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DESIGN FOR LOW MATERIAL PROCESSING: SHOWCASES USING SALVAGED TIMBER

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ABSTRACT: Sustainable use of wood-based products in building construction is essential to fully utilize the environmental benefit offered by the limited natural resource of wood. One promising approach is to give the timber "waste" a second life by salvaging for new applications, particularly structural purposes. Due to the inherent characteristics of salvaged timber, which often comes with short and random lengths, its value is often considered significantly lower compared to raw materials and, therefore, not preferred for further processing. Design difficulties occur when using salvaged timber for new applications because of this limitation. To overcome it, innovative approaches are needed for the design of efficient structures with minimal material processing. In this paper, a concept of Design for Low Material Processing (DfLMP) is proposed and explored based on a contextual rationale that emphasizes preserving the material's original state. By examining both historical and contemporary examples of low-processed timber, primarily round wood, we identify four key aspects of DfLMP for further analysis: fabrication, joint design, structural form, and architectural quality, as well as the consequential life cycle performance. Based on these aspects, salvaged timber is intended to be used with minimal processing and designed for easy assembly and disassembly. Through two built showcases, the benefits and challenges offered by the DfLMP concept are discussed, encouraging further discussion and exploration of its potential applications.

KEYWORDS: low material processing, material availability, salvaged timber, round wood, life cycle performance

1 – INTRODUCTION

Timber has been increasingly used in construction during the past decades, among others due to its environmental potential. To utilize the full environmental potential of limited natural resource of wood, responsible practices in managing raw wood materials and wood-based products are essential. According to New EU Forest Strategy for 2030 [1], it is important to follow circular economy principles, where better use, reuse, and recycle are prioritized to prolong the life cycles of wood and wood products.

One promising approach is to salvage timber "waste" for new applications. However, due to the inherent characteristics of salvaged timber, which often comes with short and random lengths, its value is often considered significantly lower compared to raw materials, and therefore, not preferable for further processing. Design difficulties occur when using salvaged timber for new applications because of this limitation. To address this, novel design approaches are sought with a particular focus on low material processing. Early discussions in this direction have been performed in [2, 3], where low material processing is not just a strategy to enhance the usability of salvaged timber but also a design driver for exploring emerging aesthetics of available materials. However, this concept has been applied only within specific projects [4], without extending to a broader design framework. Consequently, establishing a clear rationale for the low material processing concept and identifying its related design challenges will offer valuable insights for its further development.

This paper introduces the concept of Design for Low Material Processing (DfLMP) and explores its related design challenges in the context of using locally salvaged timber. Building on the initial idea on minimizing material processing, we aim to examine the underlying rationale of DfLMP for timber construction from a general perspective (mainly the use of low-processed round wood), addressing its motivations across various contexts, potential structural applications, predominant practical design challenges, and consequential life cycle performance. As demonstrations, two built showcases are presented, where the benefits and limits of DfLMP are further discussed.

2 – WHY LOW MATERIAL PROCESSING? – TWO DISTINCT CONTEXTS

DfLMP has long been part of timber construction including both structural and non-structural applications, but its motivation has shifted over time. In short, historically, it arose mainly from material, tool, and labor constraints [5], whereas today, it is primarily driven by the need for sustainable construction.

2.1 HISTORICAL CONTEXT

In the pre-industrial age, it was a common practice for ancient master builders to use wood materials as local and raw as possible, due to limited material availability and

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heavy labor required for material processing. However, limitations sometimes bring imaginations. Great works have been done through history with material limitations, where various approaches were attempted to minimize material processing in timber construction [2]. In vernacular timber architecture, locally available wood materials were selected for specific structural members of the building with minimal processing, where master builders normally made the matching based on their experiences and intuitions [5]. As early as the 18th century, Johann Jacob Schübler remarked: "The readily available timbers with naturally grown curves" would "offer greater benefits" than those obtained from "straight and precise timbers" [6]. This indicates the motivation of low material processing beyond the material, transportation and labor constraints. Both structural and non-structural applications of low-processed timber, mainly round wood, are available in history.

