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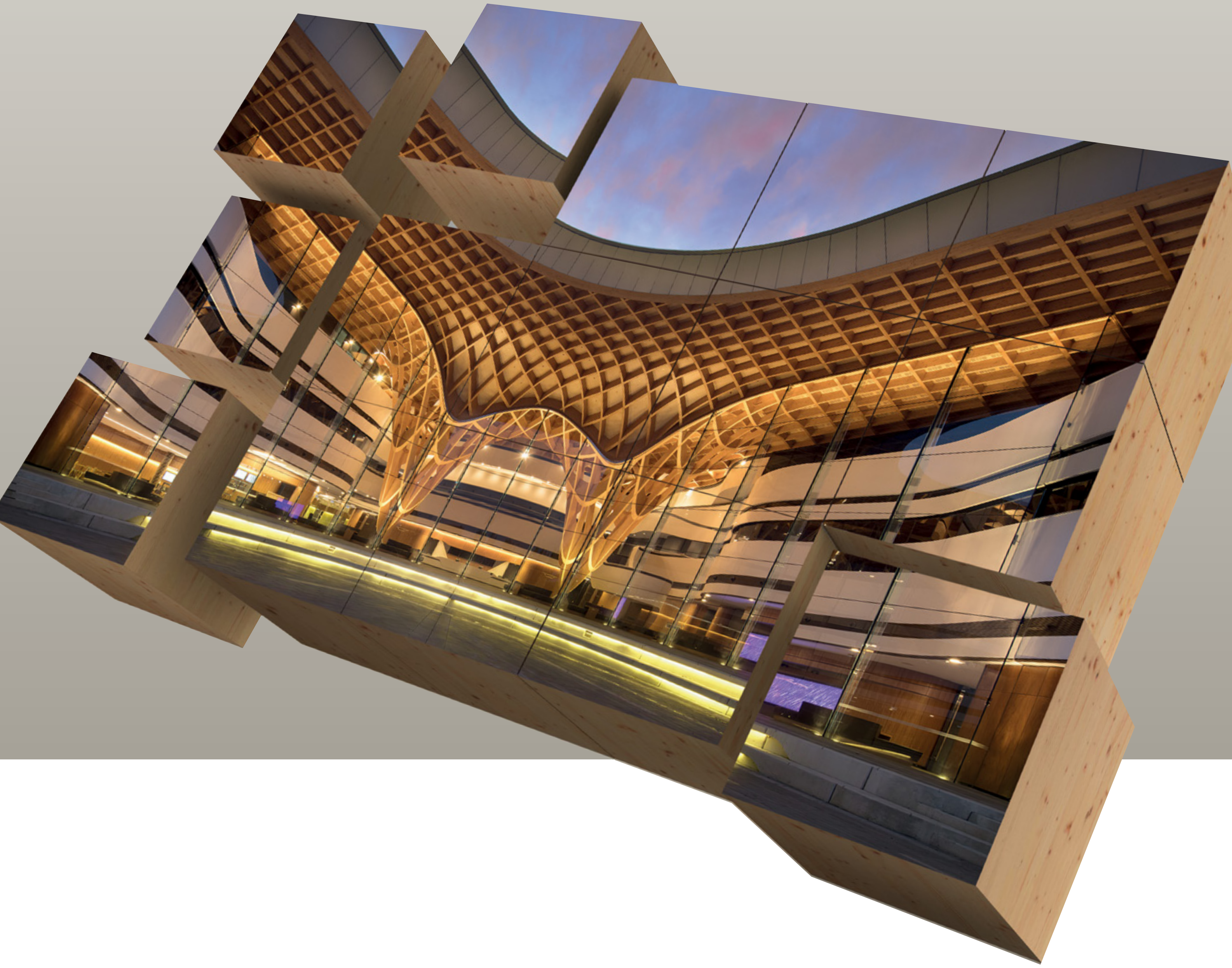

Cost Engineering of Mid-rise Timber Buildings

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1 Introduction

This guide provides reference data and methodology advice for cost engineering activities directly and indirectly associated with the design, procurement and installation of wood structures in Australia, especially with reference to mid-rise buildings (four or more levels).

