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Design concept for prefabricated elements from CDW timber for a circurlar building

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Abstract. The EU funded project RE[4] (REuse and REcycling of CDW materials and structures in energy efficient pREfabricated elements for building REfurbishment and construction) looks into opportunities for prefabricated, CDW timber elements (structural and non-structural) for circular buildings. Main goal is to minimise resource consumption for building construction but also waste generation related to building dismantling. An innovative design concept for a fully reversible, prefabricated, multi-story residential building from waste wood has been established that reflects robust but flexible and adaptable solutions to extend the buildings-life cycle. Reversible connections, reusable elements and recyclable materials shall minimise future waste generation, when such buildings reach their end of life. A prefabricated façade element manufactured for a two-story prototype shall deliver figures for easy installation, dismantling and future reuse. The study aims to show how current challenges can be overcome and design for disassembly can be promoted.

1. Introduction

In 2014 the building sector contributed with approx. 750 million tons of construction and demolition waste (CDW) significantly to the overall waste generation in Europe [1]. Recovery rates (50%) are relatively low, especially as recovered materials are mainly used for low-grade applications or diverted to energetic recovery [2]. Vast amounts are still directed to landfill, as existing buildings were not designed for disassembly. The dismantling of timber elements (columns, beams etc.) from existing buildings illustrates evidently the wasteful approach the industry is still pursuing. To avoid time consuming investigations related to the application of wood preservatives, timber elements are predominantly classified as Waste Wood Class AIV. This in turn implies thermal recovery as only exploitation method. As a result, high quality timber is lost for future applications. Furthermore, CO_2 stored in the element is released back into the atmosphere. In light of the forthcoming legal changes that stipulate the reduction of CDW by 70% in weight until 2020 (2008/98/EC), the industry needs urgently innovative concepts for circular construction that minimise the reliance on fossil resources and high-tech solutions in order to meet such ambitious goals set out by the European Union [3].

2. Requirements

2.1. Prerequisites

Although waste wood is one of the few materials that offer unique opportunities for direct reuse, this resource is mainly diverted to landfill or send to energetic recovery. Cheap access to fresh wood, low

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disposal cost and time-consuming detection methods for application of wood preservatives are currently the main barriers for circular timber construction. If waste wood shall be reused or recycled for construction purposes, the following prerequisites have to be addressed. Recovered sections must be free of:

- wood preservatives;
- other pollutants, resulting from previous uses that might have penetrated the wood;
- wood-destroying fungi and insects;
- any metal impurities that could damage machinery for reprocessing and
- demonstrate sufficiently strength, large cross-sections and lengths.

2.1.1. Harmful substances. The Waste Wood Ordinance regulates the handling of salvaged timber and implies that the absence of harmful substances must be proved in order to allow its reuse or recycling [4]. In the absence of any commercial rapid on-site test, material samples from retrieved elements (Figure *1*) have been examined in a certified lab. Instructions for removal of timber layers were given by the respective expert, in case of evidenced wood preservatives, which in turn permitted the utilization of salvaged sections instead of thermal recovery.

2.1.2. Pollutants from previous uses. In case harmful substances or pollutants were used or applied in a building identified for dismantling, suitable investigations must prove that timber identified for reuse or recycling is not affected. As such cases could be excluded for the salvaged waste wood within the RE^4 project, no special investigations in this field were carried out nor required.

2.1.3. Metal impurities. Metal fittings are one of the main barriers that prevent the reuse and recycling of waste wood, as such impurities can considerably damage wood working machinery, if they remain undetected. All timber sections have therefore been examined by means of simple metal detectors to identify any kind of metal impurity, which have then been removed by means of hand tools (Figure 2).

2.1.4. Strength grading. CDW timber has to be strength graded according to harmonised standards [5], [6], [7] and national grading rules. On-site inspections have been carried out by an expert to categorise the timber, measure available sections and identify the extend of decay, defects and damages. Based on these results, timber sections have been sorted and separated on site for further reprocessing and strength grading. All impurities (paints, coatings etc.) were removed to obtain clean raw material that was cut and planed into rectangular cross sections. As access to a drying chamber could not be established, timber was not technically dried so that the average moisture level of 20% required for strength grading was not always achieved.

