was realized at Aalto University, Finland.

The fabrication for the flat modular elements was conducted as a workshop co-organized by Aalto University and Kouvola Region Vocational College (KSAO) in Kouvola. Elementit-E Oy provided a manufacturing space and the needed devices for the workshop.

The fabrication process of flat modular elements follows the same design princple of the prototype structure. The process has mainly four steps: (i) selecting suitable timber boards, (ii) arranging the timber boards, (iii) marking the nailing pattern, and (iv) nailing the timber boards together. To speed up the process of timber board selection and arrangement, we built a working table which has three boundaries (two at the end and one in the middle) to form areas with the same size of modular element. The working table, on one hand, helps achieving "clean" ends of the modular elements, which can be easily installed on site in longitudinal direction, on the other hand, it helps attaining a planar surface by assembling in an upside-down way. For the connection, we selected a nailing approach by following the minimal spacing requirements provided by EN-1995 (CEN 2014). Accordingly, a template for marking the nailing pattern helped speeding up the later nailing process. So far, twelve modular elements have been finished and stored in the same space where they were fabricated. To explore the appearance of the trail, some modules were linearly assembled to form a trail path by again using wood-based waste as supports, as shown in Figure 12.

The central plaza is a customized and creative version of our developed prototypes. Its fabrication was integrated into the multi-disciplinary design-build course *Structures and Architecture: Informed Structures* at Aalto University, as a hands-on part for the students (the detailed information of the course is introduced in the fifth feedback loop). The students' task was to realize parts of the plaza area, which has been initially designed to have a twisted backrest sticking out of the deck and irregular boundaries (Figure 13). This part of the

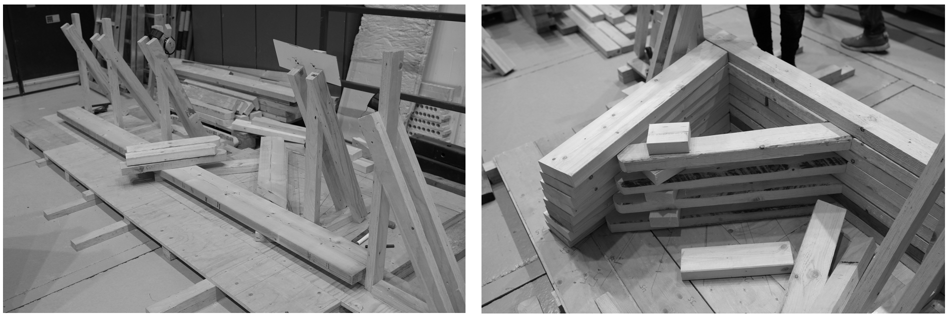
Figure 13. Design sketches for the plaza area of the trail project: (a) plan view of the plaza structure, and (b) side view of the seating area.



(a) (b)

plaza (the red part in Figure 13(a)) was divided into eight elements, of which the sculpturally twisted backrest comprises six parts. The structure was assembled with wooden nails only, following the arrangement developed in the second feedback loop.

Before the workshop, both, physical and digital preparations were carried out. In the physical preparation, a similar idea of the working table for the fabrication of flat modular elements was adopted, realized as a 4 m-long platform (Figure 14(a)). Since the surfaces of the structure are not planar on both sides, the structure was built in a vertical way. This means that each layer was plied up on the previous one and connected with wooden nails (Figure 14(b)). In parallel, the digital preparation provided technical drawings with all needed dimensions of the members of the twisted backrest, such as the inclination and length of each member. This information has been transferred to the working platform by mapping the position of the first timber board of each element. As we proposed in the first feedback loop we now used nail guns with a 15°-inclined tip provided by the Beck Group (Figure 15).



(a) (b)

Figure 14. Making the plaza structure: (a) the working platform, and (b) the arrangement of timber boards.