There has been a rapid growth in the use of Engineered Wood Products (EWPs) across the property industry. Since the delivery of Australia's first mid-rise contemporary wood building – Forté Living from Lendlease – structural wood products have been used to construct a variety of buildings across the country. This trend has been supported by amendments to the National Construction Code (NCC), which since 2016 has provided a Deemed-to-Satisfy (DtS) solution for timber construction to an effective height of 25 metres (from 2019 applicable to all building classes), and has been further backed by the WoodSolutions free advisory program in this field.

While many detailed guides have been published on the design and maintenance of timber structures, there has been relatively little focus on the specifics of costing and ultimately building them. This guide has been prepared to address the specific cost-related knowledge and approach that needs to be considered throughout the development process, with respect to the Australian Cost Management Manual and other relevant publications.

Written in conjunction with Rider Levett Bucknall, a leading independent organisation in cost management, quantity surveying, project management and advisory services, this guide has been divided into sections associated with the typical activities of a cost engineer. While each section is complete on its own, the reader will gain most benefit by considering them to be inter-related, and it is recommended that the document is read as a whole.

This guide refers to projects that are based on either individual Wood Products or systems, or their combinations. Further information on the nature, performances and design of such products and systems can be found, with a comprehensive and comparison-based approach, in *WoodSolutions Technical Design Guide #46 Wood Construction Systems*. Other guides within the WoodSolutions library offer more detailed information specific to a given application.

This guide identifies and explains the typical differences between the costing of wood-based projects with respect to those using other systems, as described by the six main categories shown in Figure 1.2. Drawing on examples from a database of relevant completed projects, the text discusses several considerations under each category of difference, suggesting how they may be best measured and allowed for. Table 1.1 summarises what these differences have typically been shown to include.

Figure 1.1: The office built by Lendlease at 25 King Street, Brisbane, embodies the advantages of timber construction for all six categories described in Figure 1.2 (Lendlease)

Figure 1.2: The main advantages of using Wood Products with respect to other systems.

Table 1.1: Summary of the main advantages of using Wood Products.

Differential value	• Cost-effective elements are possible for some optimised designs, due to the high strength-to-weight ratio of Wood Products. • Fewer variations and defects are typically achieved thanks to tighter dimensional tolerances. • Increase in net sellable or rentable areas in some cases, with reduced wall depths for equivalent structural, fire and acoustic combined performances.
Improved safety	• Larger working platforms and pre-installed edge protection are typical. • Simpler and easier anchoring for safety harness in most points. • Easier handling and fixing, with smaller and lighter tools. • No hot works or welding on site.
Faster delivery	• Follow-on trades can start immediately, with no props and curing time, because the floors are readily stable and load-bearing. • Higher number of panels for each truck delivery. • Accelerated construction programs can lead to lower cost of finance. • BIM-ready with shop drawings typically from manufacturers.
Lower preliminaries	• Lifting is quicker and can be achieved with smaller cranes and/or shorter equipment rental times and related costs. • Shorter on-site programs resulting in reduced costs of temporary works. • Scaffolding can be limited or even avoided in some instances. • Storage areas are reduced in size and can be easily organised on floors. • Site accommodation is reduced as the crews are smaller, with more work happening off site.
Reduced foundations	• Lighter above-ground structure with respect to reinforced concrete, reducing foundation size for the same sized superstructure, and significantly improving designs in weak soils and vertical extensions over existing buildings. • Higher built volumes have been possible in some projects, a big plus for the developer.
Lower impacts	• Less noise, dust, vibrations and truck movements result in less disruption of neighbourhoods and existing activities and tenants. • Credits for CO_2 storage (carbon sink) and/or renewable materials are sometimes applicable. • Demonstrated benefits on occupants' health and wellness may justify higher rental fees.

Figure 1.3: The Monash Peninsula student accommodation in Frankston, a Passive House design for 150 beds and related amenities from JCB Architects and AECOM (engineers), was completed in 2018 by Multiplex only 16 months after being engaged for the D&C contract, with a track record of three months for assembling the carpentry, zero site accidents and significant time savings for the installation of services and interior finishes. Images: http://www.jcba.com.au and Multiplex.

