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CHALLENGES IN THE DESIGN OF A MODULAR MULTI-STOREY CLT BUILDING USING IRISH TIMBER

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ABSTRACT: Cross Laminated Timber (CLT) has been developed in recent years to the stage of automation in production, from timber classification, joining boards, applying adhesive, assembly pressing and CNC machining to form completed CLT panels. Volumetric buildings incorporating CLT are now being developed and completed, showing promising results as sustainable solutions for the construction industry. The majority of European CLT panel manufacturers use grade C24 timber, while countries such as Ireland also have an increasing supply of Sitka Spruce grade C16 timber which has been shown to be suitable for use in CLT. This paper presents elements of a larger research project and focuses on the preliminary design and development of a proposed modular seven-storey building in CLT manufactured from Irish timber, addressing the usage of CLT in volumetric modular construction. Challenges in delivering a building of this type are addressed in terms of building layout, loading arrangement, transportation, and structural design of panels. Design for deconstruction is also considered for the connections between the units to enable future reuse.

KEYWORDS: Modular construction, Circular economy, Cross-Laminated Timber (CLT), Irish timber

1 INTRODUCTION

The current level of housing demand and projected future population growth of 1.5 million people by 2051 in Ireland [1] places pressure on residential building construction – a requirement for an average rate of completion of 33,000 new homes per annum is projected within the next decade [2]. This figure has the potential to rise as high as 50,000 and is a significant challenge as current completion rates lie just under 30,000 per annum as of 2022 [3]. As the supply of raw material from Irish forests has been forecasted to double between 2017-2035 [4], there exist opportunities for the promotion and development of engineered wood product solutions for the sustainable construction of homes to both meet this housing demand and achieve lower building carbon footprints.

In parallel to this, the increase in the prominence of modern methods of construction over the past couple of decades, including automation and offsite manufacturing, has included the development of modular building systems. Modular building systems can generally be categorised into one of two types: 2D panellised, where components such as walls and floors are installed on site to form the building, or 3D volumetric, whereby whole finished modules are installed directly on site [5]. Where a project allows for repeatable building units (2D or 3D), these systems offer faster construction with reduced time on site, higher quality control and efficiency associated with factory assembly and prefabrication, and lower environmental impacts compared to traditional approaches. Developments in the automation of offsite manufacturing procedures have normalised low-rise modular construction, typically 4 storeys or less. However, Thai et al [5] note that modular construction for high-rise buildings is not yet as popular due to lack of design guidelines, inter-module connection techniques and sufficient understanding of structural behaviour, global stability and structural robustness of modular buildings. The majority of multi-storey modular buildings are constructed using reinforced concrete or steel (including cold-formed light gauge steel), or composite construction using both [5]; structural stability is typically provided by a steel bracing system, reinforced concrete cores or walls, or again, a hybrid of both.

Although concrete modular systems tend to have better fire resistance, water proofing and acoustic performance than steel systems, due to its heavier weight, modular concrete units incur higher costs for lifting requirements by crane, and can offer less flexibility in terms of design and connections. For these reasons, as modular buildings become taller, steel or hybrid systems can be preferred, particularly if 3D volumetric modules are being used to reduce internal finishing requirements on site. More

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recently, developments in timber offer alternative solutions with similar benefits.

Harte [6] outlines the introduction to the construction industry of mass-timber products, such as Cross Laminated Timber (CLT), with excellent load carrying characteristics that over the past two decades have enabled timber to be used in larger and more complex structures, including modular construction. CLT panels for use in structures can be fabricated at lengths up to 16 m, widths up to 3 m and thicknesses up to 500 mm. Currently, the tallest all timber building in the world is the mixed-use 18-storey Mjøstårnet building in Norway, completed in 2019 and standing at 85.4 m [7]. Examples of modular mass-timber buildings include the 14 storey, 49 m tall Treet Building in Bergen, Norway which was completed in 2015 and was constructed using volumetric CLT modules achieving Passive House standard [7]. However, the majority of existing modular CLT buildings tend to be 7 storeys or less in height [8].

The success of timber modular construction to date has been reported as being dependent on local or regional production capacity and regulations [8], and its development has been focused primarily in Europe, followed by North America. Bhandari et al. [8] acknowledge that there is a need for a systematic review of modular CLT connection systems in terms of constructability, reuse and potential for rapid building deployment, including further study of the impacts of the transportation distance on cost and efficiency. Furthermore, with increasing demand for sustainable building solutions, international best practice in modular timber construction is expected to become more widespread.