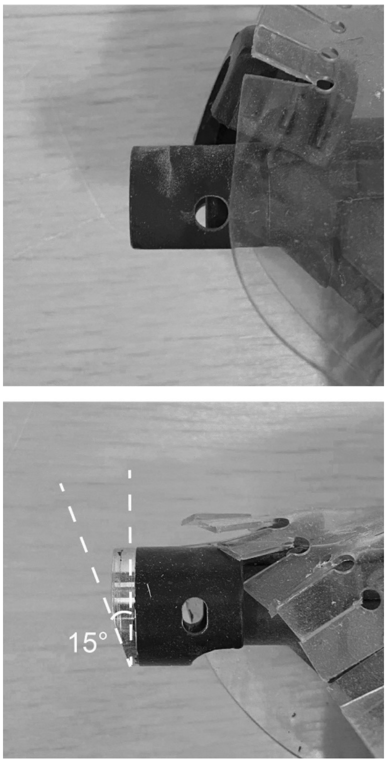


Figure 15. The tip of the nailing gun: (top) without inclination, and (bottom) with 15° inclination.

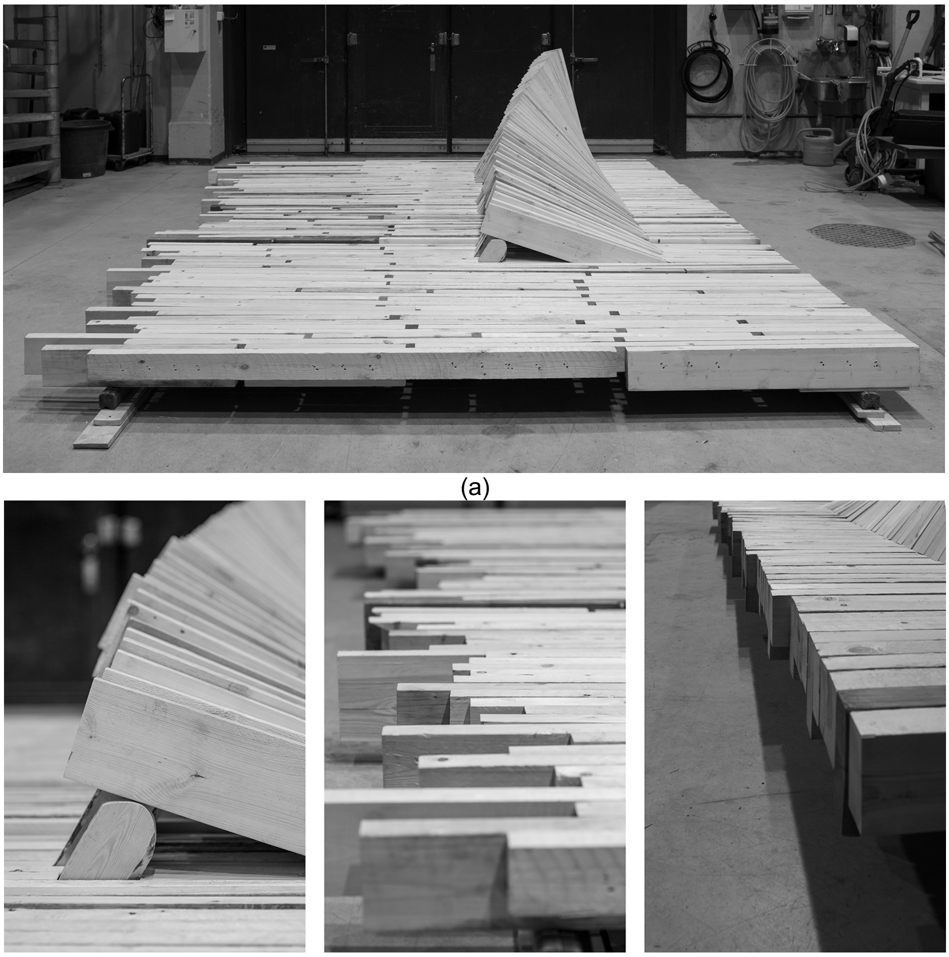
For making the twisted backrest the materials need to be processed. The backrest consists of two parts: long timber boards with a constant length to create the twisted surface, and short timber boards with changing lengths to form the support of the surface (Figure 13(b)). Each layer of the twisted backrest has a 1°-rotation change. The timber boards of the support part were arranged in every second layer. To achieve a smooth and simple-to-fabricate contact between the two parts, a standardized, rounded end of timber boards was made, as shown in Figures 13(b), 16(a) and 16(b). For the deck part of the plaza, we picked up relatively long timber boards and cut twice for each board with its corresponding angles to form the three members of the deck below the triangular structure.

