FINAL REPORT

InFutUReWood:

Innovative Design For the Future – Use and Reuse of Wood (Building) Components

(VN/4236/2018)

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1. Summary

Long-lived wood products, such as those used in building construction, store the atmospheric carbon sequestered during tree growth until the wood is oxidized either through biodegradation or burning. Further, when wood products replace materials such as steel and concrete, additional substitutive benefits accrue. To conserve primary resources and to prevent waste, there is significant incentive to reuse, or recycle waste wood recovered from building demolition in material form, prior to combustion with energy recovery. In work package 4 of the InFutUReWood project, our objectives were to conduct an inventory of wood products used in residential houses, investigate demolition methods to identify if changes could be made to recover a higher proportion of waste wood with quality suitable for cascading. Moreover, our objectives were to create a set of quality criteria against which to measure the quality of recovered wood and to create a tool for predicting the volumes and quality of waste wood arising from building demolition.

We assessed the stock volume and created an inventory of wood products incorporated in the structure of residential attached and detached houses in Finland, finding that around 17,5 million tons of wood products are embodied in the structural parts alone. Similar studies conducted in Ireland and Spain illustrated that even buildings built of brick and stone, contained quantities of wood products suitable for cascading, albeit the wood intensity was lower in these building types. A survey of demolitions highlighted that speed of demolition is prioritized over material recovery, since there is currently a very limited market for waste wood (other than for energy). Pre-demolition audits could, however, highlight buildings where there was sufficient material suitable for cascading to warrant disassembly, rather than demolition using heavy and destructive equipment. A set of quality criteria were developed for waste demolition wood, which were assessed with a sample of commercial waste wood. Finally, a tool to predict the availability and quality of waste wood arising in the future was developed, based on national statistics, to provide the input flow, and various mathematical functions to predict the outflow.

2. Background and objectives of the project

The InFutUReWood project (*"Innovative Design For the Future – Use and Reuse of Wood (Building) Components"*; VN/4236/2018), began on 1.3.2019 and ran until 28.2.2022, though was extended to end on 31.5.2022. This report, prepared for the Finnish Ministry of the Environment, summarizes the project activities in relation to Work Package 4 *"Inventory, deconstruction, and quality of recovered wood"* performed by the Finnish partner, Aalto University, from the beginning of the project up to its completion. A summary report, providing an overview of the results from the project is, at the time of writing, being prepared and will be submitted to the Forest Value ERA.net secretariat. The summary report refers to other, more specific, reports and publications prepared by individual work packages.

2.1 Background

Wood used in construction ranges from ancient hewn timbers to CE marked strength-graded construction lumber, as well as various forms of engineered wood product like glue laminated timber (glulam), laminated veneer lumber (LVL) and wood-based panels like plywood, oriented strand board (OSB) and particleboard. Frequently, different wood products are combined to form sub-systems within a building (e.g., shear panels), or are attached to one another to perform a certain structural function (e.g., roof trusses), making their separation, and the subsequent recovery of the wood products themselves more difficult, and can lead to a reduction in both quality and dimensions during demolition (Sakaguchi *et al.* 2016). Added to this, different buildings utilize wood in different ways and to different extents, largely depending upon their type and function, geographical location, local building traditions, as well as when the building was built. The result is that it is often difficult to know what wood products are used in a building and how they are used. This then has a direct bearing upon how easy it is to recover wood products for reuse, as well the condition and useable dimensions of the recovered wood. This subsequently impacts upon the cascading potential of the recovered material (Sakaguchi *et al.* 2017).

The total amount of wood incorporated in buildings can be estimated using statistical approaches (e.g., Kalcher *et al.* 2017; Nasiri *et al.* 2021). Whilst this approach is useful in determining the "order of magnitude" of waste wood that is potentially available for recovery, reuse, and recycling, it provides little information about the dimensions and quality of waste wood that is necessary when considering how to implement cascading in practice (Sakaguchi *et al.* 2016). In WP4, we investigated the types of wood products and their dimensions used in buildings and their relative proportions, to add "granularity" to data on the total volumes of wood incorporated in buildings. Much of the intrinsic "quality" and dimensions of wood products that is not lost during installation and use, is lost during the deconstruction/demolition process. Identifying key factors in the demolition process that can affect the quality and dimensions of the wood material is essential to pinpoint actions that could be taken to retain quality and dimensions as well as suggest possible design strategies that can enable rapid deconstruction. The quality of waste wood is presently not well understood and currently there are no criteria to describe waste wood quality. During

InFutUReWood we developed a set of criteria, that could be used to assess and measure the quality of waste wood in practice, and we tested these criteria against waste wood obtained from a commercial waste management enterprise. Further, we developed a materials flow analysis model to predict the future availability of waste wood, its quality, and dimensions.