The increased use of timber in construction has tended to be perceived as having the potential to make a significant contribution to reducing greenhouse gas emissions from the construction sector, particularly when it is being used in place of reinforced concrete or steel. This is becoming of greater significance now as many countries are introducing policies and initiatives that target net-zero emissions, such as the European Green Deal [9], with associated regulation and carbon footprint limits for new buildings. There has been limited research published on the lifecycle impact of modular volumetric CLT construction but recent research [10] has highlighted the significance of the energy production profile for this type of construction. The product, construction and end-of-life stages hold the most significant share of the building's lifecycle impact, while optimising the modular CLT building configuration and use of efficient fasteners can reduce the overall impact by around 5% [10]. The authors are also carrying out ongoing research on the lifecycle assessment of timber buildings and modular CLT construction as part of the wider Modular Mass Timber Building for the Circular Economy (MODCONS) project. This paper presents aspects of the MODCONS project on the preliminary design and manufacturing of a seven-storey residential building in CLT based on material properties of Irish C16 timber, following the volumetric modular approach. While 2D panellised solutions can offer flexibility, a 3D volumetric modular approach also offers a number of advantages, including the quality control and efficiency associated with factory assembly and reduced sitework. The volumetric approach also has the advantage of producing whole modular units that can be reused or refurbished, supporting a circular economy in construction and offsetting the need for virgin materials. European CLT panel manufacturers primarily use grade C24 timber, which has slower growth rates but higher strength than fast-grown Irish Sitka Spruce (*Picea sitchensis*) grade C16 timber. It follows that the capacity and opportunity for the increased supply of Irish timber to be used in added-value products in construction must be illustrated, supporting a reduction in the carbon footprint of the built environment [6]. The following sections outline the preliminary building layout and design including reuse, loading arrangements, transportation requirements, and the associated challenges.

2 DESIGN CONCEPT AND DEVELOPMENT

Following the current Irish building regulations (and associated technical guidance documents on structure, fire safety, access) [11], planning guidance [12] and European standards for actions on structures and structural design [13-16], the design of the volumetric units was developed assuming mass production of prefabricated units under factory conditions. The milestones of the preliminary design workflow are highlighted in Figure 1 below, beginning with (i) the selection of the volumetric construction method, (ii) the design and layout of individual modular units and plan design, meeting transportation requirements and internal sizes in line with the minimum area required by the local regulations [12], and (iii) structural design of the CLT panels required to transfer loads from the floors and ceilings to walls and foundations. Lifting systems and connections are also key considerations in the design for deconstruction targeting future reuse, however, limited discussion is provided here on consideration of these.

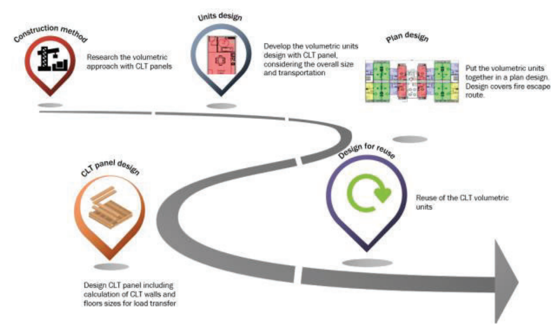

Figure 1: *Milestones of the design development*

2.1 SITE LOCATION

The site location for the seven-storey residential building was assumed in an urban location in Dublin, Ireland. The ground conditions and foundation design are not considered in this paper but based on existing

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developments in this location, it is assumed that the geotechnical conditions will be suitable for the proposed building. The focus here is therefore on the building superstructure only.

2.2 ACCESS AND TRANSPORTATION

The design criteria for the CLT units are also informed by transportation within this urban location i.e. by access, size and weight limits. The modular unit height is limited at 4.65 m from ground to the top of the load being carried or top of the vehicle. This can be increased by a local authority permit [17]. The modular unit length is limited at 12 m + 3 m overhang for one piece [17,18]. This can be increased to 27.4 m with a permit from An Garda Síochana, and increased to more than 27.4 m with a local authority permit [17]. The modular unit width is limited at a maximum of 2.9 m (including a 300 mm overhang) [17,18]. This limit can be increased to 4.3 m with a permit from An Garda Síochana, and over 4.3 m with a local authority permit. Based on the above limitations and assuming the necessary permits are obtained, the size and dimensions of the modular CLT units were therefore limited to 4.3 m external width, 15 m external length, and 4 m in external height. Figure 2 provides an example illustration of the modular unit size for transportation, showing the unit overhang on the transporting vehicle. provides Supporting beams, not shown here, are also required to ensure the unit is supported by the walls during transportation.