One example that applies DfLMP is found in Seurasaari Open Air Museum at Helsinki, Finland, where 80 separate buildings were relocated from different regions of the country. For instance, the Niemelä tenant farm, which was originally built in 1844 in Konginkangas in central Finland and moved to the current site in 1909, was constructed with low-processed round wood for both main structure and roof. The farm is surrounded by a fence that uses small tree branches (or saplings) for vertical support and split timber for horizontal rails tied together using flexible tree roots (Figure 1). A building nearby the Niemelä tenant farm, which serves as a shelter for boats, is also constructed using low-processed timber: large round wood for the timber framing and wall elements, while smaller pieces for corner-bracing and roof base spars (Figure 2). The round woods used for walls in the longitudinal direction are not perfectly straight, however, their different height positions are allowed by a double-column arrangement of the frame.

Another example of DfLMP comes from Iceland, where timber buildings were traditionally constructed using driftwood collected from shore. The driftwood is a dynamic and unpredictable marine resource for construction, boatbuilding, and the production of all manner of objects [7]. For instance, the Viking village at the foot of Vestrahorn mimics the traditional Icelandic timber construction by using driftwood: the small branches and twigs were used as wall fillings through weaving, utilizing the advantage of the natural shapes of materials (Figure 3), while the straight logs were used as the main framing structure, wall elements and fences (Figure 4). An example for roof construction shows in the Commonwealth Farm in Thjorsardalur, Iceland (the current building was built in 1977 based on the original layout of the former manor farm), where the irregular, small-diameter timbers are arranged parallel to one another to support the weight of the stones above (Figure 5).

In some cases, irregular trees were used on purpose. For instance, tree forks have been used as supports for roof

Figure 1: Niemelä tenant farm: timber fences using small tree branches and split timber, Seurasaari Open Air Museum, Helsinki, Finland.

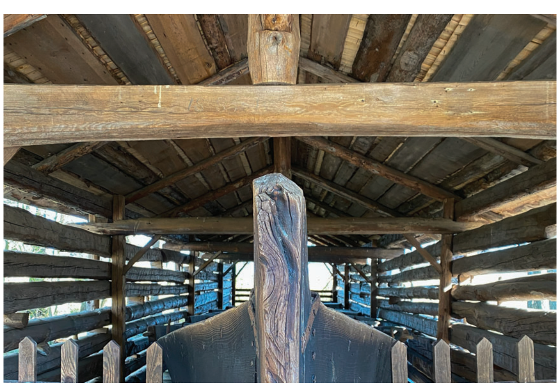

Figure 2: A boat-shelter constructed by round wood in different sizes, Seurasaari Open Air Museum, Helsinki, Finland.

Figure 3: Timber fences that utilize the natural shapes of tree branches and twigs through interlocking in the Viking village near Vestrahorn, Iceland.

Figure 4: Timber buildings built with driftwood in the Viking village near Vestrahorn, Iceland.

Figure 5: Roof structure of the Commonwealth Farm in Thjorsardalur, Iceland.

Figure 6: An example of using tree forks to support a beam in Jiangxi Province, China.

Figure 7: Xianju Bridge: a typical woven timber arch bridge in southeast China.

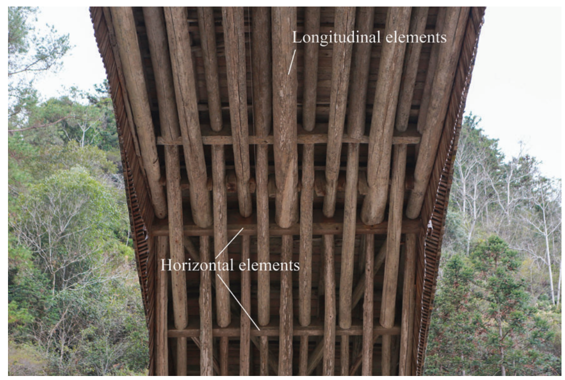

Figure 8: Xianju Bridge: a view from below.

beams in their natural shapes, as shown in Figure 6. Another example can be found in the half-timbered house (known as "Fachwerkbauweise" in German), where "bowed" wood was often used as wall bracing and, over time, became a sought-after decorative feature [5].