2.2 Aims and objectives

The overall aim of WP 4 was to understand the volumes, dimensions and quality of material that could currently be recovered and reused, and which might be recoverable in the future following the implementation of design for deconstruction principles. In this WP, we conducted an inventory of wood materials used in the construction of the current building stock as well surveying the demolition methods most frequently used nowadays. Our goal was to establish the wood products most frequently used in buildings (Task 4.1) and to understand how the demolition methods employed affect the "quality" and dimensions of wood that could be recovered (Task 4.2). Waste wood is essentially a "new" material resource and, whilst there have been limited studies conducted about the properties of waste wood, there are no established criteria by which to assess the quality of waste wood. One of our aims was, therefore, to establish new criteria for waste wood quality (Task 4.3). Being able to predict the future volumes, dimensions, and quality of waste wood from demolitions is important to establish a cascading system. For this, a materials stock and flow model, that combines both the volumetric flow of waste wood exiting the building stock, as well as information about its dimensions and quality, is needed. In Task 4.4 our aim was to develop a bottom-up stock and flow model, incorporating information about the (wood) product type, dimensions, and quality.

3. Project partners and methodology

3.1 Partners involved

WP 4 was led by Aalto University (Partner #7), contributing 21 PM. Also contributing to the WP substantially were University College Dublin (Partner #4), contributing 8,8 PM, Universidad Politécnica de Madrid, UPM (Partner #10), contributing 10,75 PM, University of Ljubljana (Partner #5), contributing 8,86 PM and National University of Ireland Galway, Ireland (Partner #3), contributing 2,3 PM. The remaining partners, especially, Research Institutes of Sweden (Partner #1) and Edinburgh Napier University (Partner #2), contributed significantly to the WP through cooperation activities with other WPs.

3.2 Methodology

Task 4.1 was to conduct an inventory of wood materials currently used in construction. To do this, typical building typologies within the geographies represented by the project were identified (e.g., a standard 3-bedroom single family house) using, e.g., statistical sources, and, for selected building types, the wood products used in their construction, their types, typical *in situ* dimensions, location within the building and function, as well as whether they have undergone any treatment etc. were assessed. The geographical locations chosen for this task were Finland, Spain, and Ireland.

The task was accomplished by studying design drawings and/or modeling the selected buildings using proprietary software (e.g., Revit® BIM software) to extract data about the dimensions and types of wood product incorporated in the structures of the selected buildings. This was supplemented by consulting literature sources and (limited) on-site assessments. Later, this information was combined with statistical data (e.g., building production statistics from Statistics Finland) on the overall volumes of wood products used in construction to provide estimates of the materials that are potentially available for re-use in cascaded products.

Our aim was to describe what type of elements, wood species and timber quality currently used; how much of it is glued, impregnated, or treated against fire. We also wanted to ascertain whether the elements are exposed or covered with other materials such as OSB or gypsum board and how this affects the integrity of the elements. Data that needed to be collected included: dimensions, species, basic condition, presence of adhesives, whether the wood is impregnated or not, the presence of fire-resistant coatings, nails or screws and any grooves or indentations arising from jointing, together with and other relevant data that might affect the usability of the wood, such as weather exposure. In this way a full inventory of wood materials used in construction could be made to identify where it could be substituted for more energy-intensive products.

This task provided not just an overall value for the volume of the wood products available but provided this at the level of individual wood products and their dimensions. This enables future modelling of the available volumes of wood material by type, location and dimensions that will be vital in the development of cascaded wood supply chains.

Task 4.2 was to study current demolition/deconstruction practices. In conjunction with WP 3, we developed a survey instrument to investigate current demolition practices used in the partner countries. Our aim was to study both normal practices as well as, where identified, examples in which deconstruction is undertaken with re-use as the goal. The focus was not only on complete demolition / deconstruction, but also refurbishments / renovations, where significant volumes of wood with potential for reuse may arise. The aim was to identify a) ways of improving current demolition methods to maximize material recovery and b) to identify problem "hot spots" in current building construction methods that would enable easier disassembly.