1.1 Definitions

Several terms relevant either to timber construction or development in general have been used in this guide. While an in-depth explanation of many of these terms is available in *WoodSolutions Technical Design Guide #46 Wood Construction Systems*, a brief set of definitions has been provided here for ease of reference.

Bracing Panel: A panel resisting shear loads in either vertical or horizontal planes that adds overall stiffness to a structure.

Computer Numerical Controlled (CNC) Machine: An automated electro-mechanical device that manipulates shop tools using computer programming inputs. In the fabrication of Engineered Wood Products, CNC machines are used to cut elements into the designed shapes through cutting, drilling, routing, or other processes, typically with millimetre precision.

Connectors: The items used to connect one element to another. Typically made of steel, aluminium or timber, connectors include products such as: screws, bolts, nails, dowels, nail plates, angle brackets, flat plate brackets, and bespoke designs.

Crew: The group of people involved in the installation of engineered timber products. Typically, a crew will consist of 4–8 people, with work tasks including setting out/organising, installing/landing panels, and nailing/fixing.

Cross-laminated Timber (CLT): A panel composed of layers of solid wood boards, typically 12-45 mm thick and 40-300 mm wide, finger-jointed, face-flued (and edge-glued in some instances), each layer at 90° to the next. CLT panels are typically 57 mm – 320 mm thick and made up of 3, 5, 7 or more layers. Panels are available in 1.25 to 3.5 metre widths and up to 16 metre lengths. More detailed information on CLT can be found in *WoodSolutions Technical Design Guide #16 Massive Timber Construction Systems: Cross-laminated Timber (CLT)* and in the producers' technical literature.

Deemed-to-Satisfy (DtS) Solution: A design that follows the Deemed-to-Satisfy Provisions in the NCC, which includes materials, components, design factors and construction methods that, if used, are deemed to meet the Performance Requirements.

Fire Protected Timber: A timber element that, through the application of a non-combustible fire protective lining, has an FRL appropriate for that element.

Glued-laminated Timber (Glulam): A timber element consisting of a number of strength-graded, kiln-dried, finger-jointed laminations, face bonded together with adhesives. Elements can be manufactured to practically any length, size or shape. Beams are often manufactured with a built-in camber to accommodate dead load deflection or curved to follow the design. A wide variety of strength grades and section sizes are available, with depths from 90 mm to more than 1,000 mm, and thicknesses from 40 mm to more than 135 mm.

Laminated Veneer Lumber (LVL): Engineered Wood Product made from peeled veneers that are bonded together with adhesive under heat and pressure to form panels. Most veneers are oriented so their grain runs parallel, leading to high capacities of compression parallel to the grain. LVL can either be used as a massive timber element (e.g. a panel, beam, or column) or cut into smaller sections for framing.

Lift: The operation (or amount of time) for a crane on-site to hook a load, lift it to the desired location, unhook it, and return the hook to the starting position.

Lightweight Framing (or Stud Framing): Timber frame construction assembled from lightweight timber studs and plates with either wood panel or metal strap bracing, and using fasteners like nails, staples or screws as connectors. Individual timber products used in framing generally have at least one dimension measuring 45 mm or less, but multiple or staggered studs can be used to increase design strength and stiffness properties.

Massive Timber: In the NCC, an element not less than 75 mm thick as measured in each direction formed from solid or laminated components.

Modified Resistance to the Incipient Spread of Fire (MRISF): As per definition for RISF, but allows for the delay in temperature rise experienced with massive timber elements under fire load by specifying the minimum amount of time taken for the surface of the timber element to reach 300°C for the system to comply with the DtS Solution.

Resistance to the Incipient Spread of Fire (RISF): In the NCC, the ability of the ceiling or wall membrane to insulate the space between the ceiling or wall and the adjacent sole occupancy unit, so as to limit the temperature rise of materials in this space to a level which will not permit the rapid and general spread of fire throughout this space.

Tabulated rates: Costing rates made available in tabular form in commercially published guides such as Rawlinson's Construction Cost Guide, or the Australian Institute of Quantity Surveyors' 'Building Cost Index'.

Timber: Short synonym for 'structural wood component' or 'Engineered Wood Product (EWP)'.

Take-off: A detailed measurement of materials and labour needed to complete a construction project.

