Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)
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Development of life-cycle inventory for timber products to support the circular economy in construction

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ABSTRACT: The supply of raw materials from Irish forests is forecasted to double between 2017-2035, creating opportunities to increase the output of timber products for construction. Furthermore, residential building construction in Ireland needs to achieve an average annual rate of completion of up 35,000 within the next decade to meet housing demands and population growth. A significant challenge for sustainable construction globally is materials with high embodied carbon, like steel and concrete, remain the primary structural material choices. Although the potential increase in carbon emissions from future construction can be minimised through substitution using timber products, full lifecycle assessment and comparison of such structural solutions to quantify the climate mitigation benefits can be limited by a lack of detailed lifecycle data. Therefore, this paper summarises the development of a national reference database for this lifecycle information and presents a quantification of the lifecycle impacts of Irish timber solutions for sustainable construction.

1 INTRODUCTION

The latest assessment report launched by the IPCC showed we are currently at 1.5 times the greenhouse gas (GHG) concentrations compared with the 1850 level (IPCC, 2014). In Ireland, the total GHG emissions (excluding LULUCF) in 2021 were 61.53 Mt CO_2 eq (EPA, 2022), with agriculture, transport, and energy industries being the first three influential sectors, accounting for 71.9%; still, the contribution of the building sector is not clearly stated in this report. A recent study outlined that the Irish built environment is responsible for 37% of Irish GHG emissions in a standard year (i.e., 2018), containing operational (23%) and embodied carbon (14%) (IGBC, 2022). To mitigate the pressure of climate change, Ireland has committed to reducing GHG emissions to half of the 2018 level by 2030 and reaching net zero by 2050. In the total emissions reduction, the building sector is allocated to a challenging 44-56% burden within executive measures, such as retrofitting houses and introducing renewable energy heating systems for both existing and new dwellings (Government of Ireland, 2021). Moreover, similar to global trends, the Central Statistics Office (CSO) reported that Ireland's population is forecasted to increase to between 5.6 and 6.7 million by 2051, bringing more housing demand simultaneously. The National Development Plan 2021-2023 predicts that 600,000 new homes will be required by 2040, meaning roughly 33,000 new residential buildings are needed each year. Considering the rising housing demand and the significant load the building industry takes to mitigate GHG emissions, timber is an excellent structural material option for building construction.

Unlike traditional building materials like concrete and steel, timber is a low embodied carbon material; its use in place of concrete and steel can considerably reduce the embodied carbon emissions in building projects. Operational carbon emissions (OCE) and embodied carbon emissions (ECE) are two leading indicators to assess a building's atmospheric impact. OCE indicates the emissions caused by energy consumption during the building's use stage, while ECE is mainly related to the emissions from materials and other stages like construction,

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transportation, deconstruction, etc. Many studies have substantiated the excellent performance of timber in decreasing carbon emissions. Skullestad et al. (2016) studied timber and reinforced concrete structures under different building heights, finding that the former caused 34-84% less climate change impact than the latter. Assuming natural gas heating is replaced by the incineration of recovery wood residues, the climate change impact saving by timber structures can be increased to 220% approximately (Skullestad et al., 2016). Laurent et al. (2018) studied an existing arena in North America that integrated glued laminated timber beams with steel. They found that the hybrid structure reduced the total emissions by 83 tonnes of CO2 eq compared to the whole steel structure. Moreover, Murphy et al. (2015) localised LCA research on Irish timber products in seven manufacturing scenarios. They found that GHG emissions can be further reduced by integrating combined heat and power (CHP) plants with sawmills, as CHP plants can transform the co-products during production (e.g., sawdust) into energy and feed it back for production (Murphy et al. 2015).

Considering the great potential of wood in GHG emissions reduction, this paper focuses on timber construction products and subsequent contexts are organised as follows: Section 2 analyses the Irish timber products and gives some reasons for low timber frame application in Ireland. Section 3 introduces the lifecycle assessment (LCA) and compares Irish and international LCA practices in timber construction. Section 4 presents a general lifecycle inventory (LCI) model for Irish timber products. After a simple application of EPD, Section 5 discusses several controversial points in timber's lifecycle assessment.