Task 4.3 was to develop quality criteria for recovered wood. Based on the concepts of assessing the quality of recovered wood previously developed (Sakaguchi *et al.* 2016, 2017),

criteria to assess the quality of wood recovered from deconstruction in terms of: damage, contaminants, metal fasteners, recoverable length/dimension etc. were developed in conjunction with WPs 3 and 5. These criteria were subsequently tested on samples of waste wood obtained from wood waste management companies to assess the quality of wood recovered from demolition / deconstruction projects.

Task 4.4 was to model the volumes and quality of recoverable wood now and following the implementation of design for deconstruction. An input-output stock and flow model was developed from work done as part of Task 4.1 (Nasiri *et al.* 2021) and implemented in the Python environment. The model uses as input statistical data generated in Task 4.1 and combines this with output based on various mathematical functions to represent building survival. The input-output model is then combined with the quality characteristics of recovered wood to create tool to predict the volume nd quality of waste wood becoming available for cascading.

4. Results of the project

4.1 Results

The objectives of Task 4.1 were to identify the building types with the highest content of timber, identify the characteristics of the timber products used in their construction, and quantify the timber contained in the selected building types. Typical building typologies in Finland, Ireland, and Spain were identified and, for selected building types, the wood products used in their construction, their types, typical *in situ* dimensions, location within the building and function, as well as whether they had undergone any treatment etc. was assessed. This was achieved by studying design drawings, consulting literature and where possible, conducting on-site assessments.
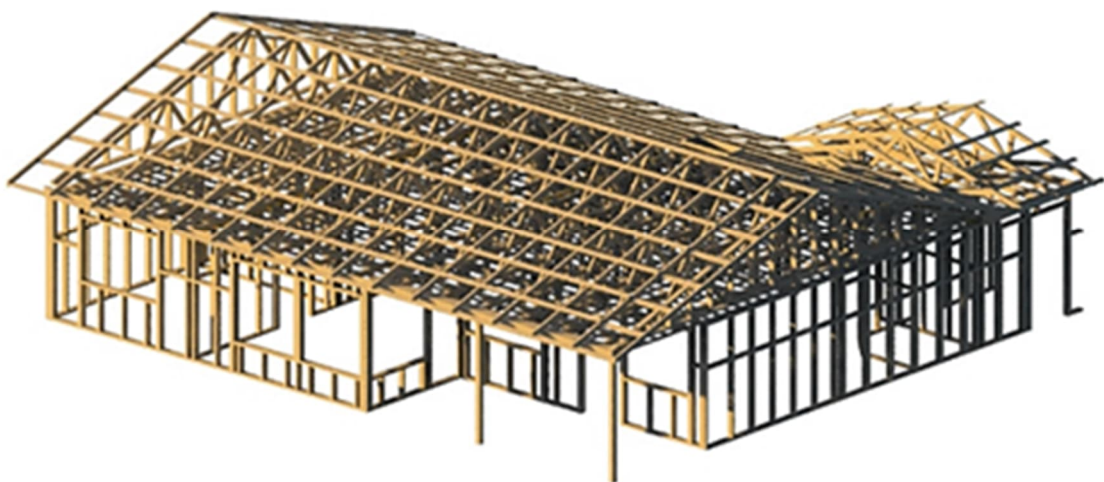