In ancient bridge construction, low-processed round woods are also often used. For instance in China, the woven timber arch bridge is a typical bridge type that utilizes round wood with different sizes as main structural elements. One representative example is the Xianju Bridge in Zhejiang Province in southeast China (Figure 7). This type of bridge has two separated timber arches that "weave" together in order to form an interlocking system so that the bridge can reach a span longer than its individual timber elements. In such structure, a systematic joint construction is performed, where mainly two basic timber joints, mortise-and-tenon and dovetail, are applied in order to achieve the right angle of inclination at each joint [8]. It is also possible to use slightly curved or twisted timber elements in the longitudinal direction only if they provide enough length to connect two horizontal beams, as seen in Figure 8. The limit of this structure is that high joint accuracy is required.

Another traditional bridge type that aligns with low-processing concept is the A-frame bridge ("Tukiansassilta" in Finnish), in which the superstructure consists of main beams that are stiffened by diagonal members under the bridge (see e.g., [9]). The type of construction allows use of fairly short timber members.

2.2 CONTEMPORARY CONTEXT

In the contemporary context, the motivation for DfLMP has shifted towards two key aspects: (i) appreciations for the natural aesthetics of wood in its original form, and (ii) sustainable building solutions that prioritize concepts such as circularity, low cost, minimal energy consumption, and low environmental footprint [10]. Both round wood and salvaged or reclaimed wood are within this context.

2.2.1 Round wood construction

The natural shape of tree has often been appreciated in contemporary architecture. Designed by Aino and Alvar Aalto, the Villa Mairea features naturally shaped slender tree trunks used in the entrance (see Figure 9), highlighting its connection to the forest surrounded. A recent example is the Pikku Finlandia in Helsinki, Finland, where tree trunks are used as supports for the overhang above the external corridor (Figure 10). In this case, the tree trunk has been treated to withstand environmental conditions.

One initiative addressing modern use of low-processed round wood was the research project by Technical Research Centre of Finland (VTT) and their collaborators [11]. The project investigated use of low-processed small round wood that is obtained from thinning of forests, for construction purposes. It appears that available inventory of small round wood is fairly large, for instance, Finnish forests contain millions of m^3 suitable material. Yield of round wood depends on multiple aspects, but best yield is obtained when

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Figure 9: Villa Mairea, Pori, Finland.

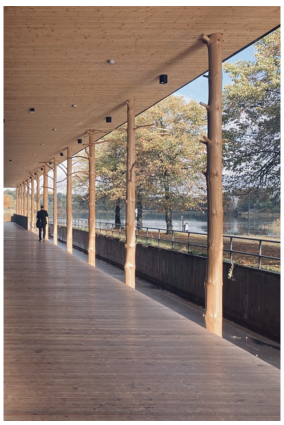

Figure 10: Pikku Finlandia, Helsinki, Finland.

timber is only debarked. For cylindrically peeled timber, yield is only half compared to debarked timber. Study also indicated that bending strength of small round wood is significantly higher compared to the sawn timber made of same logs. However, the study also indicates multiple obstacles in the use small round wood: lack of guidelines, lack of skills and experience of personnel involved in design and construction, and lack of commercial availability of the material. Furthermore, drying can cause large longitudinal cracks, which can compromise the strength of the connections. The weakness can be mitigated with suitable connection design. Since the report [11] was released in 1999, there has been significant research effort on low-processed timber. A recent review [12] surveys research and developments from late 1990's to late 2010's on what they call "whole timber". Their term covers not only solid round wood, but also hollowed, flat-sided or profiled timber produced from logs.