2 IRISH TIMBER PRODUCTS ANALYSIS

Timber products used in Ireland can be broadly classified into structural and non-structural use. Sawn timber and wood-based panels (WBP) are the most representative products in the former category, and the latter includes wood used for energy generation, paper production, horticulture, etc. Sawn timber indicates products made from large diameter logs, which can provide excellent performance for structural use. WBP commonly refers to the panels comprising compressed layers of wood, typically combined through adhesives or fasteners. Based on the wood size used in panels, this paper divides WBP into four levels, shown in Figure 1. The smallest wood size level is the fibre level, of which medium-density fibreboard (MDF) is a typical representative. Strand level products include oriented strand board (OSB), laminated strand lumber (LSL) and parallel strand lumber (PSL); PSL organises wood strands in parallel - OSB and LSL are layered in perpendicular directions. At the veneer level, normal plywood laminates wood sheets with adhesives in a direction where the grain of adjacent layers is perpendicular to each other. In laminated veneer lumber (LVL), the grain of all layers is oriented in the same direction; laminated veneer board (LVB) organises internal layers in a grain-parallel way, with outer layers perpendicular to the inner direction. The last level is the semi-manufactured level, meaning the wood used in these products has already been processed. Cross-laminated timber (CLT) and glue-laminated timber (GluLam) are both manufactured by gluing layers of sawn lumber together, but the grain in adjacent CLT layers is cross-oriented and GluLam layers are in parallel. Unlike CLT and GluLam, dowel laminated timber (DLT) and nail laminated timber (NLT) use wood dowels and metal nails, respectively, to fasten multiple boards to make larger panels.

Ireland is export-oriented in the forest products sector, and over 80% of WBP is exported overseas, where the UK, Germany, and Benelux countries are the primary markets. However, the application rate of timber frames in Ireland is much lower than in many other European countries. The Timber Frame Housing Report 2002 estimated that timber frame housing accounted for up to 15% of the total output in 2001 and 2002 (Government of Ireland, 2002). The Irish Timber Frame Manufacturers Association (ITFMA) also pointed out that about 30% of new dwellings are timber frame (IFFPA, 2016), and as of 2022, this figure could be as high as 50% for low rise residential buildings. However, these figures are far lower than Finland's at 80%, Scotland's at 83%, and Sweden's at 90% (Kitek Kuzman et al., 2017). In addition, annual woodflow reports by COFORD from 2010 to 2018 show that the average proportion of timber products used in construction is 26%. However, Ireland's total roundwood harvest (including firewood) keeps increasing from 2.9 million cubic meters in 2010 to 3.7 million cubic meters in 2018 and is forecasted to double to 7.9 million cubic meters in 2035 (IFFPA, 2016). In summary, there is significant potential to increase the use of Irish wood for construction applications.

The reasons for Ireland's low timber frame application rate can be boiled down to two points. First, Ireland has the lowest forest area (%of land area) in EU countries, excluding Malta and the Netherlands. Although Ireland has extended its forest area from 6.7% in 1990 to 11.4% in 2020, it is still lower than the average value (i.e., 34.1% in 2020) of EU countries (The World Bank Group, 2020). Secondly, there is no significant culture of building with wood in Ireland, and there are many misconceptions about how timber frame construction will behave in Ireland's climate. Finally, there is a lack of lifecycle assessment data on Irish timber products which would give the general public and building specifiers confidence when specifying environmentally sustainable solutions such as wood for buildings. Addressing this final point is the focus of the paper, and the next section will specifically analyse the gaps between Irish and international LCA practices in timber construction.

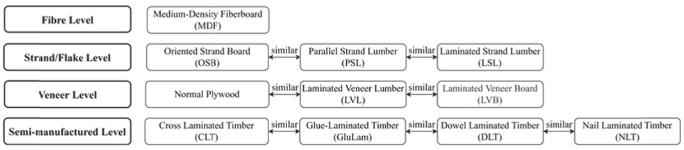

Figure 1. Classification of the wood-based panel (WBP).