Figure 1: Representation of timber used in domestic house in Finland

The building types identified as having the greatest amount of wood products in them were detached and attached houses in Finland, detached houses (Fig. 1), semi-detached houses and terraced houses in Ireland, and corridor and traditional block type construction in Spain. In Finland, detached and attached houses are constructed predominantly from timber and comprise, on average, 82,5% of the completed gross floor area (contrasting with a mere 2,5% of completed gross floor area (GFA) of blocks of flats built from wood). Because the main structures of Finnish detached and attached houses are of wood, the amount of wood products used in their construction is consequently greater than in either Ireland or Spain, were masonry or a combination of masonry and timber framing are commonplace. For houses built around 1950 in Finland, the buildings incorporate approximately 0,17 cubic meters of wood per square meter (m^3/m^2) of GFA (the "timber intensity"). This contrasts with a timber intensity of around 0,35-0,38 m^3/m^2 for buildings completed earlier; the difference being accounted for by the earlier houses being constructed of logs, whilst the later houses were built using the balloon framing method. Interestingly, an analysis of CLT construction in Spain yielded a timber intensity of 0,2-0,3 m^3/m^2, commensurate with log building – another form of "massive" timber construction. In Ireland, the comparative timber intensity was found to be an average of 0,031 m^3/m^2, a figure over five times lower than that of Finland: the reason for this difference being due to the predominant masonry construction of houses in Ireland, with timber use being restricted to roof structures, flooring and internal partition walls, rather than the main load-bearing structure. In Spain, the timber intensity of the post and beam construction of the corridor and traditional block type construction was found to be on average 0.085 m^3/m^2, which is intermediate between the masonry construction of Ireland and the wood construction of Finland, albeit the building type in Spain differs from the domestic houses of Finland and Ireland. These results clearly show not only country-to-country variation, reflecting the available timber resources, but also differences arising from the different construction methods used. What is evident is that even masonry construction has useful quantities of timber that could be reused or repurposed, so not only "timber constructions" should be targeted, but any construction where wood is used can be seen as a potential resource. Another factor worth considering is that since timber intensity varies with construction type, if carbon storage is the goal, then "massive wood" construction can provide an excellent opportunity for carbon storage, though naturally, more (wood) resources are used in the first place.

Regarding the mix of wood products found in the buildings, these were almost exclusively solid (sawn) timber products, due to the age of the buildings studied. Most wood products embodied in each house (see Fig. 2) in terms of volume comprise the following cross-sections: 22 mm × 100 mm, 20 mm × 100 mm, 22 mm × 125 mm and 40 mm × 125 mm, with the 20 mm × 100 mm cross section constituting by far the highest volume in all case studies. Similar analyses were carried out in Ireland and Spain. In Ireland, for example, the most common section size used is 37,5mm x 112,5mm, accounting for approximately 60% of all linear meterage, which in total amounts to an estimated 475 million linear meters in the current national housing stock.
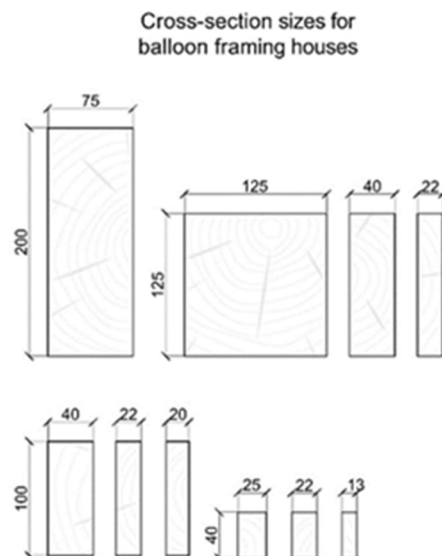
Figure 2: Typical cross-sections of sawn timber used in building construction

Even though different approaches had to be adopted in each of the three countries when quantifying the amount of timber in buildings, the timber intensity coefficients determined are logical when the different construction types are considered. Since each country has different statistical data and information available upon which to calculate the timber intensity coefficient, it is encouraging to see that there is no need for a "one-size-fits-all" approach to quantifying timber intensity reliably though, naturally, the investment in time and effort will vary depending on the method adopted.

The aim of task 4.2 was to investigate current demolition practices to identify problem areas where, potentially reusable, material is lost and to determine what improvements could be made to recover more re-usable material. Data were collected by visiting demolition sites and through the responses received from a survey questionnaire that was developed in collaboration with WP 3. The demolition site surveys investigated several different building types, ranging from a large concrete-built multistorey public building from the 1970s to a domestic dwelling house built in the 1930s. There were commonalities in all the demolitions studied.

Generally, the demolitions had three major steps: first, the interiors were demolished, this was followed by heavy demolition of the main structure, and third demolition of underground structures (e.g., foundation). Even the concrete public building contained around 120 m^3/ 55 tones clean wood, which had formed the interior fittings of the building. This amount of wood was of the same order of magnitude as the domestic dwelling, however, as with the other demolition case studies investigated, the wood material was damaged significantly during the demolition of the interior and the heavy demolition steps. One of the main findings was that useful quantities of wood could be recovered from all building types.