The individual elements were assembled after their completion in the laboratory at Aalto University, Finland (Figure 16(a)). The continously twisted backrest (Figure 16(b)), the random board ends on one side of the plaza structure (Figure 16(c)) and the slightly shifted edge of the seating area (Figure 16(d)) can be featured after the assembly of the structure.

Lessons learnt

In this feedback loop, the fabrication and assembly process has been practiced in a similar way but in different contexts and with different aims. For an industrialized purpose, as for the modular fabrication in Kouvola (KSAO), a fast and economic fabrication process is required. In this regard, a simple form, which follows an easy-to-build idea has been realized by using a simple fabrication rule and developing working tools, such as the working table and the marking template. For an explorative purpose, as for the plaza fabrication at Aalto Univeristy, a customized design solution has been realized, based on the original modular idea. In this regard, the fabrication process also shows its potential for parametric design and digital fabrication. Combining the precise cutting of the different boad inclinations with the standardized solution of the rounded ends of the short boards allows for both, the acceptance of tolerances and a fast way of assembly.

However, the two different approaches, a more industrialized and standardized (KSAO) and a more customized (Aalto) that were separately explored, may expand the design space for using salvaged timber and wooden nails from 2D to 3D. The sculpturally twisted backrest indicates the potential of a merger into spatial applications.



(a)

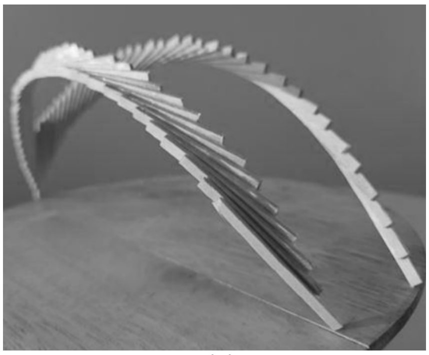
(b) (c) (d)

Figure 16. Realization of the plaza structure: (a) the entire structure, (b) the detail of the twisted structure in the seating area, (c) the random end at the one side of the structure, and (d) the slightly shifted edge in the seating area.

Feedback loop V – structure and form (spatial)

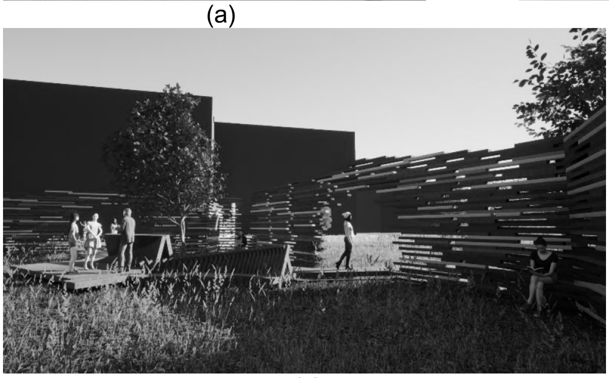
The fifth feedback loop was carried out to further explore the potential of using salvaged timber and wooden nails at the threshold of structural and architectural design. This approach was explored in the course *Structures and Architecture: Informed Structures*, where students from both, the master's programme in Architecture, the School of ARTS and the master's programme in Building Technology, the School of Engineering participated. The aim of this course was to expand the design space and alternative uses of salvaged timber and wooden nails based on the lessons learnt from the previous feedback loops. In order to equip the students with sufficient pre-knowledge, first input lectures, which presented the gained knowledge from the previous feedback loops were offered. After a phase of developing individual design proposals, the course was complemented with the workshop for plaza fabrication as a hands-on practice and experience for the students. There, they learned dealing with all phases from preparing drawings to cutting and assembling salvaged material into a full scale structure. After completing the workshop, the students were expected to rethink and propose their original designs for a final submission. However, the design scope of the course was without any constrians in terms of structural and architectural forms, but limited to the use of salvaged timber and wooden nails as the only material and connection. The students formed groups, each group with one architect and one engineer, to enhance multidisciplinary collaboration between the School of Arts, Design and Architecture and the School of Engineering at Aalto University, Finland (Filz et al. 2021).