3 COMPARISON OF LCA PRACTICES IN TIMBER CONSTRUCTION

Lifecycle assessment (LCA) in the construction industry indicates the environmental impact estimation of building projects within a defined system boundary. A typical LCA starts with the goal and scope definition, then followed by inventory analysis and impact assessment, and ends with specific interpretations (ISO 14040:2006). For particular projects, LCA is flexible in the research object and system boundary definition. The studied target can be the whole building or a single product, and the system boundary can be cradle-to-gate, cradle-to-grave, and cradle-to-cradle. I.S. EN 15978:2011 defines the system boundary for the building's lifecycle assessment, composed of four stages: (i) the product stage, (ii) the construction stage, (iii) the use stage, and (iv) the end-of-life stage (Figure 2). The cradle-to-gate system refers to the first stage (i.e., A1-A3), and the cradle-to-grave system indicates the whole building life (i.e., A1-C4). After considering materials recovery and reuse within the boundary, it can be called the cradle-to-cradle system or circular economy (i.e., A1-D). If categorised by the type of carbon emissions, B6 and B7 phases are related to OCE, and ECE happens in the rest phases, of which A1-A3 contribute the most. This paper focuses on the embodied sector of Irish and international LCA practices for four timber products frequently used in construction: sawn timber, OSB, MDF, and CLT.

3.1 *Overview of Irish and international LCA practices*

Environmental product declarations (EPDs) provide a universal approach to comparing and evaluating the environmental performances of a product. The international EPD system is now the oldest operational EPD programme in the world and the reference of many national programmes. In March 2018, the Irish Green Building Council (IGBC) activated a localised EPD programme, EPD Ireland, enabling Irish manufacturers to develop EPDs for their products. However, there are no mandatory regulations or laws for their use in Ireland, which limits their use. By contrast, MPG (Milieu Prestatie Berekening) is already in force in the Netherlands for every environmental permit concerning all new-built residential and office buildings over 100 m^2, whether public or private. The MPG combines all environmental indicators into the shadow cost of materials applied in the building with the unit of Euro per square meter GFA (gross floor area) per year. France also issued a decree (No. 2021-1104) in

July 2021 on energy and environmental performance requirements for all new buildings, including residential, office, and primary or secondary educational buildings. The climate impact indicators include two categories, one for materials and site impact (similar to OCE) and another for energy consumption (similar to ECE).

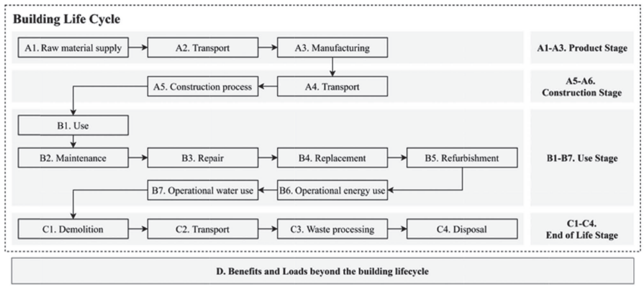

Figure 2. System boundary definition.

In addition to the absence of mandatory regulations, Ireland falls behind many nations in the amount of declared EPDs, particularly for wooden products. Several EPD websites were searched using the following keywords: timber, lumber, wood, CLT, MDF, and OSB. At the time of writing, the EPDs published by EPD Ireland have just exceeded 80 EPDs, with about 11 linked to wood products. In comparison, the IBU of Germany has collected 1734 published EPDs, of which 50 EPDs are related to wood products. The INIES of France contains approximately 150 EPDs about wood products of 6977 environmental data in total. The following section discusses the differences between the EPDs of selected timber products between Ireland and other countries.

3.2 *EPD comparison*

The comparison examines five EPDs from different countries (including Ireland) for four timber products, as outlined in Table 1. All selected EPDs comply with ISO 14025 and I.S. EN 15804, so they are comparable with each other. The UK or European level is chosen as a reference where an EPD from Ireland is unavailable, and only three EPDs are collected and compared for OSB.