Currently, practices prioritize speed of demolition, using heavy demolition equipment, over the recovery of material, resulting in a loss in wood quality and dimensions. In Finland,

recovered wood, is however, separated on site into "contaminated" (i.e., containing preservatives) and "clean" wood. Among the reasons cited for not prioritizing material recovery were the design of the building, motivation of the demolition contractor and demolition method, which prioritized time and money over material recovery. In general, the recovery of wood in good condition has not been profitable for the contractor as there has not been a market for it (Husgafvel *et al.* 2018).

An estimated 132 m^3 of clean wood was recovered from a 1930s domestic dwelling, however, much of the wood recovered from the building was rotten as it had been poorly maintained. Nevertheless, trusses and floor beams were of untreated wood which made it favorable for cascading. However, microbial degradation was suspected. Damage due to microbial degradation was often cited as a reason for the demolition of wooden buildings, suggesting that initial design, and maintenance, are crucial to material recovery. Moreover, the wooden elements within the building were connected using metal fasteners which is a barrier to reuse and recycling.

Manual dismantling can be used to recover wood for reuse or recycling though, naturally, it takes more time, but the method does retain the wood quality, thus might be a viable alternative if it can be established that there is material of sufficient quality to warrant recovery. A pre-demolition audit may reveal the underlying quality of the material and if it is deemed valuable from a materials perspective, alternative demolition methods could be used.

The aim of task 4.3 was to develop criteria to assess the quality of recovered wood. Based on the concepts of assessing the quality of recovered wood previously developed by Sakaguchi *et al.* (2016, 2017), criteria to assess the quality of wood recovered from deconstruction in terms of: damage, contaminants, metal fasteners, recoverable length/dimension etc. were developed in conjunction with WPs 3 and 5. These criteria could be used to assess the quality of recovered wood from demolition projects to ensure, as far as possible, comparability of data obtained from multiple demolition projects, undertaken by different contractors, in different European countries/geographical location and different building types. Data about the quality of recovered wood can later be combined with material flow analysis models to predict the quantity of recoverable wood from demolition.

The aim of task 4.4 was to create a model to predict the volumes and quality of recoverable wood. To calculate the flow of materials, the dynamic-stock-model package of Python was used and adopted to Finnish data. The historic inflow of new constructions built between 1966-2020 by volume were used as input to extrapolate future scenarios of the outflow of wood until 2060. The outflow of wood was developed according to two decay functions most often used in similar studies, normal distribution, and Weibull distribution to see how they affected the results. The results showed wide variation, with significant effects on the forecast of waste production. In general, the longer the lifespan of a building is, the longer wood stays in the building, and the longer it stores carbon. Additionally, our results emphasize the importance of lifetime data and the choice of a suitable decay function and its variables (Miatto et al., 2017).

The results of the study show that the Weibull distribution with beta equal to 2 works best on Finnish buildings, which is in line with the conclusion that demolition is not only affected by the building life. There is, however, the need to conduct further research on Finnish building lifetime trends, including whether demolitions are affected by the building type and the year of construction. Further analysis in this area is required, especially in Finland, as such analyses will help policymakers understand the quantity, quality, location, and the time when the material becomes available, enabling them to introduce policies that prioritize reuse, recycling, DFD(R), and adaptation over energy recovery and demolition.

All buildings, irrespective of type, potentially contain useful quantities of wood products that could either be reused or recycled, rather than incinerated with energy recovery. However, in practice the demolition methods used, which in turn are dictated by the economics of the demolition process and the lack of a market for recovered wood, result in the wood being significantly damaged and the dimensions reduced. This in turn, naturally affects the market potential. In other words, we have a vicious circle to contend with. In addition, the initial design, as well as maintenance, affects the condition of the wood contained in buildings. Design and poor maintenance often lead to fungal decay, making reuse impracticable.

To quantity the amount of wood embodied in buildings, we can use different approaches, based on the available statistical sources and computed material intensity coefficients. Nevertheless, even where access to statistical data is good, there are often gaps in the data, or simply the data is missing, making it difficult to create accurate models, especially when information and statistics about demolitions is lacking. It might be fruitful in the future to explore alternative methods and approaches to modelling the outflow of wood, such as those based on GIS (Global Imaging System).

Having material of suitable quality for reuse or recycling is imperative, and to determine what is of good enough quality requires criteria against which to assess it. We created a set of criteria as part of WP4, which has been tested against recovered wood obtained from a waste management company. Further validation should now take place to assess the validity of the criteria and determine if any further amendments are necessary.