An overview of students' works is presented in Figure 17, exemplifying the design approaches, the developing processes and the selected structural and architectural forms developed by the student groups. The proposal *Twisted arch* (Figure 17(a)) explores the relationship between the force low through the connections and the form, following a similar idea of designing masonry arches (Ochsendorf 2002). *Reciprocal frame (RF) structure* (Figure 17(b)) inspired by RF's flexibility of form in plan (Larsen 2007) searches for an easy and fast fabrication process with an optimized use of wooden nails. The concept of this proposal has even been explored by the students in full scale. The *Tunnel pavilion* (Figure 17(c)) focuses on a simple arrangement of salvaged timber boads, in order to highlight the resulting patterns and rhythm of the material arrangement. Inspired by Anni Albers' artworks on weaving (Albers et al. 2017) and Leonardo da Vinci's self-supporting structure (Di Carlo 2008), *The net* (Figure 17(d)) is a free-form fence-like structure, exploring the interrelation of artistic expression and its structural features.

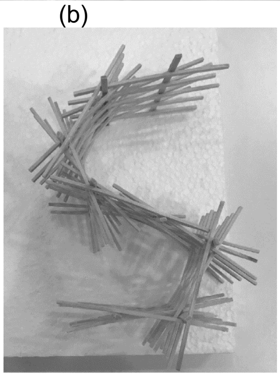


(a)

(b)



(c)



(d)

Figure 17. Design proposals from the students in *Informed Structures* course: (a) Twisted arch, (b) RF structure, (c) Tunnel pavilion, and (d) The net. (photos provided by Elettra Cremonesi, Jolien Crum, Lorenzo Giordano, Kertu Jõeste, Lassi Liimatainen, Gabrielle Nocolas and Olímpia Solà Inaraja)

Lessons learnt

This feedback loop, in which the different types of structural and architectural forms were performed, shows various extents of link to the previous feedback loops. It also shows the limits of integrating all of the earlier feedback loops into one specific spatial form, as none of the proposals can fully cover all of the aspects. However, the students' proposals show the possibility of further developing the feeding back process in different directions in terms of spatial structures, and the potential to optimize from different perspectives.

Discussion

According to the feedback loops performed so far and the lessons learnt, we analyze the pathway of the feeding back process resulting from the dynamics of the involved elements and their interconnections. An overview of the feeding back process with its resulting lessons learnt through the interconnections is illustrated in Figure 18. The process performs a transition from the ease to the difficulty of integrating all the lessons learnt from the previous feedback loops, in other words, a pattern from simplicity to complexity in the design output. Our proposed approach makes sure that the process considers all the lessons learnt, including the failure and the success from each aspect, so that the output design turns out to become increasingly holistic during the process. However, it also shows an increased difficulty of coming up with a holistic design solution when an excess of aspects are involved in the process, which is the main limit for our approach. As a preliminary exploration, this paper aims to point out the importance of the mindset of searching holistic design solutions. Since the design task and the context differ from case to case, rational and suitable selection of involved aspects is needed according to the specific situation.

Different from traditional design approaches, our approach focuses on the process and its logic to derive the design output instead of only designing for an end-product. To be noted that our approach is not only learning from inside – the multidisciplinary research team itself, but also from outside – the client, who brings limits, such as the design constrains due to the specific site conditions, as well as the construction team, who brings expertise to fabricate the structure more efficiently, etc. It basically follows the idea of ancient Master Builder who continuously learns and develops their skills during lifetime and over generations.