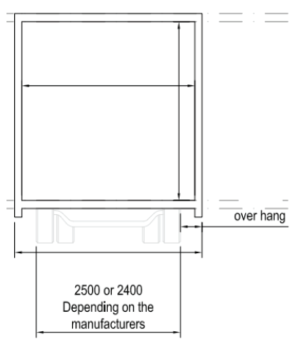


Figure 2: *Example illustration of modular unit transportation (not to scale, dimensions in mm)*

The maximum allowable modular unit weight is maintained below 24 tonnes to remain within transportation vehicle laden weight limits [19]. More detail on the weights of the designed modular units is provided in Section 2.3.

2.3 BUILDING LAYOUT AND MODULAR UNIT TYPES

The general arrangement of the building and plan layout design are dependent on the arrangement and combination of the volumetric unit types. Three apartment configurations were considered in the completed plan layout for the proposed seven-storey building, with a rectangular footprint on plan of 45 m × 25.32 m excluding balconies. The same floor plan (Figure 3) is repeated at all seven storeys, with reinforced concrete cores (3.48 m × 5.53 m on plan; 300 mm thick walls) located at each end of the building to provide access stairways, fire escape routes and lateral stability for the building structure. A central communal area is provided, meeting minimum area requirements [12]. Fire safety provisions and emergency access are based on Technical Guidance Documents B and K [11]. The stair cores are designed to be constructed on-site using reinforced concrete as a non-combustible material. The maximum distance from an apartment entrance door to the stairs is limited to 15 m. This plan is designed to ensure each bedroom receives natural light and it also allows for additional units and cores to be added.

To form the three apartment configurations, either single modular CLT units or a combination of units are employed. The four volumetric unit types designed are shown in Figure 4 – Types 1 (green) and 2 (yellow) are combined to form the two-bedroom apartments, Types 1 and 3 are combined to form the one-bedroom apartments, and Type 4 is a single studio unit (red). These exceed the minimum overall areas by at least 10% [12] while minimum widths of apartment rooms are also defined by [12]. A standardised width of 3.6 m is used for both one and two-bedroom apartments to reduce volumetric unit variation for manufacturing. However, for the studio apartment, a minimum internal width of 4.0 m is required. All modular units are l_e = 3.25 m in height, resulting in a total building structure height of 22.75 m.

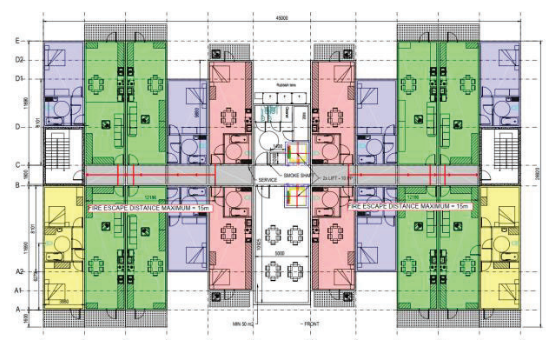
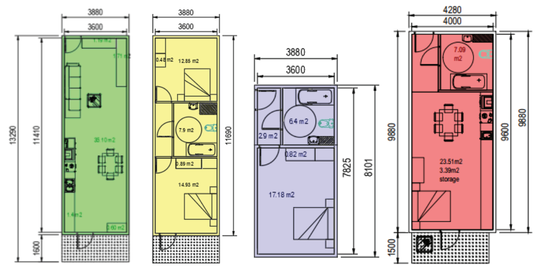


Figure 3: *Proposed building plan layout (not to scale, dimensions in mm)*

The units are designed to reduce the number of volumetric unit types required to form the building. This reduces structural variation, optimising unit standardisation to improve production efficiency. Furthermore, for the CLT panel supply chain, cost and time savings can be made when the same panel sizes can be ordered, manufactured and supplied in large quantities. The internal design of the apartments accommodates a standard plan layout. However, the skeleton frame of the volumetric units can be used with different interior designs of the apartments. This means the core CLT volumetric unit can be used in a different applications – allowing standardised mass production. Overall, the building consists of 12 apartments per floor, configured from 20 CLT modular units per floor, totalling 140 modular units.