We developed a materials flow model, based on an input calculated from statistical data and output based on mathematical functions representing building survival probability. Whist the model is functional, it requires development to improve accuracy and to predict the volumes and quality of individual wood products.

In WP4 we have developed new material stock (and flow) models to predict the volumes (and mass) of timber in three countries: Finland, Ireland, and Spain. Moreover, we have also determined materials intensity coefficients for each country.

We have identified some of the key pitfalls relating to the demolition of buildings and the recovery of wood materials for reuse, finding that beyond economic considerations, initial design and maintenance have a significant effect on the quality of recovered wood. Metals fixings etc., compromise the ability to deconstruct building and the added complexity that comes with modern building systems inhibits the recovery of materials for recirculation. In

this respect traditional forms of construction – such a log construction – can often be a "guiding light" in terms of design thinking.

We have developed a prototype predictive tool to provide information about the volumes of wood material that will become available in the future in Finland.

4.2 Achieving project objectives and planned results

Overall, the project fulfilled the original objectives of the project, namely, to conduct an inventory of wood in the building stock (Task 4.1), understand the demolition process (Task 4.2), create a set of criteria for waste wood quality (Task 4.3) and create a tool to predict future waste wood arising (Task 4.4). Despite this, there were some minor changes to the work plan, though it is not considered that this had any significant impact on the original aims of this WP.

4.3 Deviations from plans and reasons for deviations

Perhaps the biggest factor affecting the project and causing the deviations encountered was the difficulty in conducting site surveys of buildings being demolished and collecting materials from the demolition process. Although several site visits were conducted, it was not possible to collect the quantitative data as expected. This was principally a result of the ongoing coronavirus pandemic that meant that travel and face-to-face meetings were curtailed from March 2020 onwards, just at a point when it would have been important to conduct site visits. Despite this, we were able to refocus our activities and replace many of the face-to-face activities with online meetings and source the required information from the literature.

5. Effectiveness/impact of the project

Overall, WP4 explored the potential resource afforded by the wood embedded in the structural part of buildings. For instance, it was found that approximately 17,5 million tons of wood are embodied just in the fabric of Finnish domestic housing at the current time (Nasiri *et al.* 2021). This not only represents a significant stock of material that will potentially be available in the future for reuse or for reprocessing into new products, but it also signifies a substantial stock of stored carbon, contributing to Finland's carbon neutrality targets.

The analysis conducted in the frame of the project was limited to domestic housing, so it would be worthwhile exploring the wood products contained in other building types as well exploring how much more wood (and carbon) could be stores by increasing the proportion of mid-rise buildings constructed from wood.

Whilst not all this wood will be suitable for reuse or recycling, we now have criteria by which to measure the quality of waste wood, thereby helping to underpin a wood cascading system.

Moreover, we have established some of the key reasons why the quality of waste wood is reduced during demolition and what could be done to improve this.

Importantly, the stock and flow model developed as part of WP4 provides the basis for a tool to predict the future availability of waste wood from demolitions, that could help enable an industrialized cascading process.

6. Implementation and results of communication

A website was set up at the project outset (https://www.infuturewood.info/) that hosts various communication materials form the project in general. From WP4 a peer reviewed article has been published: Nasiri, B., Piccardo, C. and Hughes, M. (2021) Estimating the material stock in residential houses in Finland. *Waste Management*, 135, November 2021, 318-326.   https://doi.org/10.1016/j.wasman.2021.09.007.   Further   peer-reviewed publications are in preparation.

Regrettably, due to the coronavirus pandemic there has been no possibility to attend conferences and workshops in person, however, the project researchers have been able to present some of the results of the project at various online fora including:

1. Mark Hughes, keynote speaker at the "16th Annual Meeting of the Northern European Network for Wood Science and Engineering" (WSE 2020), 1st and 2nd December 2020. Title of talk: "*Wood and the circular economy: challenges to its recirculation*"
   https://www.helsinki.fi/en/conferences/wse2020/programme#section-100506
2. Mark Hughes, speaker at "Wood Sustainability: Data visualization beyond the sensory - online seminar", hosted by The Royal Danish Academy, Copenhagen, Denmark, 23rd November 2020. Title of talk: "*Cascading wood: a reality or a fantasy?*" https://www.youtube.com/watch?v=9SvBPbZPCrk&t=4s
3. Mark Hughes, speaker at "Forum Wood Building Nordic 2020", Digital Conference from Trondheim – Norway. 13th to 16th October 2020 hosted by Norwegian University of Science and Technology – NTNU, 13th October 2020. Title of talk: "*Sustainable re-use of wood and cascading - SDG 12*" https://www.forum-holzbau.com/nordic/
4. Bahareh Nasiri, speaker at the InFutUReWood project webinar – Timber buildings: reuse and recycling for sustainability on 20th October 2020