Variation: Alteration to the scope of works in a construction contract in the form of an addition, substitution or omission from the original scope of works. This can occur because of technological advancement, statutory changes or enforcement, change in conditions, geological anomalies, non-availability of specified materials, or simply because of the continued development of the design after the contract has been awarded. Also known as a variation instruction or change order.

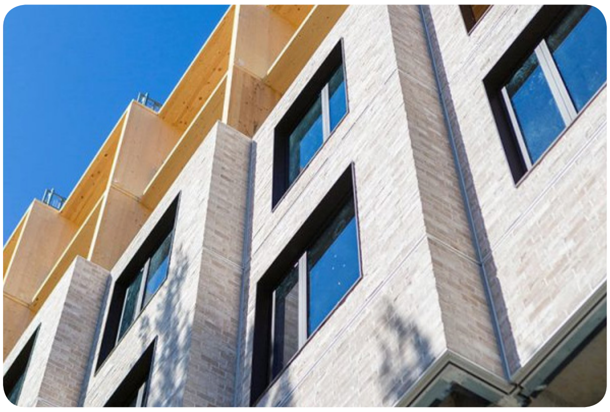


Figure 1.4 – The Kambri precinct of Australian National University (Canberra, 2019) incorporates two large mass timber construction buildings: the 450-bed student accommodation and the five-storey collaborative teaching building. Designed by BVN (architects) and constructed by Lendlease, the student accommodation was also the first building in Australia to use a new prefabricated facade system from Inclose that enabled 13-metre-long fully complete brick facade sections to be installed within 20 minutes. Images: Lendlease

2 Database

The content of this guide has been developed and supported by the observations and experiences recorded from 26 significant projects, sourced from both Australian and international markets. Special care has been taken to ensure that all the international projects were completed in a similar work environment to that in Australia, with a major focus on Occupational Health & Safety (OH&S), a similar magnitude of labour costs, hire costs, and so on.

While all identifying characteristics of these projects have been withheld for confidentiality reasons, their relevant metrics are described in Table 2.1.

Table 2.1: Fundamental metrics of the reference projects built with Engineered Wood Systems.

#	Type	Levels	Crew	Crane(s)	m^3 EWP	Lifts	m^2 GIA	Lifts/d	GIA/d
1	Residential	6	8	2	1,510	936	4,682	16	78
2	Residential	8	5	1	1,082	994	3,072	20	61
3	Residential	8	8	2	1,853	1,299	6,154	16	77
4	Residential	8	8	1	1,515	1,323	4,154	19	59
5	Residential	7	7	4	3,930	1,514	12,276	14	76
6	Residential	7	5	1	1,506	1,310	3,883	17	49
7	Residential	10	7	2	4,649	2,810	14,001	14	68
8	Residential	6	5	1	533	514	16,84	16	42
9	Residential	8	5	2	3,170	1,586	9,797	14	86
10	Residential	9	5	2	2,967	1,622	8,650	16	82
11	Residential	8	5	2	2,735	1,486	8,032	16	85
12	Residential	7	5	2	1,667	839	4,887	16	81
13	Residential	9	5	1	1,000	759	2,431	13	41
14	Residential	18	9	1	2,233	n.a.	15,120	n.a.	336*
15	Residential	9	5	1	926	n.a.	2,890	n.a.	107
16	Residential	4	12	2	2,208	1,557	5,824	28	106
17	Residential	6	12	2	1,750	935	6,500	17	96
18	Residential	9	8	1	2,700	1,376	9,478	16	110
19	Residential	7	7	1	2,300	1,534	9,330	21	128
20	Residential	8	7	1	3,084	2,258	13,166	25	145
21	Residential	7	9	1	2,525	1,541	9,896	19	124
22	Residential	12	6	1	3,084	2,346	10,220	14	59
23	Commercial	7	5	1	1,162	503	4,149	14	40
24	Commercial	10	n.a.	1	6,270	3,097	14,900	24	115
25	Commercial	7	8	1	2,950	1,750	7,910	19	88
26	Commercial	7	8	1	4,700	1,750	10,000	17.5	100

Note: Residential includes also similar floorplans such as aged care, hotel and student accommodation.
** this project experienced significantly faster installation times due to extensive planning and an efficient design*