Figure 1. Timber for recycling

Figure 2. Metal detection

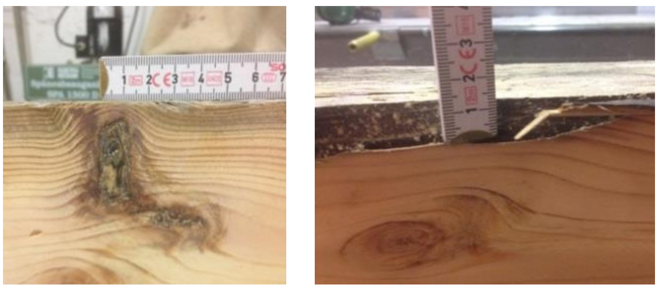

Figure 3. Strength grading: assessment of defects, decays, cracks and dimensions, location + orientation of branches

The actual strength grading process was carried out on cleaned timber sections, which were assessed with regards to dimensions and location of cracks, branches and slope of grain (Figure 3). Classification according to DIN 4074-1:2012 [8] into the relevant sorting classes led in turn to the respective strength

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class according to EN 338:2016 [9]. Additional requirements for lamellas, designated for glued laminated timber, regulated in superior standards were applied during production [7]. Lamellas were then used for the production of timber beams and columns as well as thresholds, plates and studs for non-load bearing façade elements.

3. Design concepts

3.1. Load bearing timber beams and columns

The general design for load bearing timber elements for the bearing structure of the building complies with EN 14080:2013 [7] and follows the principal of glulam timber, where single lamellas are joined together. Glueless connections of single lamellas have also been investigated but will not be elaborated in this study. The design concept pursues the idea of maximisation and optimization of usable sections from waste wood, which is illustrated in Figure 4.

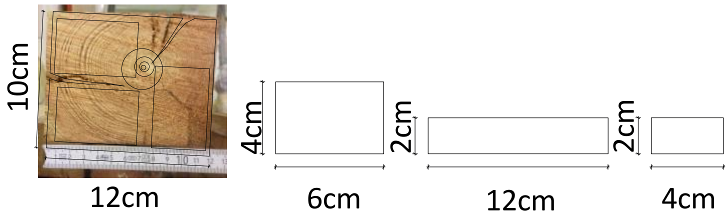

Figure 4. Possible division of salvaged timber sections

For the construction of the elements, cracks have been cut away from salvaged sections and obtained dimensions were assessed for suitable use in beams and columns. Initial trials have been undertaken and lamellas of 4/6/12 cm x 4 cm have been joined with glue in vertical and horizontal direction. (Figure 5 - Figure 7).

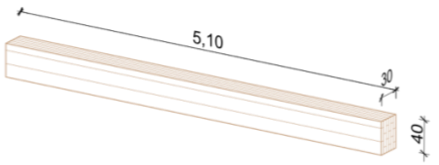

Figure 5. Design concept for glulam timber beam from CDW timber

Figure 6. Glulam beam

Figure 7. Glulam timber beam, with lamellas joined in vertical and horizontal direction

3.2. Non-load bearing, prefabricated timber façade elements

The design concept for a prefabricated, reversible, rear ventilated façade element made from CDW timber proposes a non-load bearing timber frame construction. A self-supporting stud system is covered either side with stiffening wood fibre boards. In certain load cases a wood fibre hardboard might structurally be required to replace the wood fibreboard on the inside. The panel is insulated with a blow in insulation, based on recycled timber flakes or fibres. The weatherboards are fixed with screws to a batten and counter batten system to enable future dismantling. An earthen plaster made from recycled aggregate is applied as final finish to the interior, to provide a healthy and comfortable interior climate. All connections are either screwed or plugged as carpenter connections. Figure 8 shows the general design concept for the prefabricated timber façade element and illustrates the single components.