Tables 1 and 2 highlight that Ireland only has EPDs for MDF and OSB. The International EPD System is the most frequently used programme among the 18 studied EPDs, e.g. EPD Turkey and EPD Australasia are aligned as regional members of this system. Following the global standard, the IBU of Germany is the second programme with high adoption, covering all four products. Although EPD Ireland is independent of the International EPD System, IGBC has joined the Eco Platform, an organisation of European EPD programme operators, ensuring that all the EPDs published by EPD Ireland can be visible across Europe.

Furthermore, differences can be found in some specific EPD items between Irish and international LCA practices. First, nearly 80% of the studied EPDs select 1 m^3 as the declared unit, and some use 1 m^2 with a defined thickness for WBPs, while Ireland uses 1 tonne to calculate the environmental impact of MDF and OSB. Second, I.S. EN 15804 was revised in July 2019 (i.e., I.S. EN 15804+A2), increasing the required indicators to nineteen from eleven. In the latest version, the global warming potential (GWP) is divided into three sub-indicators: GWP-F, GWP-B, and GWP-Luluc, accounting for GWP related to fossil fuels, biogenic carbon and land use and land use change, respectively. In Table 1, nearly half of EPDs contain all three categories, and some only include the total GWP value due to their early issue time. The EPDs published by EPD Ireland have not incorporated the GWP-Luluc.

Finally, I.S. EN 15804+A2 states that modules A1-A3, C1-C4, and D must be declared in all construction products unless the conditions to exclude modules C1-C4 and D are met. The declared modules of EPDs are shown in Table 2, where 50% of them cover all the required stages, and 80% incorporate environmental impacts from the wood waste treatment (i.e., modules C3-C4) and corresponding benefits and burdens beyond the building life (i.e., module D). However, the EPD for MDF from MEDITE omits the D stage, and the EPD for OSB from SMARTPLY only declares the A1-A3 stages. Therefore, Ireland still has a long way to go compared with other countries in LCA practices for timber products.

Table 1. EPDs used in comparison.

Category	Declared unit	EPD owner	Validity	Scope	Programme
Sawn timber	1 m^3 kiln dried planed or machined sawn timber used as structural timber[1]	Wood for Good	10/04/17-09/04/22	UK	BRE
	1 m^3 sawn kiln-dried softwood	Wood Solutions	14/02/22-14/02/27	Australia	EPD Australasia
	1 m^3 kiln dried, rough sawn and planed EGGER timber	Fritz EGGER GmbH	29/07/21-09/05/26	Germany	IBU
	1 m^3 Swedish sawn dried timber of spruce or pine	Swedish Wood	22/01/21-22/01/26	Sweden	International EPD System
	1 m^3 radiata pine sawn board	Baskegur	07/10/19-03/10/23	International[2]	International EPD System
MDF	1 t MEDITE clear MDF	MEDITE	12/03/21-12/03/26	Ireland	EPD Ireland
	1 m^2 uncoated MDF, 200mm thick	Daiken New Zealand Ltd	25/01/19-25/01/24	New Zealand	EPD Australasia
	1 m^3 EGGER MDF, uncoated	Fritz EGGER GmbH	10/05/21-09/05/23	Germany	IBU
	1 m^3 raw MDF	Financier Maderera S.A.	12/04/22-12/04/27	Spain	International EPD System
	1 m^3 MDF	Kastamonu Entegre Agac Sanayi ve Ticaret A.S.	10/02/21-09/02/26	International[3]	EPD Turkey
OSB	1 t SMARTPLY OSB3	SMARTPLY	11/11/19-11/11/24	Ireland	EPD Ireland
	1 m^3 EGGER OSB	Fritz EGGER GmbH	03/09/18-02/09/23	Germany & Romania	IBU
	1 m^3 Norbord OSB	Norbord Europe Ltd	31/01/20-30/01/25	International[4]	International EPD System
CLT	1 m^2 of coated Rock Mineral Wool CLT, 100 mm thick[5]	Knauf Insulation Sprl	10/12/21-10/12/26	Europe	International EPD System
	1 m^3 CLT, packaged	Red Stag Wood Solutions	08/02/22-08/02/27	New Zealand	EPD Australasia
	1 m^3 of Binderholz CLT BBS	Binderholz Bausysteme GmbH	20/03/19-19/03/24	Austria & Germany	IBU
	1 m^3 CLT	Stora Enso	10/02/21-11/02/26	Austria & Sweden	International EPD System
	1 m^3 Crosslam Kuhmo CLT	CrossLam	12/04/21-28/01/26	Finland	RTS

1 Take the UK level as the reference for Irish sawn timber.
2 The EPD data is from four companies, representing 65% of the sawn wood in the Basque Country.
3 The assumptions of the C and D modules are referred to as the global.
4 The OSB is manufactured by two factories in Inverness (UK) and Genk (Belgium)and supplied globally.
5 Take the European level as the reference for Irish CLT.