(a) (b) (c) (d)

Figure 4: *Plan layouts of volumetric modular CLT units (a) Type 1 (b) Type 2 (c) Type 3 (d) Type 4 (not to scale, dimensions in mm)*

The estimated weights of the volumetric units are provided in Table 1; these values assume the prefabrication of the units including balconies for a conservative comparison with permitted transportation limits i.e. weight under 24 tonnes and length less than 12 m + 3 m overhang. All unit widths are under 4.3 m. Common practice would likely dictate site installation of balcony units post assembly of the building modules. Mobile cranes with suitable capacity are available for these modules and building dimensions, such as the Demag AC220-5.

Table 1: *Modular CLT unit dimensions and weights*

Type	External width (m)	External length including balcony (m)	Estimated weight (tonnes)
1	3.88	13.29	20.32
2	3.88	13.29	22.78
3	3.88	9.7	18.11
4	4.28	11.38	21.86

3 CLT PANEL DESIGN

3.1 LOADING

Figure 5 shows an indicative cross section for the modular CLT units, showing the proposed balloon arrangement of CLT panels for walls, floors and ceilings. This allows modules to be stacked on top of one another with gravity load transfer directly between walls, removing the risk of compression perpendicular to grain in floor panels in the more popular platform construction approach. For unit types 1-3, the clear span for floors and ceilings is the 3.6 m internal width, while for unit type 4, the clear span is 4 m. The floor and ceiling panel designs are based on the larger L = 4 m span.

The gravity loading acting on floors and ceilings is adopted based on [14], while wind loading is calculated based on the Irish National Annex to Eurocode 1 - Part 1-4 [14], giving a peak wind pressure of 1.27 kN/m^2. The characteristic variable action (unfactored imposed load) adopted for the unit floors is 2 kN/m^2 based on domestic loading, while the ceiling panels are designed for imposed loads of 0.6 kN/m^2 during the construction stage only. A flat roof is assumed with limited access for maintenance and repair only, with ceiling panels in units at roof level designed for an imposed load of 1.5 kN/m^2; this can be reduced to 1.0 kN/m^2 where permanent access to those panels is not provided. Including self-weight, the ultimate design loading for a 1 m strip of the floor is 4.47 kN/m. For the ceilings, the corresponding loading is 2.12 kN/m. All corridors and access areas are designed for an imposed load of 4.5 kN/m^2. Floors in corridors are to be supported by the CLT module walls and are included for loading calculation purposes only.

The preliminary wall design is based on the maximum gravity loading experienced by ground floor walls, allowing the resultant design to be used at any floor. It is assumed that the walls are encapsulated with plasterboard providing at least 60 minutes of fire resistance – this is expected to be a minimum requirement under current Irish practice. As the building is multi-storey, the total imposed loading on the walls has been reduced by a factor of 0.79 in accordance with Equation (6.2) of Eurocode 1: Part 1-1 [14]. These loads result in an ultimate axial design load on the wall of F_d = 112 kN/m. The ultimate transverse load acting on the wall due to wind, calculated using the peak wind pressure, is $q_d = 1.5 \times 1.27 = 1.91$ kN/m^2.

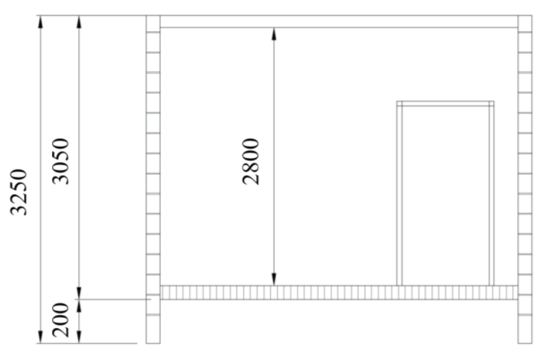


Figure 5: *Indicative cross section of volumetric modular CLT units (not to scale, dimensions in mm)*

3.2 MATERIAL PROPERTIES AND SOURCING

Irish Sitka Spruce (*Picea sitchensis*) grade C16 timber is assumed for the design of all CLT elements. While C24 grade timber is more commonly used for the manufacture of CLT in Europe, this study is intended to illustrate the feasibility of using locally sourced rather than imported timber, which at a minimum, can offer potential savings in transport emissions. This is also being investigated by the MODCONS team at University of Galway but is beyond the scope of this paper. The relevant adopted material properties for design in accordance with Eurocode 5 [15] are presented in Table 1 below, adopted from [20-22].