Similar as for beams and columns, the general design aims to minimise material usage. In addition, the concept follows the approach of a cascading use and looks into opportunities for using cut offs from reprocessing and manufacturing for production of other components that are part of the element. Exemplary investigations regarding source material (Figure 9) and possible outcome (Figure 10) after cutting have been carried out on planks, which were the main source for the production of the façade element. At first, the plank was cleaned and planed. In a second step, required sections for structural

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members were cut to size. As a result, different usable sections, various cut offs, shaves and sawdust were obtained. Table 1 provides an overview about the different sections and provides details regarding dimensions and final amounts. Larger sections were used for the structural parts of the element (threshold, plate, stud), whereas smaller sections were applied as weatherboards. It is intended to use cut offs and sawdust for the production of stiffening boards (wood fibre hardboard) and wood chips or shavings as insulation material. Smaller cut offs shall be separated further for production of wood fibreboards. For the time being, commercial products have been used for such components.

Figure 8. Design concept for timber element, Model: 1:20

Figure 9. Source material (plank)

Figure 10. Outcome of usable material

Once the element has reached its end of life, single components can be reprocessed and recycled. Weatherboards can be dismantled, planed to remove decayed parts and further processed for the use of wood chips, suitable for the production of chip boards or wood fibre boards or insulation. All structural parts offer similar potential for a timber cascade.

Table 1. Outcome of usable material after cleaning and cutting

Piece	Length in dm	Width in dm	Height in dm	Vol. in dm^3	Vol. in %
Total	**32.9**	**2.35**	**0.558**	**43.14**	**100**
Usable wood 1 (UW 1)	22.5	1	0.5	11.25	26
Usable wood 2 (UW 2)	19.73	0.92	0.55	9.98	23
Usable wood 3 (UW 3)	26	0.48	0.18	2.25	5
Off cut 1 (metal) (OC 1)	6.35	2.35	0.58	8.66	20
Off cut 2 (metal) (OC 2)	6	0.95	0.58	3.31	8
Off cut 3 (cross) (OC 3)	4.1	1	0.5	2.05	5
Offcut 4 (longitude) (OC 4)	27.2	0.05	0.53	0.72	2
Offcut 5 (cross) (OC 5)	0.25	0.48	0.18	0.02	0.5
Offcut 6 (longitude) (OC 6)	26.7	0.05	0.22	0.29	0.5
SUM				**38.53**	**90**
Sawdust	**25 liters / 1.74 kg**			**4.61**	**10**

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For material efficient studs, different design concepts have been developed (Figure 12 - Figure 14). A supporting framework allows the optimised use of different timber sections obtained from processing CDW timber. Dimensions and layout of the single lamellas are set out according to static calculations but consider sizes of salvaged cross sections and possible divisions (Figure 11). For thresholds and plates massive sections were produced.

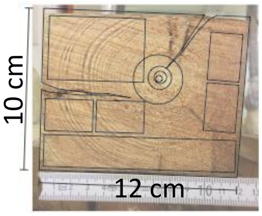

Figure 11. Salvaged cross section, division for material optimised studs

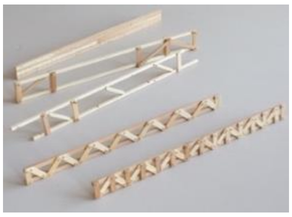
Figure 12. Models of material efficient studs


Figure 13. Framework studs, battens with different or same sizes, assembled eccentrically


Figure 14. Framework stud, different sized battens, assembled centrically

For the final production of the panel, the structural components (threshold, plate and studs) have been assembled to a frame, based on the standard grid for timber construction. The frame has then been covered with the wood fibre hardboard, to provide the required stiffness for the element. As a next step, wood fibreboards and blow in insulation have been applied in parallel (Figure 15 - Figure 16). Finally, weatherboards have been fixed to a support structure of battens and counter battens (Figure 17). The CDW earthen plaster will be applied on site. Reversible connections have been provided by means of screws and metal brackets. In a next step, it is intended to apply timber in timber connections where possible, to minimise metal fasteners.


Figure 15. Timber frame with studs, incorporation of blow in-insulation


Figure 16. Application of wood fibre boards


Figure 17. Weather shell

3.3. Reversible connections
Reversible connections at component and element level but also within elements are key to enable the reuse and recycling of building parts. Investigations at component and element level have been carried out. Different timber in timber connections (carpenter connections) or metal ones have been tested. For corner connections of the frame (façade element), initial tests have been conducted (Figure 18 - Figure 19). For connection of structural components, commercial solutions have been taken into consideration, that offer viable options (Figure 20 - Figure 21).