Round wood has been also used in timber-concrete composite bridges. Such examples are log-concrete composite bridges in Brazil [13] and composite bridges built using recycled utility poles [14]. In these examples, exact shapes of the timber members are unimportant as long as a tight enough formwork can be formed for casting concrete. The main limitation is that for reliable structural performance, timber members likely need have the length of bridge span.

2.2.2 Salvaged timber for new construction

With the advancements in wood processing (peeling, planing, and shaping), wood from trees can be easily processed into standardized timber-based products with specific geometries, being graded into different strength classes. In practice, standard timber products are further processed into customized geometries according to their specific applications. On one hand, high-quality (in terms of strength property) timber products, often used for structural components, are cut into designed sizes, resulting in a significant amount of short timber cut-offs; on the other hand, low-quality timber products are often used as less-loaded structures, resulting in relatively short life-span. Timber cut-offs and used low-quality timber boards are mostly treated as waste and mainly incinerated for energy recovery, as one example shows in Figure 11. One reason is that the value of the material is too low for further processing and the value for energy resource is comparably high. In fact, the timber "waste" from standardized wood-based products can be characterized with structural values [15]. If proper design concepts are applied, it is adequate to use such material for new structural applications [16, 17], to prolong the life cycle of the materials.

A main barrier here is related to the limitation for further material processing. If less or even no further processing is required for new applications, the threshold of using salvaged timber will be much lowered, reversing the negative cost and quality perceptions of salvaged timber among the industry [18]. Some recent research projects have demonstrated the possibility of digitalizing material inputs from wood waste and integrating them into new structural applications [19, 20]. However, design concepts that prioritize minimal material processing for salvaged timber have been rarely discussed in the current context.

In this regard, valuable insights can be drawn from the use of minimally processed round wood, as it shares key characteristics with salvaged timber, namely, irregular geometries and variable lengths. In the following section, the main considerations for DfLMP and their related design challenges are concluded based on both historical and contemporary examples. With a specific focus on sustainably using salvaged timber, aspects related to life cycle performance are also considered for further discussion.

Figure 11: Timber waste awaiting for incineration in a timber housing company in Finland.

3 – DESIGN CHALLENGES FOR SUSTAINABLE PRACTICE

3.1 DESIGN CHALLENGES

As an exploratory study, this paper aims to identify the predominant design challenges in applying DfLMP in practice. With the growing demand for structural timber reuse, we specifically focus on the practical potential of utilizing *locally salvaged timber* in structural applications.

According to the rationale performed in Section 2, four key aspects related to DfLMP are proposed in order to enable further discussions: (i) *fabrication*, which focuses on enabling on-site processing and reducing resource demands for storage, transport, and labor; (ii) *joint design*, which accommodates timber in its original, varied geometries; (iii) *structural form*, which ensures sufficient load-bearing capacity while allowing modular assembly for larger structures and facilitating future reuse; and (iv) *architectural quality*, where the inherent characteristics of salvaged timber are integrated as expressive architectural features.

In this study, the salvaged timber represents timber cutoffs from production line, prefabrication and construction process. For such materials, the mechanical properties can be assumed as same as new timber. However, they typically come with short and varying lengths, several specific standardized cross-sections, mixed grading classes, and different extents of exposure to outdoor environment (due to outdoor storage before incineration). The main challenges to structurally utilize this type of materials can be consequently identified according to the above-mentioned four key aspects related to DfLMP:

Fabrication: Fabrication is heavily dependent on material availability; while the collection of salvaged timber is localized, often resulting in limited and source-specific material availability. To address this, material-based design concepts [21] might be employed. The challenge here is that such approach involves developing a tailored design process that responds directly to the available materials, thereby minimizing the need for additional processing.

Joint design: The challenge for joint design is that it needs to be holistic: easy to fabricate in order to reduce further material processing, structurally stable in order to provide sufficient resistance to applied loads, and mechanically reversible in order to allow easy (dis)assembly of the joining members.