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Table 2: Material properties for C16 grade timber used for design

Property	Value for C16	Unit
Characteristic bending strength, $f_{m,k}$	16	N/mm^2
Characteristic compressive strength along the grain, $f_{c,0,k}$	17	N/mm^2
Characteristic compressive strength perpendicular to the grain, $f_{c,90,k}$	2.2	N/mm^2
Characteristic shear strength, $f_{v,k}$	3.2	N/mm^2
Mean value of modulus of elasticity, along the grain, $E_{m,0,mean}$	8000	N/mm^2
Fifth percentile value of modulus of elasticity, along the grain, $E_{m,0,05}$	5400	N/mm^2
Shear modulus, $G_{0,90}$	500	N/mm^2
Rolling shear modulus, $G_{90,90}$	50	N/mm^2
Density, ρ	390	kg/m^3

3.3 PANEL DESIGN SUMMARY

Following the design approach based on beam theory [15,16] and outlined in [22], the assumed building layout shown in Figure 3, loading outlined in Section 3.1, and using C16 timber properties provided in Table 2, three common CLT panel build ups have been designed for the unit walls, ceilings and floors respectively for all unit types; these are summarised in Table 3. Service Class 1 is assumed. Values of k_{mod} = 0.8 for medium term actions [15, 22], k_{mod} = 0.6 for permanent actions [15, 22], γ_M = 1.25 [15] and k_{def} = 0.85 [22] are adopted for design calculations.

Table 3: Summary of panel design

Element	No. layers	Total thickness (mm)	Layer thickness (mm)	Layer orientation (degrees)
Walls	3	120	40	0
			40	90
			40	0
Ceilings	3	110	40	0
			30	90
			40	0
Floors	5	140	40	0
			20	90
			20	0
			20	90
			40	0

3.3.1 Floors and ceilings

The floor and ceiling panels both comfortably pass design checks for bending and shear, with low utilisation ratios. It is desirable at this preliminary stage to keep utilisation ratios below 75% for floors and ceilings. For example, for the CLT floor panel, the design bending strength, $f_{m,d}$ =10.24 N/mm^2 is considerably greater than the design bending stress σ_d = 2.96 N/mm^2. Similarly, the design shear strength, $f_{v,d}$ = 2.05 N/mm^2 is greater than the design shear stress, τ_d = 0.13 N/mm^2.

The critical design criteria for the floor and ceiling panels are deflections, which are limited to a maximum of L/250 = 16 mm here for the L = 4 m span [15]. The net final deflections are calculated here according to equation 7.2 of [15], reproduced as Equation (1) assuming zero pre-camber:

$$w_{\text{net,fin}} = w_{\text{inst}} + w_{\text{creep}} \tag{1}$$

where $w_{\text{net,fin}}$ is the net final deflection, w_{inst} is the total instantaneous deflection (variable + permanent) and w_{creep} is total deflection caused by creep (variable + permanent). For permanent actions, $w_{\text{creep,g}} = k_{\text{def}} w_{\text{inst,g}}$ and for variable actions, $w_{\text{creep,q}} = \psi_2 k_{\text{def}} w_{\text{inst,q}}$ where $\psi_2 = 0.3$.

For the floor panels, $w_{\text{inst}} = (w_{\text{inst,q}} + w_{\text{inst,g}}) = (4.24 + 1.16) = 5.40$ mm under variable and permanent actions, respectively, which is less than the corresponding limit of L/300 = 13.33 mm. The net final deflection $w_{\text{net,fin}}$ = (2.16 + 5.32) = 7.48 mm (< 16 mm). Reducing the outer layer thicknesses by a typical step size of 10 mm or greater would cause the section to exceed the 75% utilisation ratio in deflection thus no further changes are made to the section size and layers.

In terms of vibration serviceability requirements, the natural frequency of the floor is $f_{1,fl}$ = 12.93 Hz, and that for the ceiling is $f_{1,ceil}$ = 9.27 Hz, calculated using equation 7.5 of Eurocode 5 [15]. Both of these panels satisfy the simplified vibration serviceability calculation method in Eurocode 5 for residential floors however, it should be noted that the acoustic performance has not been assessed here - this is part of a larger task on the MODCONS project.