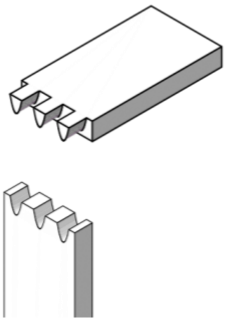

Figure 18. Carpenter connection (dovetail)

Figure 19. Screwed connection facade element

Figure 20. Bolted connection column - foundation

Figure 21. Reversible joist hanger (© Sherpa)

3.4. Design concept for reversible buildings

The design concept for a reversible building focuses on the lifespan of various building elements and enables meaningful divisions so that elements demonstrating a significantly shorter lifespan can relatively easy be maintained or exchanged. In addition, a high level of flexibility, decent ceiling heights and opportunities for adaptation shall generally increase the service life of a building (Figure 22). Although building elements are modular, they offer variation in size and shall be designed in such way that they can easily be dismantled and reused in future applications. In addition, they follow the concept of material purity or allow for easy dismantling so that different components can be separated and reused or recycled if necessary [10]. Additionally, the use of high quality materials shall further increase the durability as well as the lifespan of the component and therefor also the building.

The design proposal suggests a timber skeleton support structure with reversible connections in combination with a stiffening core and a wooden non-load bearing façade system (Figure 22). All elements and components are made out of CDW timber. The column system offers the highest level of flexibility when it comes to adaptation of floor layouts (Figure 23). The non-load bearing facade system allows for a complete exchange of the elements, once they have reached their end of life or in case of a use change of the building requires a different configuration. Reversible connections, still under investigation, are planned for all connections. It is anticipated that they can either be realised as carpenter connections or through reversible, metal fasteners or connections.

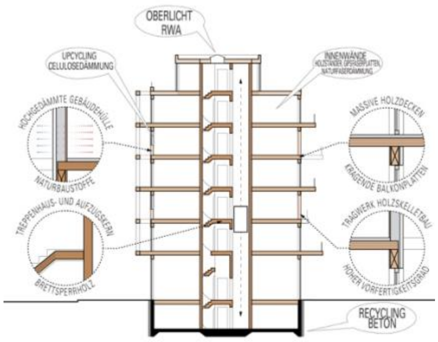

Figure 22. Design concept for a reversible timber skeleton building

Figure 23. Skeleton system with stiffening core

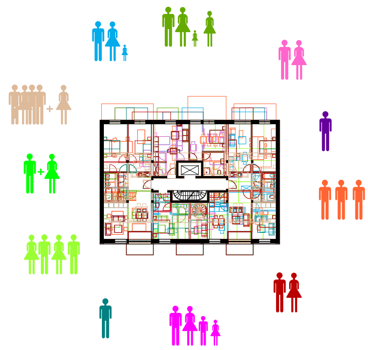

Figure 24. Adaptable floor layouts offer a high level of flexibility

4. Results and discussion

4.1. Prerequisites

On-site inspections have proved to be an appropriate strategy to identify whether existing timber structures might be suitable for a direct reuse or recycling. Although, strength grading according to standard has been carried out on cleaned timber sections, initial on-site assessments delivered reliable results regarding the general structural capacity of the installed timber components and elements.

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Furthermore, it could be established through firm lab testing that not all constructions were treated with wood preservatives so that salvaged timber could be directly reused. On-site investigations were also suitable for the assessment of timber regarding insect and fungi infestation. Furthermore, it could be proved by means of simple metal detectors that all metal impurities were identified. The final strength class of the assessed timber achieved either C16 or C24, which is suitable for the development of structural timber elements.

4.2. Material and design concept for load bearing timber elements

The material and design concept for load bearing timber beams and columns could successfully be implemented. Material efficient construction could be achieved through application of standardised sizes for lamellas. Cracks and branches were cut off without major losses of material. Although not tested in the lab, industrial finger joints enable the incorporation of shorter sections. The use of glue for connection of single lamellas has proven to be very time and cost efficient and delivers frictional connections also for waste wood. As developed elements can be classified according to DIN 68800 as use class 0, the application of wood preservatives is not required [11].