Table 2. LCA modules declared in EPDs.

Category	Indicators[1] (GWP-)	A1-3	A4	A5	B1-7	C1	C2	C3	C4	D
	T	X	X	X		X	X	X	X	X
	F/B/T	X						X	X	X
Sawn timber	F/B/Luluc/T	X				X*	X	X	X*	X
	F/B/Luluc/T	X				X	X	X	X*	X
	T	X								
	F/B/T	X	X				X	X	X	
	F/B/T	X						X	X	X
MDF	F/B/Luluc/T	X				X*	X	X	X*	X
	F/B/Luluc/T	X				X*	X	X	X	X
	F/B/Luluc/T	X				X	X	X*	X	X
	F/B/T	X								
OSB	T	X						X		X
	T	X	X							
	F/B/Luluc/T	X	X	X	X*	X*	X	X*	X	X
	F/B/T	X						X	X	X
CLT	T	X		X			X	X		X
	F/B/Luluc/T	X	X	X	X*	X	X	X	X	X
	F/B/Luluc/T	X	X	X		X*	X	X	X	X

1 GWP-F: GWP fossil fuels, GWP-B: GWP biogenic, GWP-Luluc: GWP land use and land use change, GWP-T: GWP total. * No environmental impact in the stage, although it is declared.

4 THE LIFECYCLE INVENTORY FOR IRISH TIMBER PRODUCTS

In terms of the gaps identified during the comparison, this sector develops a general lifecycle inventory (LCI) for lifecycle analysis of Irish timber products. Before the LCI analysis, the studied system boundary needs to be defined; modules A1-A3, C1-C4, and D are mandatory stages (I.S. EN 15804+A2). In addition, as the contribution of GWP-Luluc in different stages for the eight EPDs is less than 1%, this indicator is excluded from the following discussion.

4.1 *Modules A1-A3*

Modules A1-A3 refer to the production stage, from the raw materials supply to the packaging of finished products, also called the cradle-to-gate system. For timber products, this stage should include all steps from tree seeding to the completed products leaving the factory. During the production phase, the sources of GHG emissions and removals are from three sectors: (i) energy consumption, (ii) materials, and (iii) waste treatment.

Energy consumption to produce timber products must consider electricity and thermal energy, as almost all the manufacturing of timber products requires the drying process to reduce the moisture content. In 2020, the energy input to Ireland's electricity generation was still dominated by natural gas (i.e., 52%), although the contribution of renewable energy has increased to 42% from 6% in 2005. Thanks to the greener energy mix, the CO_2 intensity of Ireland's electricity grid has decreased to 296 g CO_2/kWh in 2020 from 636 g CO_2/kWh in 2005 (SEAI, 2020). As for emissions from thermal energy, it depends on how much carbon is stored in the wood waste used as biomass fuel. Thus, factory-specific data needs to be recorded during the manufacturing process.

Different from conventional construction materials, such as concrete and steel, timber contributes carbon removals due to CO_2 sequestration during its growth. The stored, or biogenic, carbon relates to the GWP-B indicator. I.S. EN 16449 provides a formula to calculate CO_2 from the biogenic carbon in wood, and all studied EPDs comply with this method.

$$P_{CO_2} = \frac{44}{12} \times cf \times \frac{\rho_\omega \times V_\omega}{1 + \frac{\omega}{100}} \tag{1}$$

where 44/12 indicates 1 kg biogenic carbon equals 44/12 kg CO_2; cf = carbon fraction of woody biomass (default value is 0.5); ω = moisture content of the product (%); ρ_ω = density of woody biomass of the product at that moisture content (kg/m^3); V_ω = volume of the wood material in the product at that moisture content (m^3).