Unlike the ancient Master Builder model, the main difficulty of our approach is that the feedback loops used to study all related aspects can no longer be covered by a single person. Today's more complex requirements and the associated comprehensive understanding of the various aspects and parameters require increased collaboration between multiple disciplines, which is likely to be the biggest challenge in complex building projects. In this regard, it makes sense

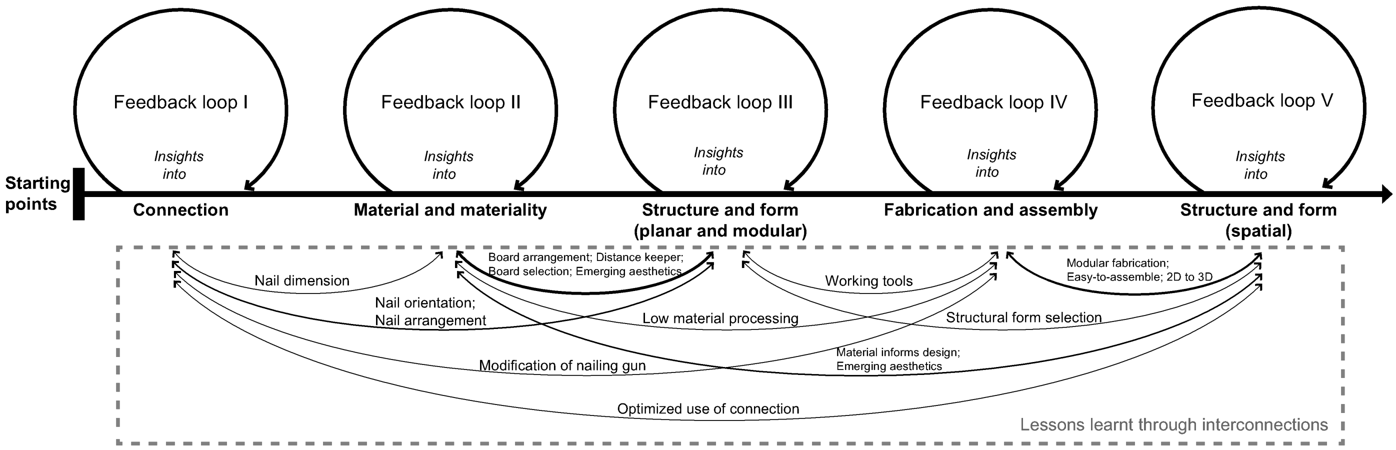


Figure 18. The feeding back process with its resulting lessons learnt through the interconnections.

to either suggest the approach for a limited range of applications, mainly for small project or specific structural form, as referred in Charleson (2014), or to rethink and expand the concept of building information modelling to a design supporting tool. However, this is also in line with the idea of ancient Master Builder who normally works for a specific structural form or uses a specific building material. Moreover, even for large scale or complex project, the proposed approach using feedback loops, which attempts to integrate various disciplines into a collaborative design process, may bring inspirations for new design approach and lead to changes in the building industry.

One more difference shows in the starting point of design process which is, in our approach, not the conceptual work, not from the general shape or the spatial program, but from the material, its availability, and the way of connecting. Due to the unusual way of starting a design process, the integration of different disciplines becomes challenging. In our approach, the concept of feedback loops is used to provide a common ground for multidisciplinary collaborations, from which a holistic solution might come up. It is the contribution to Baukutur, which aims for a high-quality, socially integrated, and sustainable built environment (Swiss Federal Office of Culture 2018), also to the culture of architectural design. In addition, the way we see and use waste will change, so not as dirt or less valuable, but from the point of view of upcycling. Since the aesthetics of future objects will be different, this could in the long run change the perception and aesthetic sense of people.

From a practical perspective, our approach seems less efficient compared to traditional approaches. Since the proposed process aims to feed back every step in each loop, it might be more time-consuming. However, as mentioned above, and based on the readiness of mindsets, it provides a common ground for different disciplines, which integrates the lessons learnt into a continuous process. It is meanwhile well known that design thinking and creative design practice, in short, investing in early design phases, are not only beneficial for the final object, product or consumer experience, but also transcended into a comprehensive innovation management approach, facilitating entrepreneurship and innovation (Auernhammer & Roth 2021; Deo et al. 2020; Rittel 2013). Apart from the immediate and direct benefits from the lessons learnt, it also contributes in our particular case to the further development of the project using salvaged timber or wooden nails as an exemplary case of merging architectural and structural design.