Structural form: Searching for a proper structural form that allows the use of short elements with varying lengths and at the same time provides sufficient structural integrity is the main challenge. At the same time, the structural form ideally needs to be a modular system that allows (dis)assembly of the entire structure.

Architectural quality: The primary challenge lies in how to arrange salvaged timber in a way that its inherent characteristics–such as variations in size, irregular geometries, and differences in color, texture, and grain–are thoughtfully integrated to enrich the architectural quality of the entire structure. In addition, the arrangement must align seamlessly with the structural system.

3.2 CONSEQUENTIAL LIFE CYCLE PERFORMANCE

In sustainable construction, life cycle performance is essential in the design process. Therefore, we also assess its impact on decision making (regarding the DfLMP concept), in all relevant aspects. In principle, the life cycle performance may be assessed by multiple factors, such as environmental impact, circularity, economic, and social impact. The pertinent advantages and disadvantages of each aspect are briefly described below.

Environmental impact: DfLMP may contribute to a reduced carbon emission and raw materials for manufacturing, as well as prolonged carbon sequestration. It has challenges in the balance of material and energy, considering the goals of "carbon reduction" and "renewable energy resources" (e.g., [22–24]), and issues related to the LCA calculation for quantifying the environmental impact.

Circularity and economy impact: DfLMP may contribute to material circulation by enabling multiple reuse or recycling loops, minimizing waste, potentially increasing material value within the supply chain, aligning with circular economy strategies (e.g., [25]), and reducing costs associated with production and the purchase of new materials. However, challenges remain, including the inconsistent availability and acceptance of salvaged timber, uncertain market demand, and regulatory constraints.

Social impact: The social benefits include support for local businesses, enhanced community engagement, and the promotion of sustainable practices. However, several concerns remain, such as stakeholder doubts regarding structural, material, and building performance; potential misconceptions among users about the durability and aesthetics of reused materials; and the need to comply with health and safety standards.

4 – SHOWCASES USING SALVAGED TIMBER

To explore the feasibility of the DfLMP concept and to address the design challenges outlined in Section 3, two design built cases, a beam-type pedestrian trail and a reciprocal frame (RF) floor system, were analyzed. For each case, general information is provided, followed by a detailed discussion of the design challenges. The consequential life cycle performances of both cases are summarized at the end.

4.1 TWO DESIGN-BUILD SHOWCASES

The first showcase is a pedestrian trail composed of multiple simply supported modules, following a concept similar to nail-laminated timber [26]. The structure features a straightforward design: an assembly of short timber boards arranged parallel to each other and connected using nails. To ensure adequate structural resistance, sufficient overlapping length must be maintained between neighboring boards for nail placement. A customized version of the trail design was realized using wooden nails (Figure 12). The backrest, featuring a twisted shape, was inspired by a batch of salvaged timber boards, each measuring 90 cm in length. To achieve this design with minimal processing, several considerations were made: for instance, the available long

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boards were cut at angles matching the orientation of individual boards in the twisted backrest (Figure 13 (left)), and the supporting boards were sanded to a rounded end to allow for easy angle adjustments (Figure 13 (right). A detailed discussion follows on the four key aspects of design challenges associated with DfLMP:

Fabrication: The timber materials were salvaged from the production line of a local timber housing company. In this case, most of the salvaged timber boards have varying lengths and heights, but almost equal thickness. To form each layer with specific lengths, pre-planning was required. To achieve the defined element length, two or three timber boards were selected from the material storage and arranged linearly with gaps in between. The gaps were limited to 5 cm in length, however, offered enough tolerances for the timber arrangements.

Joint design: Nail connection was used for the reason of fast and cheap production process. Wooden nails were used here, which brings the opportunity to incinerate the entire structure directly after its service life as it consists only wood. The wooden nail connection provides sufficient structural resistance to shear, as evaluated by [27]. However, a main disadvantage of using wooden nail connections is that the timber boards can not be easily separated after nailing, which complicates further reuse of the nailed timber boards.