The projects referred to in Table 2.1 vary in height, floor area, usage and site setup. The average project in this database is eight storeys with a Gross Internal Area of 7,811 m^2, and requires an installation team of just seven people to complete the structure at a rate of 94 m^2 per day. These metrics represent the average of a sample and may not be directly applicable to non-standard projects. When segregated by building use, these metrics refer to:

- ***residential*** projects on average extending to eight storeys with a Gross Internal Area of 7,551 m^2, and requiring seven people to install at a rate of 95 m^2 per day
- ***commercial*** projects averaging seven storeys, with a Gross Internal Area of 9,240 m^2, and required on average an installation team of seven to achieve an installation rate of about 86 m^2 per day.

While there are a number of factors that could explain these slight differences in productivity, it has widely been observed that the most significant factor in a project's overall productivity is its number of storeys. Evidence suggests that installation rates are slowest where precisely cut timber elements interface with less accurate in situ concrete surfaces or steel elements, often requiring packing and levelling to achieve a tight assembly fit or an even footing. Once the first level is complete, timber projects experience an immediate and substantial increase in productivity, with install rates quickly making up for any time lost in the first level. Variance in install speeds can also be due to design complexity, size of elements, typology of building, climactic conditions, number of cranes, level of prefabrication, or a range of other variables.

Figure 2.1: The Brock Commons student accommodation (Vancouver, CAN – 2017) is an 18-storey post and slab structure in glulam and CLT with concrete cores and a prefabricated facade, designed by Acton Ostry Architects. It was considered by the local Fire Brigade to be "the safest building of this type in town" because of encapsulation of most of the Engineered Wood structure which, together with the prefabricated façade, Urban One Builders erected in only 66 days with a crew of nine.
Images: Top left Seagate Structure; top right Neil Taberner; bottom: Michael Elkan.

3 Estimating

The process of cost estimation differs little between timber and other construction systems. Nevertheless, there are several key areas for consideration in any estimate of a timber structure to ensure that the outcome represents the design as accurately as possible:

- Reference to ***tabulated rates*** is seldom available and, when it is, typically has quite large safety factors because the evolution of the products (with many being proprietary products instead of commodities) and the local conditions (with the influence of logistics) account for significant differences
- Price ***variations over time*** are typically smaller than for other materials and/or may have a different origin. Depending on the location of the supplier of timber elements, costs may also change subject to the season in which they are purchased. For example, peak supply period for European suppliers is between April and December and purchases within this period may attract a higher rate than those in the off-peak period (European winter). This cost differential is less pronounced in Australia, as construction typically proceeds year round.
- ***Preliminaries and workmanship*** are normally a significant part of the building costs and are sometimes 'hidden' within other line items. For timber structures these may be the main source of cost efficiency. We suggest they are always specifically and accurately analysed and reported.
- A key function of the estimator role, the take-off is quickly becoming more automated with the growth of building information modelling. With engineered timber elements produced and fabricated in accordance with a digital design file, timber construction is highly adaptable to modern construction environments utilising building information modelling for design, programing and estimating.

This section highlights some of the factors any estimator should be aware of when preparing an estimate for a timber project.

3.1 Engineered Wood Components

3.1.1 Products and Systems

Subject to the loads and spans designed for, Engineered Wood can be utilised in either panelised form (as is typical with cross-laminated timber (CLT), floor cassettes or stud-framed wall panels) or in linear sections (as is common with both glue-laminated timber and laminated veneer lumber (LVL) used for beams, columns or joists).

Timber panels are widely used as loadbearing walls and floor elements and are therefore well suited to repetitive 'honeycomb' designs, such as student accommodation, hotels and some multi-residential designs. Complementary to this system, linear products can be used as a column or beam to provide larger open spaces, and widely used in projects requiring large open floor plans (with spans up to 12 m under office loads).