7. Sustainability and exploitation of results

7.1 Sustainability and tangibility of results

In the fight to mitigate climate change and to reduce resource consumption and waste, the use of wood in construction, and the application of circular economy principles to building in wood, are important subjects. The results from InFutUReWood contribute to this topic by highlighting the need not only to adapt our design thinking towards wood construction, making it more circular, but also to regard existing building as a source of valuable materials, potentially available for future use as new construction (or other) products.

The work conducted in WP4 substantiates that there are significant volumes of wood in existing buildings and, whilst "wooden buildings" clearly contain a greater proportion of wood in their structures, even buildings that might be classified as "masonry", or "stone" still contain appreciable amounts of wood (e.g., in roof structures, floors and partition walls), that could be available for reuse or recycling in material form.

Promoting the reuse and materials recycling of waste wood from buildings helps extend the lifetime of wood products, thereby prolonging the time that the embodied carbon in wood is stored and not released back to the atmosphere. Moreover, by reusing wood in material form, the use of more "energy intensive" materials might be further avoided, providing additional substitutive benefits. Perhaps one of the most significant benefits provided by cascading wood is to reduce the necessity to harvest primary wood in the first place, enabling forests to provide necessary ecosystem services beyond carbon sequestration, such as the maintenance of biodiversity. Frederic Mosley, who conducted his MSc thesis as part of the InFutUReWood project, investigated the potential of wood cascading to contribute to the emissions reduction targets of Finland. In his simplified approach, he estimated that compared to business as usual, reusing 10% of wood structures from detached buildings constructed after 1920 could reduce annual carbon emissions to the atmosphere by 7,4 %, while 10 % reuse of structures from buildings built 1920 - 2020 and 50% from buildings constructed after 2020 (i.e., following the adoption of design for disassembly) could result in a reduction of 18,5 % over a 100-year period. Whilst further research is needed to further substantiate these calculations, they are not insignificant, and could make a meaningful contribution to the carbon neutrality targets of Finland.

In terms of carbon storage capacity, "massive" wood construction would seem to offer the possibility of providing more storage capacity than "light frame" construction. This, however, clearly comes at the expense of greater primary resource use, except if the wood products for massive wood construct can, themselves, be produced using secondary resources. Some form of optimization is required depending on the projected levels of wood construction in a particular locality to ensure that primary wood is harvested within the bounds of sustainable forestry practices, and that building design takes this into account.

Whilst questions remain about e.g., the quality of recovered waste wood, the results of WP 4 have shown that there is a significant resource that could be tapped into. The next step is to

make cascading a reality. Putting cascading into practice will require incentives to help relevant stakeholders alter their practices and create dialogue between, e.g., architects and building developers, so that they might adopt such practices as design for disassembly.

7.2 Utilization of the results

Although research questions remain unanswered concerning, for example, the quality and quantity of wood material available for reuse from the Finnish building stock or how can we incentivize demolition contractors to recover material for reuse, rather than for energy generation, the benefits in terms of resource efficiency and emissions reductions, of establishing wood cascading are clear. We now need to move purely academic studies to more "practical" projects that begin to implement wood cascading. At the time of writing (June 2022) a group of Finnish researchers and industry partners are planning a project with the aim of demonstrating the technical and business feasibility of implementing industrial wood cascading.

Practical examples of wooden buildings designed according to design for disassembly are needed to act both as a testbed and to generate information about the quality and quantity of materials that can be recovered in the future. These kinds of results are needed to refine stock-and-flow models, that can support a wood cascading system in Finland.

8. Financial report

Please refer to separate attached financial report.

A major part of the budget was related to the hire of doctoral candidate Bahareh Nasiri who has worked more-or-less full-time on the project from beginning to end. Bahareh was recruited directly to the project, completing her master's thesis as part of InFutUReWood and then continuing to her doctoral studies. Bahareh is an architectural engineer by background, and this has proved to be very suitable for this project.