3.3.2 Walls

The wall design is more critical due to the loading accounting for vertical load from 7 storeys and wind loading. Following Clause 6.3.2 of [15] for combined compression (due to F_d) and bending (due to q_d), the 120 mm thick panel is checked for the 11.69 m long wall in unit Types 1 and 2. Due to openings for windows, the effective width, $b_{ef,}$ of the wall is taken as 6.5 m. Buckling is checked in the ultimate limit state according to Equation (2).

$$\frac{\sigma_{\text{c,0,d}}}{k_{c,y} f_{\text{c,0,d}}} + \frac{\sigma_{\text{m,y,d}}}{f_{\text{m,y,d}}} \leq 1 \tag{2}$$

where $\sigma_{\text{c,0,d}}$ is the design compressive stress along the grain, $f_{\text{c,0,d}}$ is the design compressive strength along the

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grain, reduction factor $k_{c,y}$ can be obtained using equation 6.5 in [15], $\sigma_{\mathrm{m,y,d}}$ is the design bending stress about the principal y-axis, $f_{m,\mathrm{y,d}}$ is the design bending strength about the principal y-axis. $\sigma_{\mathrm{c,0,d}}$ can be calculated based on a 1 m strip of wall (from the width b_{ef}) as $N_{\mathrm{d}}/A_{\mathrm{x,net}}$, as per [22]. Here, $N_d = 201$ kN is the vertical load and $A_{\mathrm{x,net}} = 80{,}000$ mm^2 is the cross sectional area of the two outer layers, giving $\sigma_{\mathrm{c,0,d}} = 2.51$ N/mm^2. $\sigma_{\mathrm{m,y,d}}$ can be calculated as $M_{\mathrm{y,d}}/W_{\mathrm{x,net}}$, where $M_{\mathrm{y,d}} = \frac{q_d l_e^2}{8}$ is the design moment due to wind loading and $W_{\mathrm{x,net}}$ is the section's net moment of resistance. Here $\sigma_{\mathrm{m,y,d}} = 1.95$ N/mm^2. With $k_{c,y} = 0.43$, $f_{\mathrm{c,0,d}} = 8.16$ N/mm^2 and $f_{\mathrm{m,y,d}} = 7.68$ N/mm^2, Equation 2 can be evaluated as $0.97 < 1$, which passes but with a high utilisation ratio. Any further increase in thickness to reduce this utilisation ratio is not desirable as it would increase the weight of units beyond the 24 tonne transportation limit. However, further refinement of panel thicknesses is possible between unit types with consideration of the impact of increased variation in manufacturing.

3.4 CONNECTIONS AND DESIGN FOR REUSE OPPORTUNITIES

The common panel design for all units allows the modular units to be used in alternative arrangements i.e. the same unit can be used at any storey within this seven storey building. Furthermore, this also enables provision for reuse of the units at the end of, or during, the building's design life which supports the reduction of its environmental impact. While 2D panellised CLT systems may remain more popular and practical for construction, the whole unit reuse option remains an advantage for volumetric units. There are two options for reusing the units: (i) reuse the fully completed CLT units (with interior fit out) and (ii) reuse only the structural frame; the latter has been employed for volumetric construction in steel. However, associated challenges exist, for example, in the limited capacity to add new openings to walls, the detailing of demountable connections, maintaining overall building stability and modularisation of Mechanical and Electrical systems. Alternative solutions currently being assessed include straightforward options such as connections using screws instead of nails, no adhesive used to connect components to CLT, recessed lifting points located at the top of the unit wall panels etc. Connection groups currently being reviewed for this building system include:

- Alternative options for wall to floor and wall to ceiling connections, including standard angle brackets and timber rails above or below panels considering fire protection
- Inter-module connectors i.e. as part of the lateral stability system
- Connections for lifting and transportation
- Volumetric unit connection to substructures

4 CONCLUSIONS

This paper has demonstrated the feasibility and capacity of CLT panels manufactured using Irish C16 grade timber to be used in multi-storey volumetric modular residential construction. Due to a common CLT panel design between the four modular unit types proposed for use across all 7 storeys, wall panels at the ground floor level are the critical elements. However, the current design with 5-layer 120 mm thick wall panels provides flexibility to use the same volumetric modular unit at any of the seven floors. While 2D panellised systems grow in terms of popularity and standardisation, volumetric modular systems still hold the advantage of enabling reuse of a whole finished unit. The MODCONS project team's ongoing work involves the review the lifecycle impacts of this, considering the comparative ease of deconstruction of panellised systems for reuse. Furthermore, the proposed design, detailing, structural testing, and fire performance testing of connection systems for both volumetric and panellised systems using Irish C16 timber is ongoing.

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