The estimator should consider the following when either preparing or checking a take-off:

- Different timber-based products and systems are sometimes fully interchangeable (same performances and therefore, for instance, same structural depth). In other cases they differ to such a point that the costs/benefits associated with a substitution must be considered. This is currently typical with proprietary products like CLT, LVL and I-joists, that have different lay-ups, or with studs, joists and glulam beams that have a range of structural grades for the same cross sections. In these cases, assuming a generic rate/m^2 or /m^3 could be misleading. Further information and comparisons of different products and systems can be found in *WoodSolutions Technical Design Guide 46 - Wood Construction Systems.*
- A system is not worth just the sum of its components, as both the amount and cost of labour for its assembly will significantly differ when this is performed on-site or off-site. Also, the associated costs of transport and installation will vary.
- Product certification (both for performances and for sustainability) follows different standards, which are typically quite similar, but not identical. An experienced designer or consultant will provide enough information about the applicable standards and the acceptable tolerances and deviations. If this is not the case, the estimator needs to request the relevant information before making their own assumptions.

The influence of these elements will be detailed further in this chapter.

While a late-stage detailed estimate relies on an elemental take-off of the project, this level of detail is not available for early-stage estimates. At this stage of a project an estimator can provide an order of magnitude estimate based on a rule of thumb that has been developed in the industry, and is observable in the projects listed within this guide's database. The rates in Table 3.1 are provided as a high-level reference and can be interpolated when the structure is a mix of the types assumed for reference, then a parametric costs/m^3 obtained from a supplier can be applied. Interestingly, these rates can be reduced with an optimised design and the use of high-strength wood components, that may provide a cost-efficient alternative to lower grade materials.

Table 3.1: Fundamental metrics of the reference projects built with Structural Wood Systems. Note that these metrics are relative to supply only in 2018-19 (including connectors but excluding installation). There are indicative and should only be applied at a high level basis. For updated, more accurate and project specific costs please contact the relevant supplier.

m^3/m^2	Structure type	\$/m^2
0.20-0.30	Light frame residential designs (e.g. 4-6 storey)	$300-450
0.30-0.40	Post and beam open plan with panelised floor system	$550-650
0.27-0.32	Massive timber residential, standard design (e.g. 4-6 storey)	$350-$450
0.32-0.40	Massive timber residential, standard design (e.g. 7+ storey)	$400-$500

Figure 3.1: The Murray Grove residential building (London, UK, 2009) is an iconic CLT structure from WaughThistleton architects and has been a real ice-breaker that inspired many design teams. CLT brought significant savings in the program: only 49 weeks instead of the 72 estimated for the equivalent concrete building. A mobile crane eliminated the need for a tower crane and scaffolding was needed only to fix the cladding. A five-man crew accomplished the entire superstructure erection in 27 working days. The architects recently wrote: "If built today, it could use 30% less timber due to modern analytical tools." Images: http://waughthistleton.com

3.1.2 Wood species and finishes

Engineered timber elements are typically produced out of softwood plantations or sustainably managed forests, a fully renewable resource grown around the world under various climates and soils conditions. Alternatively, they can be produced out of sustainably sourced hardwoods, capable of achieving smaller sectional depths for the same loading capacity and featuring a colour and texture specific to the species of timber. The results are different, although generally comparable when the standards for product testing and certification are. However, in certain cases it is quite difficult to compare and substitute one species with another.

Timber elements can be supplied at a range of visual grades, varying from industrial non-visual through to premium visual finish. In addition to this, some suppliers offer a rough brushed finish, which removes the soft fibres on the surface and provides an 'exposed grain' texture. As one may expect, higher standard finishes and increased levels of processing typically attract higher costs.

Beyond their natural finishes, all timber elements can be painted or stained as required, however, it is important to note that applied finishes may require maintenance in exterior uses and re-application at 2-10 year intervals. For further information refer to *WoodSolutions Technical Design Guide #13 Finishing timber externally* in conjunction with product-specific manufacturer documentation.

3.1.3 Cutting and Fabrication

Engineered timber elements are produced in a safe factory environment and can have penetrations and connections pre-cut by a Computer Numerical Control (CNC) machine to a tolerance of just +/-1 mm, allowing a perfect fit on site every time. Appendix 1 describes the guidelines for the quality of execution of timber structures that are typically used in Europe, based on established practises.

While CNC cutting is a highly beneficial aspect of off-site timber construction, CNC machine time is expensive and poorly nested or un-optimised designs with a lot of cutting may be quite costly. Basic design optimisation and simplification can typically make a significant difference.