Other materials required in timber products, such as glue for the lamination of wood boards, should also be considered. The EPD owner should ask for the original data from material suppliers to calculate corresponding GHG emissions if the materials are not produced in the same factory. Finally, the processing up to the end-of-waste state should be included for all wastes in this stage, like wood and packaging materials.

4.2 *Modules C1-C4 & D*

Modules C1-C4 (i.e., end-of-life stage) start from building dismantling to transportation of wastes and end with waste treatments. As module D needs to declare the benefits and burdens related to waste treatments, it is also discussed in this sector. Furthermore, modules C1-C2 are excluded because the product market might be worldwide, and four end-of-life scenarios are listed below.

Table 3. GHG emissions in four end-of-life scenarios for wood material.

Scenarios	C3	C4	D
Reuse	BR	ND	Benefits of avoiding producing the same amount of new products
Recycling	BR + emissions from processing wood waste to a ready-for-recycling state	ND	Benefits of avoiding producing the same amount of new materials
Incineration	BR	ND	Energy recovery
Landfill	ND	ND	ND

BR: biogenic carbon release. ND: not declared.

In all studied EPDs that cover modules C3 and C4, 33% use mix scenarios for the wood waste treatment and 26% calculate the ECE separately in different scenario assumptions. Only one scenario is taken into account for the remainder, with 5 EPDs considering incineration and 1 EPD considering landfill. As shown in Table 3, each scenario can get corresponding benefits declared in module D except for landfill. However, the landfill gas generated from degrading organic carbon in the wood waste can also be combusted for energy recovery, and EPD Australasia has already applied this. In terms of Ireland, the EPD for MEDITE MDF defines a 50/50 allocation for incineration and landfill. However, research showed that about 96% of the wood waste in Ireland is used as biomass fuel; only 4% goes to landfill (Cristescu et al., 2020). The differences between product EPDs and the national market highlight that as much data as possible should be collected and analysed for precise end-of-life scenario allocations.

In addition to applying reasonable end-of-life assumptions, other data should be considered. For example, most EPDs assume wood properties will not change during usage, but the density and moisture content in the wood waste should be remeasured for a more accurate biogenic carbon estimation. Moreover, it still requires data related to energy consumption in waste processing and facility efficiency in energy recovery for GHG emissions calculation.

4.3 *A simple EPD application in Ireland*

An EPD application on a typical Irish timber frame house with 2 storeys (Table 4) reveals more issues waiting to be solved. It can be seen that modules A4-A5 and C1-C2, omitted in the LCI analysis, contribute 40% of the total GWP when applying the EPD owned by Wood for Good. These components are too significant to be excluded. Moreover, the EPDs of EGGER and Swedish Wood both assume 100% incineration at the end-of-life, but the figures vary significantly (i.e., -4941 and -1415 kg CO_2 eq, respectively) for adopting different incineration efficiency and energy types for recovery.

Table 4. Application of EPD for Irish sawn timber (12.2 m^3).

EPD owner	GWP-T (kg CO_2 eq)								
	A1-A3	A4	A5	C1	C2	C3	C4	D	Total
Wood for Good	-8686	95	506	155	90	9455	112	-3062	-1336
Wood Solutions	-9321	-	-	-	-	0	706	-3	-8618
Fritz EGGER GmbH	-8491	-	-	0	18	9833	0	-4941	-3581
Swedish Wood	-9077	-	-	3	81	9443	0	-1415	-965
Baskegur	-8320	-	-	-	-	-	-	-	-8320

5 CONCLUSION

Based on the EPDs reviewed in this paper, modules A1-A3, C3-C4, and D are expected to be included in the LCA for Irish timber products. Considering that the UK is the primary market for Irish timber, modules A4-A5 and C1-C2 should also be added according to typical transit modes and construction styles in the UK. To build a precise Irish LCI for timber products, further research will be oriented towards (i) obtaining more specific details on Irish wood products to make suitable assumptions in filling the gaps in required modules and (ii) determining a realistic end-of-life scenario for Irish wood waste.

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