It is important to highlight that there is lack of physical practice in the current trend in architectural and engineering education, where students are often required to acquire the skills of using digital programs for architectural design or structural analysis, but there are few chances offered for building practice, especially in real scale. The knowledge obtained from the building process, which can be understood as the intuitive part of the Master Builder, is therefore missing. In our approach, the conceptual design, the theoretical analysis, the experimental testing, and the hands-on part have been integrated into one package, which allowed students to perceive the material, the structure, and the form from various perspectives, and more importantly, it offered them an opportunity to practice by integration of the different aspects into one design proposal, based on their own design languages, but in dialogue (Ylirisku & Filz 2018).

Since the research team is multidisciplinary, there are two essentials to be highlighted. Firstly, from a material and sustainability point of view - we aim to use salvaged wood with as little further processing as possible. Secondly - from an artistic and architectural point of view - we want to provide the client with a novel design that is also new to society and has a social impact that can change people's perceptions and meets educational purposes. Due to the task itself, where safety is a top priority, we decided to start from a structural perspective.

However, it is also possible to start from other more experimental, social, or artistic points of view, such as the general shape of the structure, which could prove to be freer and more innovative in the first feedback loop. At the same time, these approaches could lead to a less efficient process in the following feedback loops. An important point is that in the long run, through continuous learning from trials and errors in the process, it does not make much difference where you start at the beginning. However, the importance of awareness of the potential discoveries from different viewpoints is shown throughout history, when for example some tombs proof evidence of the Egyptians' understanding of the mechanics of the arch, whereas these structures were never explicitly used at that time (Hanlon 2006).

Conclusions

In this paper, we search for a sustainable design approach in the context of global warming, focusing on the design process and the use of material. Inspired by the ancient Master Builder, we innovatively use a concept of feedback loops and their lessons learnt for the design process. To experiment and showcase the approach, we select salvaged timber and wooden nail connections as the starting points to initiate the process based on an integrated architectural and structural design idea. Aspects of connection, material and materiality, structure and form (planar/modular), fabrication and assembly, and structure and form (spatial) have been explored so far. According to the performed feeding back processes, we conclude the benefits and limits of our proposed approach, its potential for spatial applications as well as some inspirations for future work.

In our proposed design approach, the idea of using feedback loops and their lessons learnt provides a systematic way of thinking in architectural and structural design. The design output is derived from a step-to-step process by exploring and analyzing the related aspects and their interconnections, which is highly beneficial for finding holistic design solutions.

The starting point of design process which is, in our approach, not the conceptual work, not from the general shape or the spatial program, but the material, its availability and the way of connecting. It is the contribution to Baukutur, which aims for a high-quality, socially integrated, and sustainable built environment. Moreover, the way we see and use waste will change from dirt to resource for upcycling. This will have impact on the aesthetics of future objects and, in the long run, change the aesthetic perception of society.

As a showcase, we apply our design approach to a natural trail project, where two design aspects – a modular/economic version and a customized/creative version, have been successfully realized. This shows the flexibility of using the approach for different design tasks, contexts and the use of state-of-the-art technology in design and fabrication.

The limit of our proposed approach mainly shows in the high requirement of comprehensive understanding on the various aspects involved in the process and enhanced collaborations between multiple disciplines, and the increasing difficulty and complexity of integrating the aspects as the number of feedback loops increases.

For future work, we will continue exploring feeding back processes based on our present experience. The potential of our current research has inspired the above-mentioned students' proposals, which in return emphasizes the need of continually being explored and expanded to include the spatial possibilities of using salvaged timber and wooden nails from an architectural and structural standpoint. For example, the RF structure as a specific structural and architectural form seems worth to be further explored due to its flexibility of using short timber members (Ruan et al. 2022b).

Overall, our approach of limiting the architectural and structural design approach to salvaged timber and wooden nails only, seems to foster radically creative ideas and processes, which may have impact on aspects of beauty, Baukultur and a future sustainability-based, aesthetic perception of our society. Consequently, the feeding back process proposed in this paper is an alternative way for both industry and society to find new ways of using materials, of exploring potentials, and of creating structures and spaces by considering various aspects. The main concept of the new Master Builder model is therefore, not a debate about who takes and keeps the lead in this process, but aims to create more sustainable and beneficial solutions for future generations through alternation, exchange and dialogue.

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