Structural form: A simply-supported beam-type structure is applied for the module. While each element forms a flat surface, its height varies. To ensure a consistent overall height, the support heights must be adjusted for each module. This structural form allows for predictable behavior, as the system is primarily governed by two factors: the mechanical properties of the timber and the shear resistance of the nail connections. When using wooden nails, nail failure is anticipated. Based on this assumption, a predictive model for the structural behavior was developed [27].

Figure 12: Pedestrian trail–a customized spatial version.

Figure 13: Material processing during the fabrication of trail modules.

Architectural quality: To embrace the material's natural characteristics, salvaged timber was used without surfacing, allowing the inherent color variations to create a distinctive pattern. The boards were arranged so that random holes appeared across the trail surface, forming a key architectural feature that enhances its visual and textural quality. Another highlight in this structure is the irregular edge, a direct result of the inherent randomness of the salvaged timber and the DfLMP concept, as the end boards were left in their original lengths without cutting.

Another showcase applies the concept of slide-in RF system [28, 29]. Through applying a multi-layered arrangement, the single beam element in a planar RF unit can be realized by using short, salvaged timber. In this case, no additional material processing is needed for making the connection between two beam elements, since the slide-in connection can be formed by leaving an opening between the two neighbor boards in the middle layer. For a larger scale or a more complex system, the same principle can be applied by adding more layers and/or leaving more openings in the element. Different layouts can be realized using this concept [30]. One showcase is a 4.2 m × 2.8 m structural floor system using the offcuts from local GLT production [31]. The structure was built with less than 20 cuttings. The final structure was assembled by 22 modular elements (Figure 14). Following is a detailed discussion on the four aspects related to design challenges of DfLMP:

Fabrication: The salvaged timber had a consistent cross-section but varied in length. Based on material availability, a specific floor layout was designed, where timber lengths were defined within a flexible range rather than fixed dimensions. Prefabrication was straightforward, involving only on-site planning to assign boards to different elements based on length and simple screwing without the need for pre-drilling. The overall workload was minimal: two people completed the fabrication of 22 elements in two hours.

Joint design: To connect timber boards as individual elements, screws were used, as the fasteners would primarily bear tension loads. To connect elements into the entire structure, a slide-in connection was employed (Figure 15), allowing for material over-length (the protruding part of the slide-in connection) and enabling tool-free assembly. The entire structure was assembled only using a hammer.

Structural form: The slide-in RF system provides flexibility in assembly, disassembly, and reassembly, all achieved through simple sliding in and out. The load-bearing capacity of the structural system can be predicted using the developed analytical model [29], where material properties and the tensile capacity of the screw connections are the key factors. However, a drawback of this structure is its significant deformation under vertical loads, due to the discontinuity of the system (no single element spans the entire length). As a result, this structure may be more suitable for use in a hybrid system, where it can be combined with a stiffer layer for added stiffness.

Architectural quality: A regular, symmetric pattern was designed to accommodate materials with irregular lengths. This irregularity was integrated into the joint detail, which becomes a defining feature of the structure. The step-like

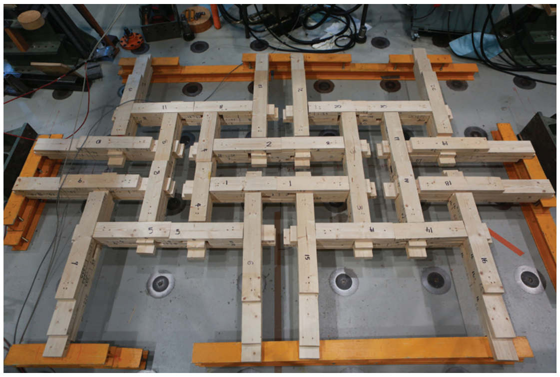

Figure 14: Slide-in RF system assembled by 22 modular elements.