In addition to Bahareh Nasiri, a master's student of architecture, Maral Alaei, worked part-time on the project during 2021 and part of 2022, modeling domestic buildings using Revit software, thus contributing to the calculation of the material intensity coefficients (MIC).

Thara Warfen, an intern from HSB Hochschule Bremen worked directly on the project from November 2022 to February 2023, contributing to the project by organizing and analyzing statistical data from Finnish National Statistics, providing input to the material inventory and stock and flow model. Furthermore, she contributed to the development of the quality criteria.

Earlier in the project, Fredric Mosley conducted his master's thesis in the frame of InFutUReWood, by investigating the potential for cascading to contribute to Finland's carbon neutrality targets.

Additional costs for travel and for some minor materials, external services and other costs were also included, however, with the coronavirus pandemic taking hold in early 2020, most of the planned project meetings were held online and so the travel budget was underspent and was used for the salaries of Bahareh and Maral. Travel that was realized included partner meetings in Edinburgh (KO meeting) and Ljubljana (partner meeting).

Other costs included open access publishing costs.

9. Recommendations for future projects and programs

Stock and flow models, based on statistical data, though useful, have their limitations due to the availability of data. Other approaches, such as the GIS approach noted above may prove useful, so would be worth exploring as an alternative, and perhaps, complementary approach.

To improve the accuracy of the model, a better understanding of the survival of buildings is required. Now, the reasons for demolition and the general survivability of buildings are not well understood. In terms of a circular economy hierarchy, extending the lifetime of existing buildings is the best way to reduce impact, increase carbon storage and avoiding harvesting of primary material. So, understanding what steps might be taken to extend building lifetimes and incentivizing these, might be a very effective way to reduce the climate impact of buildings. A project application to address exactly these issues was submitted to the Finnish Ministry of the Environment and has been approved and began in May 2022. The project title is ProWoodBuild: Promoting long-lived wood buildings for climate change mitigation and adaptation, with the aim to better understand the survival of wooden buildings and the reasons for their demolition.

The "quality" of recovered wood requires further investigation. In the frame of InFutUReWood, it was not possible to directly use the quality criteria developed, so these should be tested against wood of known provenance recovered from demolitions. Moreover, the mechanisms of wood ageing (beyond straightforward decay and mechanical damage) should be investigated as this will invariably have a big impact on its reuse potential.

Perhaps most importantly, what is needed is (a) project(s) on how to implement cascading on an industrial scale. New business models are required, along with a new grouping of stakeholders to move from the theoretical knowledge gained in projects such as InFutUReWood to practical use.

10. Summary of the main results of the project

We assessed the stock volume of wood products incorporated in the structure of residential attached and detached houses in Finland, finding that around 17,5 million tons of wood products are embodied in the structural parts alone. Similar studies conducted in Ireland and Spain illustrated that even building built of brick and stone, contained quantities of wood products suitable for cascading, albeit the wood intensity was lower in these building types.

For houses built around 1950 in Finland, the buildings incorporate approximately 0,17 cubic meters of wood per square meter (m^3/m^2) of gross floor area. This contrasts with a timber intensity of around 0,35-0,38 m^3/m^2 log construction of earlier periods. In Ireland, the comparative timber intensity was found to be around 0,03 m^3/m^2, attributable to predominant masonry construction of houses in Ireland. In Spain, the timber intensity of the post and beam construction of the corridor and traditional block type construction was found to be on average 0.085 m^3/m^2, which is intermediate between the masonry construction of Ireland and the wood construction of Finland.

A survey of demolitions has highlighted that speed of demolition is prioritized over material recovery, since there is currently a very limited market for waste wood (other than for energy). Pre-demolition audits could, however, highlight buildings where there was sufficient material suitable for cascading to warrant disassembly, rather than demolition using heavy and destructive equipment. One of the overall policy recommendations of the InFutUReWood project is that for new buildings, deconstruction plans made by designers should be demanded by the local authorities or the building authority to obtain permission to build in the first place. This would likely promote cascading.

A set of quality criteria were developed for waste demolition wood, which were assessed with a sample of commercial waste wood. With development, these criteria could be used to assess the quality of waste wood in an industrial cascading system.

A tool to predict the availability and quality of waste wood arising in the future was developed, based on national statistics to provide the input flow, and various mathematical functions to predict the outflow.

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