An astute estimator will check the consistency of the cost rates with respect to the amount of fabrication and may choose to quantify the latter separately, so it can be double-checked and/or value managed by those using the results.

3.2 Connectors

A commonly overlooked area, the connectors involved in the delivery of a timber structure, can be substantial in cost. With a wide variety available, from screws to nails, bolts, steel or timber dowels and complex proprietary products, the choice of timber connectors can affect not only the cost, but also the speed at which a structure is installed and fixed, and the productivity on site.

This is also true for the bracketry associated with timber construction, as simple angle brackets may be much faster to install than hidden dowels or plates that have a different fire performance and appearance.

An experienced estimator will check the consistency of the cost rates with respect to the type and amount of fixing materials and may choose to quantify the latter separately.

3.3 Acoustic and Thermal Performances

Designed and built correctly, timber systems are capable of achieving high standards of acoustic and thermal performance in both wall and floor/roof sections. It is important to note that this outcome has not only been predicted by advanced modelling programs, but has also been proven in several laboratory and on-site acoustic tests in Australian projects (see *WoodSolutions Technical Design Guides #22, #23, #24 and #44)*.

To be successful, a project must address three main acoustic measures being: airborne noise (Rw), impact noise (Ln) and structure-borne or flanking noise. These measures can typically be addressed through two methods including: the addition of mass to a timber element to insulate against airborne noise; and the introduction of a resilient layer or structural separation to minimise the transfer of vibration.

For example, it is common for floors to feature an acoustic build-up on top of the load-bearing wood element, such as a resilient matting product under a dry mass (e.g. CFC sheet, aerated concrete, wet-area plasterboard or particleboard), or a screed (which has the disadvantage of introducing a wet trade). Projects complying with the Deemed-to-Satisfy requirements for mid-rise timber construction also require a lining of fire-rated plasterboard to the underside of the load-bearing wood elements, and this can aid in the addition of mass. See Section 3.4 for more information about the fire requirements of floors. For walls, the use of two wall panels separated by a 20 mm air gap has been proven to provide the highest standard of acoustic performance.

The issue of structural borne (or flanking) sound is common across all materials and methods of construction, however the highly dissipative and prefabricated nature of timber construction allows this to be addressed better than with stiffer, heavier materials. This measure can be easily accounted for by placing a resilient strip in loadbearing joints between panels, effectively minimising the transfer of vibration from one section to another. Figure 3.2 shows this strip, which can be pre-applied to the top or bottom edges of a wall panels before installation on site.

Similarly, thermal comfort and durability require a number of ancillary products (thermal insulation, vapour control membranes, sealing tapes and foams) that either directly or indirectly form a significant part of the take-off.

An experienced estimator will check the consistency of the cost rates with respect to the amount of materials used for the acoustic and thermal treatment of the structure and may choose to quantify separately the latter, so they can be double-checked and/or value managed by those using the results.

Figure 3.2: Example of acoustic strip in loadbearing connections and of resilient flooring batten

3.4 Fire Safety

The NCC has different requirements according to the Building Class and height, with two pathways for compliance: the application of specific Deemed-to-Satisfy (DtS) provisions or a Performance Solution (PS) through fire engineering.

To comply with the NCC's DtS requirements for mid-rise timber construction, a timber building over three storeys and under or equal to 25 metres in effective height (from the ground floor to the top walking surface) must meet four main criteria:

- All structural timber must be fully encapsulated by sufficient fire-protective linings to meet the required Fire Resistance Level (FRL).
- Sprinklers are required throughout the project.
- Any insulation used in a fire-protected cavity must be non-combustible.
- Cavity barriers must be installed in any vertical cavities between Sole Occupancy Units (SOU).

WoodSolutions Technical Design Guide #37 – Mid-rise Timber Buildings provides comprehensive guidance to the application of DtS provisions.

Where seeking compliance with the DtS provisions, all structural timber must be enclosed in a fire-rated lining so that it meets the prescribed FRL. The fire-protective linings typically required to achieve the FRL of 90/90/90 commonly found in Class 2 and 3 buildings are summarised in Table 3.2. While the DtS requirements require all vertical elements to be fully enclosed in fire-protective material, this requirement only extends to the underside of flooring elements. This means that while the suspended floors of a DtS compliant project must be protected from underneath, there is no requirement for treatment to the top of the floor panel.