Figure 15: Slide-in connection that allows over-length of timber boards.

geometry of the joint not only facilitates effective load transfer but also serves as a distinctive architectural element. Furthermore, the architectural form represents the structural logic, with the pattern acting as a clear visual expression of the structural system.

4.2 THEIR CONSEQUENTIAL LIFE CYCLE PERFORMANCE

Environmental impact: The environmental impact related to building the above-mentioned showcases is trivial. For showcase 1, only a limited amount of wooden nails was needed, the energy consumption associated with cutting and drilling is minimal. For showcase 2, small amount of screws was used and the installation involved minimal electricity or energy consumption. In both cases, low processing of salvaged timber necessitated minimal energy consumption, also mitigated/avoided environmental impact associated with manufacturing the timber products from raw materials. Therefore, the total environmental impact/pollution induced from the material and energy consumption, during the assembly process is constrained. Moreover, carbon sequestration in the timber is prolonged. However, the utilization of timber as a material or renewable resource should be balanced, considering both the environmental goals of carbon reduction and renewable resource consumption. For instance, timber takes large share of renewable resource consumption in some country, whereas in other countries, it serves as a primary resource for mitigating carbon emissions. In addition, the salvaged timber used in the showcases have good quality, no contamination observed, thus it is highly feasible and efficient to use it for other purposes than burning it directly for heat and electricity production. In practice, the quality/status of salvaged timber largely varies, if there is imperceptible contamination involved, the relevant environmental impact benefit and long-term performance become questionable. Consequently, the quantification of the environmental impact through LCA is subjected to higher uncertainty.

Circularity and economy impact: Both showcases demonstrated the enhanced circulation of materials (enabled the reuse loop instead of the typical linear process/economy), with minimal economic cost. In addition, potential waste is reduced, the life of the timber product/material is extended while maintaining the value of the product or material. The cost associated with the production and purchase of new materials is also avoided. However, considering a wider implementation of the DfLMP concept in practice, the availability and acceptance of salvaged timber is unstable, market demand is also uncertain, and regulatory constraints could not be overlooked. Therefore, it is rather case-specific when assessing the economy impact. In addition, if this DfLMP concept is up-scaled in practice, it may have a negative impact from an economy/industrial business perspective. For instance, typical production demand, which is based on raw material resources, may be greatly reduced due to the extensive reuse of salvaged timber.

Social impact: Both showcases were served as educational prototype to teach university and vocational school students about sustainability, reusing and recycling [32], promoting sustainability practice for future construction. The demonstration of the two built cases may also bring supports to local businesses and enhance the sustainable mindset in local communities. In showcase 1, a scenic space was provided for people's recreation or relaxation. The aesthetic and sustainability values were appreciated by users, according to their feedback. In showcase 2, the possibility of industrial scale-up could be identified by using the proposed principle [19], however, the need to improve its structural performance, e.g., increase stiffness, requires additional research and collaborative efforts.

5 – CONCLUSIONS

This paper introduces DfLMP–a design concept that emphasizes using materials in their original states for building construction. By examining both historical and contemporary contexts, we trace how its primary motivation has evolved over time. Analysis of built examples reveals that low-processed round wood has been widely used in construction for various purposes, demonstrating its value not only as a historical precedent but also as a source of inspiration for the contemporary use of salvaged timber. From this contextual rationale, four key aspects of DfLMP are identified: fabrication, joint design, structural form, and architectural quality, each presenting specific design challenges. In the context of sustainable construction, considerations related to life cycle performance are also included. These

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aspects are further examined through two showcases employing locally salvaged timber. The findings highlight the potential of salvaged timber for structural applications with simple assembly logic and distinctive architectural expression, and the sustainable benefits offered by the DfLMP concept, while also addressing challenges such as limited structural stiffness, constraints on local material sourcing, and uncertain market demand.

Future work will focus on a more in-depth study of historical examples that utilize low-processed timber, seeking inspirations for future construction practices, as well as the application of DfLMP to a broader range of wood materials, including underutilized wood species.

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