4.3. Material and design concept for non-load bearing, prefabricated timber façade elements

The concept for a cascading use of timber for facade element seems very promising. The overall material that could be recycled from processed planks summed up to approx. 90 %. Nail plates would have to be removed to bring sections covered with metal back into the material cycle. Although only solid sections have been manufactured so far, the usage of cut offs for production of other components seems a viable solution. The industry is following this concept already, although with fresh wood. The concept for material efficient studs delivered also promising results. However, this approach was more time consuming in comparison to the production of solid ones. Encouragingly enough, the production of the final element was entirely carried out with hand machinery. Similar to beams and columns, the façade element can be classified according to DIN 68800 as use class 0, due to special constructive measures, set out in [11]. Therefore, the application of wood preservatives is not required. The environmental benefit regarding the reduction of environmental impact due to the reuse and recycling is currently under investigation.

4.4. Reversible connections

Initial studies were only carried out at lab scale. However, both concepts, timber in timber but also metal connections are suitable to enable reversible connections at component but also element level. Carpenter connections were more time consuming due to the lack of appropriate machinery. Additional studies and testing are required, to investigate and deliver solutions for the various different applications. However, results so far enabled the complete dismantling of elements and components.

4.5. Design concept for reversible buildings

Although the developed concept needs to be approved in real application, skeleton systems are well known for a greater level of flexibility. Also, the separation of elements according to their life spans seems to deliver viable and long-lasting buildings. The use of timber in construction offers generally much higher potential for reversible buildings in comparison to massive construction. The material is much lighter and enables dry connections. Furthermore, the concept of material purity is easier to achieve for structural elements as timber is able to take compressive, tensile and shear loads.

Regarding the service life of the single elements that have been developed, it is expected that the use of waste wood that grew under less harmful environmental impacts in comparison to today increases the lifespan of the single elements and therefore of the entire building. This however has to be verified through further investigations.

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5. Conclusions and recommendations

5.1. Prerequisites
Investigating aged timber, different factors have to be taken into account. The state of conservation, dismantling damages, and previous load condition can have an influence on the load capacity of the timber. Since the 1950's different research projects established that the influence of aging can be neglected if the state of conservation and other impurities are surveyed carefully [12].

The use of standardized cross sections can help to avoid storage costs and increase the market acceptance for salvaged timber. Finger joints make the recycling of CDW timber very attractive as defects can be cut out and shorter pieces can be finger jointed into an endless lamella that in turn can be cut into the required length.

Today, visual strength grading can be assisted by machines, which can lead to a better yield in higher strength classes. Traditionally grading machines work by bending the timber and assessing the stiffness. Today machine grading also includes technologies as flexural resonant frequency, x-ray measurements and ultrasonic wave speed.

To address the issue of wood preservatives, a kind of rapid on-site test would be desirable, as sampling and lab analysis is costly and time intensive. The Fraunhofer Institute developed a prototype for an on-site measurement device, which could be an opportunity to upgrade the classification of wood from demolition sites [13].

5.2. Material and design concept for load bearing and non-load bearing timber elements
The high level of CDW timber that could be integrated into all components and elements demonstrates the enormous potential of this approach for minimisation of both, CDW generation but also resource consumption. However, unless holistic costs for construction and deconstruction are imposed or incentives for more sustainable solutions are granted, such solutions will experience difficulties to enter the highly economically driven market.

5.3. Reversible connections
Reversible connections based on metal fittings are not common in modern timber construction to date. Without modern industrial trimming machines, carpenter connections are economically not viable. However, if circular construction becomes mandatory, suitable solution shall be implemented relatively easy.

5.4. Design concept for reversible buildings
New material and construction concepts must be developed to enable the adaptation of buildings. In addition, today's planning process of new timber structures needs to take possible disassembly and reuse into account. Reversible connections, most often more expensive, are key for the success of such concepts. The growing digitalisation and increased use of Building Information Modelling (BIM) may support the implementation of circular construction. Especially in timber construction 3D modelling is a common approach. Engaged component producers and suppliers in the aftermarket of products offering e.g. take-back systems for construction left-overs and possibly end-of use products, upgrades and repairs services etc. could support the reuse of building elements. However, without governmental interventions, attempts for circular construction might remain at pilot level.

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