Table 3.2: Indicative fire-protective linings required to achieve a 90/90/90 FRL. (This is project specific and may differ in your case. Always confirm the requirement for fire-rated linings with your consultants before allowing for it in your project).

Element	Material	Typical Lining
Wall/Column/Beam	Mass Timber	1 x 16 mm fire-rated plasterboard (or similar)
Floor	Mass Timber	1 x 16 mm fire-rated plasterboard (or similar) to underside only
Wall	Lightweight Frame	2 x 13 mm fire-rated plasterboard (or similar)
Floor	Lightweight Frame	2 x 16 mm fire-rated plasterboard (or similar) to underside only

While the DtS provisions require that all mid-rise timber projects are fitted with a sprinkler system, the 2019 update to the NCC extended this requirement to all building materials and classes for buildings of four storeys or more.

Any project either exceeding 25 metres in effective height or not complying with these criteria will need to follow a fire-engineered Performance Solution. This process can often result in a more optimised and efficient design and should be considered as a possibility at the outset of any project. Specific information, with an example relative to a mixed-use building, is provided in *WoodSolutions Technical Design Guide #17 – Alternative Solution Fire Compliance – Timber Structures* (being updated at the time of writing).

Finally, adequate fire safety is obtained when penetrations are treated as required to achieve adequate separation. A number of ancillary fire protection products, such as caulking and fire collars, are either directly or indirectly associated with a timber structure (as well as with other materials) and form an important part of the take-off.

An experienced estimator will check the consistency of the cost rates with respect to the amount of fire-rating materials and may choose to quantify separately the latter, so it can be double-checked and/or value managed by those using the results.

3.5 Preliminary Costs

The cost category of Preliminaries can often achieve some of the most significant savings across a project. Timber has several inherent properties that make it easier, faster and safer to build with, resulting in reduced time-related and other costs, as discussed here.

3.5.1 Time-related costs

Depending on a number of factors not limited to the design, the experience of the builder and the layout of the site, timber projects have been shown to reach practical completion up to 30% faster than the alternative in reinforced concrete. This observation has been reported and published for Projects 7, 9, 13, 14, 15, 16, and 18. This has also been the case in overseas markets familiar with timber construction.

While a significant portion of this total time saving can be attributed to early services rough-in (due to the absence of formwork or propping), the majority is achieved in the speed of structural assembly – commonly seen to reach completion in just half the time experienced with other materials. This speed and efficiency comes from the fact that Engineered Wood Products are lighter, easier and safer to handle and install than other components of equivalent size and performances.

This is significant when considering ongoing time-related costs such as:

- hiring times of the crane(s), sheds and other plant and equipment
- installation and maintenance of temporary services, facilitated by easier fixing, pre-drilled holes, and a reduced program overall
- wages of the workforce, which are reduced in both number and time on-site
- insurances premiums, which are related to the duration of the work and its risk (lower for wood products)
- permits and certifications, which often attract significant fees and are valid for a limited period of time.

The potentially reduced program offered by timber structures can also enable time critical projects to be realised. This can be a crucial consideration for many projects, including schools and student accommodation buildings, for which funding periods can be set and term dates and new intake levels fixed.

Figure 3.3: Lendlease designed and built the Forté Living apartments in Melbourne in 2012, as a first significant experience in the use of CLT for residential mid-rise construction. A crew of five completed the carpentry with a remote-controlled light crane in only 10 weeks, with minor disturbance to the neighbourhood. The high dimensional stability and low weight of the structure is a significant advantage during construction but also for the quality and durability of the finishes, which require a reduced level of maintenance compared with a building of comparable location, size and construction cost. Images: WoodSolutions and https://www.architectureanddesign.com.au

3.5.2 Other costs (not time-related)

The prefabricated, lightweight nature of timber elements allows for a number of efficiencies in any project. Beyond the duration of on-site works and its associated benefits, the nature of engineered timber components often allows significant economies in the type and/or size of the equipment involved in site management and logistics. