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Adapting residential envelope assemblies for full circularity

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Adapting residential envelope assemblies for full circularity

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Abstract. Residential external wall assemblies are among the key contributors to embodied carbon emissions in the building industry. Their design, however, is still largely oriented towards linear consumption trajectories of extraction-use-waste. Within this context, this paper investigates how established material recovery potential assessment metrics could be used to inform design decisions aimed at improving circularity in buildings. A redesign of a typical timber frame assembly is presented and its material recovery performance is compared to standard systems. Results show a 35%-47% improvement in material recovery potential.

1. Introduction

Single-family home construction is by far the largest and fastest growing sector in the U.S. building industry, with over 900,000 new buildings completed last year alone, and over 73% growth in the last decade [1]. For the most part, this construction activity lacks any consideration of future end-of-use waste generation. Introducing circularity into this industry is a multi-faceted challenge, which includes multiple economic, regulatory and design-related aspects. A basic precondition to tackling this challenge is an ability to accurately measure circularity potential [2]. Circularity potential assessment is relatively well developed for consumer products in aspects ranging from evaluating unfastening effort of widely used fasteners [3], through estimation of product end-of-life disassembly potential during early design phases [4], quantification of end-of-life disassembly effort and cost [5], and prediction of total time of disassembly operations for a given product [6], to calculation of disassembly depth effectiveness [7]. In contrast, far less attention has been given to circularity potential assessment in the building industry. Significant developments in this field include introduction of a decision making framework for demolition technique selection for improved material recovery [8], an evaluation scheme for recycling potential of construction materials [9] and a method for assessing loop potential for building materials [10]. These sources propose evaluating recovery potential at either the material or the system levels, but not at both.

Aiming to bridge this gap, Mayer and Bechthold [11] propose an assessment framework that quantifies recovery potential in buildings at both the product and assembly levels. The scheme relies on an existing market and liability distinction between building products (manufacturers) and building assemblies (designers and contractors). At the product level, the scheme includes four evaluation criteria: (A) Recyclability, which evaluates the availability and efficiency of existing recycling technologies from a market and an environmental perspective; (B) Surface Treatment, which examines the ability of coatings such as fireproofing to be easily removed during end-of-life recovery; (C) Binders, which assesses the potential of adhesives and mortars to allow contaminant-free separation for reuse and recycling; and (D) Material Diversity, which looks at the number of different components, coatings, and binders as a potential obstacle for full material recovery. At the assembly level, the scheme includes four evaluation criteria as well: (A) Average product scores for all products in the assembly; (B) Connection index, which accounts for separation damage, tool type required for disassembly, and



disassembly time; (C) Access index, which considers the correlation between disassembly sequence and product life expectancy, as well as the existence of layers that limit the access to other layers with shorter life expectancies; and (D) Component integration, which is based on the notion that prefabricated assemblies are likely to lead to higher recovery potential due to their ability to be easily removed from the building in one piece and allow full disassembly offsite. Using these criteria, the developed framework computes a Material Recovery Potential Index (MRPI) for the evaluated assembly. The index ranks products and assemblies on a scale of 0.0-1.0, where a higher result indicates stronger recovery potential. In this context, this paper describes an experimental implementation of the framework on an adaptation of a commonly used assembly type for full circularity.

2. Methodology

Within the single-family building type, the envelope (external walls, roof and openings) accounts for 60% of the total embodied carbon [12]. The most common external wall assembly in the American residential sector is the timber platform frame. Given the ubiquity of single family housing, this data suggests that increasing material reutilization in timber frame envelopes in this building type would lead to considerable reductions in embodied carbon emissions. With this in mind, the MRPI is used to inform a circularity-oriented redesign of this envelope type. The redesign process follows three methodological steps: (a) Evaluation of challenges in the existing assembly type; (b) addressing deficiencies through redesign using the MRPI criteria as guidance, and; (c) comparative performance assessment of the redesigned assembly. Step (a) is discussed in depth in section 3 of the paper, step (b) is elaborated on in sections 4 and 5, and step (c) is explored in section 6.

3. Case study

The growing popularity of timber frame construction in the American residential market has been a major driver of two opposing trends from a material recovery perspective. On the one hand, the constant high demand for timber frame components pushed the industry to develop highly efficient and standardized products, which in turn may contribute to greater end-of-life utilization. On the other hand, the rapid growth of this industry also rushed the demise of traditional skill-intensive timber-made connections in favor of mass produced steel products such as nail plates and staples [13]. The latter are highly problematic for material separation and recovery purposes. In addition to their dominant market presence, timber frame envelope assemblies also make a compelling test case for a recovery-oriented redesign exercise since they inherently require a separation between structure, insulation, and weather protection elements. This separation positions timber frame envelope assemblies in a preferable starting point from a material recovery standpoint. Two key circularity-related challenges are identified in residential timber frame assemblies:

Preassembly: While highly standardized, timber frame assemblies consist, for the most part, of discrete off-the-shelf products which are typically put together at the construction site. Although it offers contractors a certain degree of operational flexibility, this practice regularly results in ad hoc sub-assemblies and large amounts of irreversible connections such as staples and nails. In addition to encouraging inefficiency, it also results in far more waste than the comparable preassembled alternatives. Research shows that implementing a high degree of prefabrication and preassembly in standard campus concrete buildings, for example, reduced on-site waste production by over 97% [14]. Although no similar studies focusing specifically on timber frame envelope assemblies have been found, it is fair to assume that also in this assembly type, increased prefabrication and preassembly could lead to less wasteful and ultimately more recoverable buildings.

Material consumption: Considering only their internal wall composition, residential timber frame envelopes present ample examples of good material recovery practices: They are based on a complete separation between systems; they consist of simple and widely available products; and they offer a high degree of flexibility in accommodating life cycle modifications such as building additions and reprogramming. In terms of material properties, however, there seems to be much room for improvement. First, for the most part, timber frame envelope components consist of relatively soft materials. Even

purely structural components such as studs are produced from softwood species. This softness often invites extensive deployment of connection types such as nails and staples, which are traditionally designed for the sole purpose of rapid assembly. Second, except for vapor barriers, most of the materials in a typical timber frame envelope assembly tend to be of a generally low recovery value. The low market value of salvaged softwood, OSB, plywood, or fiberglass insulation eventually disincentivates deconstruction and material recovery efforts. Finally, the typical lack of order in site-constructed timber frame assemblies, combined with the extensive use of nails and the low recovery market value of most of their components, make demolition the preferred end-of-life solution for the vast majority of single family homes in the U.S. To conclude, in order to improve material recovery performance in this type of envelope assemblies, a reconsideration of materiality is required along with an adoption of general configuration principles.

4. Case study redesign

Given the recovery-related challenges surveyed in section 3, existing timber frame envelope assembly types require improvement on three fronts: Material composition, connection type, and level of integration. The MRPI method can be used in this case to facilitate an iterative design process, where different strategies are evaluated and compared to each other to select a highly recoverable solution. Based on the assumption that the selection of face materials largely depends on consumer taste rather than on performance, this study examines a redesign of the assembly’s inner components only.

Material composition: Apart from accommodating mechanical, electrical and plumbing systems, the inner envelope assembly fulfils four main function groups: Structure, thermal insulation, sheathing, and moisture protection. In the case of timber frame assemblies, all groups but moisture protection (vapor barrier and Tyvek) are typically made of materials with relatively low recovery potential. These materials, namely wood studs for structure, fiberglass batt for insulation, and plywood or OSB for sheathing, can easily be replaced by a number of commonly used materials with similar performance properties and higher recovery potential.

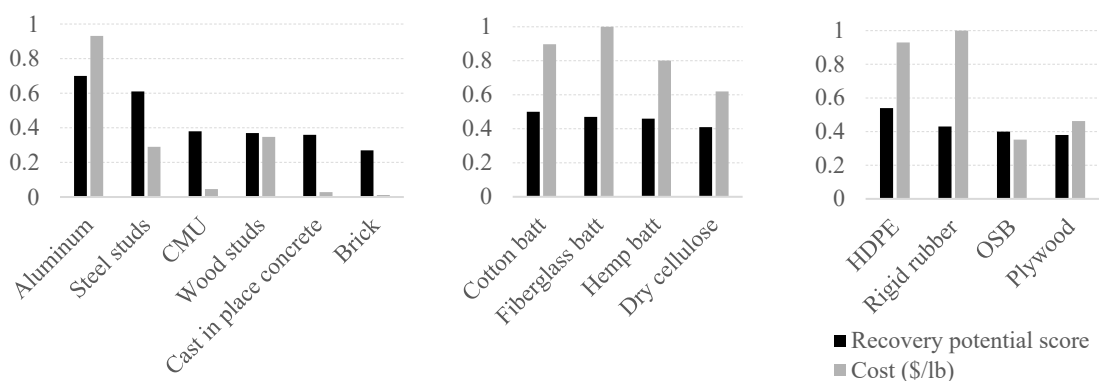


Figure 1. Recovery potential and cost of material options for structure (left), thermal insulation (center), and sheathing. Data: [16]

Figure 1 shows a comparison of MRPI scores and cost between standard and alternative materials for structural, insulation, and sheathing applications. In the structure category, extruded aluminum is found to have the highest recovery potential score, however also the highest price per lb. In the insulation category, cotton batt achieves the highest MRPI score and also costs slightly less than the standard fiberglass batt. Lastly, in the sheathing category, soft HDPE sheet is found to have the highest recovery potential, but also a substantially higher cost than the standard plywood or OSB sheet.

Connection type: In order to successfully facilitate greater disassembly depth, connections with a high degree of reversibility should be placed closer to the extremities of the envelope’s cross section. Most existing timber frame envelope assemblies however, exhibit a reversed situation: the connections which are closer to the envelope’s surface are often harder to disassemble than the ones which are closer to the

envelope's core. Figure 2 compares the typical connection type score distribution across a timber envelope assembly with that of an ideal distribution for material recovery. Note that even at its lowest point, the ideal distribution aims at a connection score of no lower than 0.85, that of a bolt and nut connection. Although other lower scoring connection types, such as screws, may allow full disassembly, they involve a degree of damage that may prevent full reuse of the assembly's components.

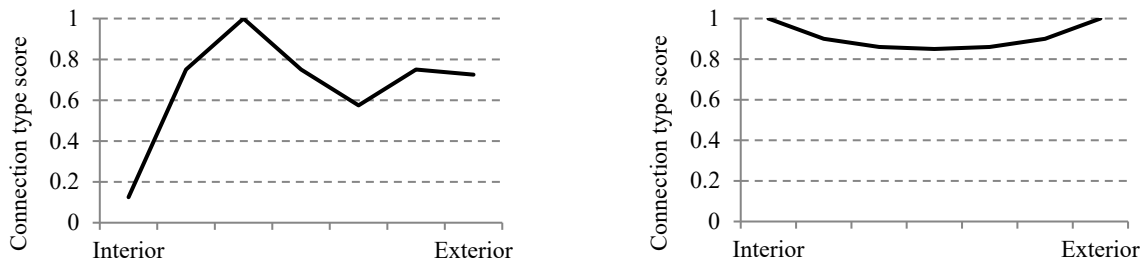


Figure 2. Left: Connection type scores describing a timber frame envelope cross section. Right: a disassembly-oriented configuration. Data: [16]

5. Configuration

The analytical process described in section 4 suggests the following design operations for maximizing material recovery potential in frame-based residential envelope assemblies:

A. From a material standpoint: For the structure, softwood should be replaced by extruded aluminum or steel. Given that the target building types are mostly low-rise, aluminum may make a better alternative as it is lighter and less susceptible to atmospheric corrosion even when untreated. The analysis also shows that for insulation, fiberglass batt should be replaced by cotton, which in addition to having a higher recovery potential is also less expensive. Finally, plywood or OSB sheathing should be replaced by soft HDPE or rubber boards. Given the more developed infrastructure for HDPE recycling, it may make a better alternative than rubber.

B. From a connection type standpoint, the typical nails and staples for timber products should be replaced by friction based or bolt and nut connections. Ideally, friction based or magnetic connections should be placed closer to the envelope face layers, however due to the assumed use of plasterboard and common siding types, the use of bolt and nut connections may be required closer to the assembly surface as well.

C. From a component integration standpoint, the redesigned assembly should strive to incorporate all systems (except face layers) into a single module. Such module should be light and small enough to be handled by one individual, however also large enough to ensure quick assembly and disassembly of the entire structure. Research shows that 30kg (66 lb) can be considered as an upper limit load for a recurring lifting activity by an average construction worker. Additionally, the width and height of the module should not exceed 149 cm (4.88 ft), which is the average arm span of an adult female [15].

Considering those findings, the resulting assembly design, shown in Figures 3 and 4, is an integrated preassembled unit containing the following: an aluminum square tube structural frame (with a HDPE thermal break), cotton insulation batt, friction-fit HDPE sheathing board, and stainless steel connector plates. Once aggregated, the units are covered by a weather barrier (Tyvek) and siding on the exterior, as well as plasterboard on the interior. The unit size described here is 24" x 24" x 7.5" (60cm x 60cm x 19cm), because at this size the weight of each unit approaches 60lb, however these dimensions can vary to correspond to project-specific considerations.



Figure 3. Full scale prototype of a wall module

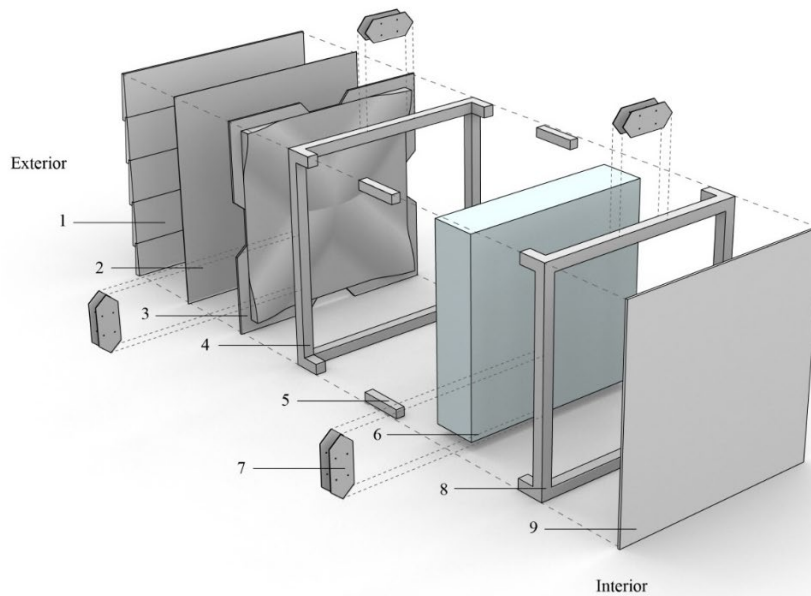


Figure 4. Exploded view of a wall module: 1. Exterior siding layer; 2. Moisture barrier; 3. Soft HDPE sheathing; 4, 8. Aluminum structural frame; 5. HDPE Thermal break; 6. Cotton insulation; 7. Stainless steel connection plate; 9. Plasterboard.

6. Results and discussion

The proposed design offers a hybrid approach which aims to combine the flexibility of frame-based assemblies with the high system integration potential in modular or unit-based assemblies. Assessing the effectiveness of the proposed design in improving material recovery potential requires a comparative study with a standard timber frame envelope assembly. Table 1 shows final assembly material recovery potential scores once for the assembly including its face layers (siding and plasterboard) and once excluding those layers.

Table 1. Assembly score for the proposed design including typical face layers (left) and excluding them (right).

MRPI assembly category	Weight	Score	MRPI assembly category	Weight	Score
Product score	0.3	0.47	Product score	0.3	0.57
Connection type	0.4	0.86	Connection type	0.4	0.82
Access	0.2	0.65	Access	0.2	0.75
Component integration	0.1	0.75	Component integration	0.1	1.00
Total score		0.69	Total score		0.75

Table 2. Assembly score breakdown of a standard timber frame assembly with pine siding.

MRPI assembly category	Weight	Score	Notes
Product score	0.3	0.43	
Connection type	0.4	0.67	
Access	0.2	0.46	The sheathing has the lowest access score in the assembly
Component integration	0.1	0.14	Drywall is the only component group assembled off-site
Total score		0.51	

A Comparison of the assembly score results of the proposed system to a standard timber frame assembly with wood siding offers a number of observations:

A. The proposed design achieves material recovery potential that is 35%-47% higher than that of the timber frame assembly. This difference can be primarily attributed to the relatively irreversible

connection types used in the timber frame assembly, as well as to the low level of integration and off-site assembly that is characteristic of its construction process.

B. The proposed design offers more balance between the various assembly categories, mainly due to its higher integration level and higher connection reversibility. Beyond the higher material recovery potential it generates, this balance plays an important role in ensuring that material recovery is allowed to occur *de facto*. In other words, an assembly which excels in only one or two of the categories and performs poorly on the rest may hinder recovery rather than facilitate it. A SIP assembly, for example, would achieve a high integration score however would in fact be much harder to recycle than a standard timber frame assembly.

7. Conclusion

To conclude, although the proposed design might benefit from further rounds of refinement, this paper demonstrates how the MRPI evaluation method could be used to produce assemblies with a higher potential of being reused or fully recycled. As with any other performance-driven design process, aiming for highly recoverable assemblies may compromise other objectives such as low cost, lightweight structure, seismic resiliency and even reducing primary carbon emissions. The MRPI method is therefore intended to serve professionals, researchers, and policy makers as one instrument in a larger toolbox. The weighing of one performance requirement against another should be performed individually for each project, and that aiming for full end-of-life recovery may not be equally ideal for all building types or life expectancies. Future research in this context will look at the thermal and embodied carbon related limitations of this work, among others.

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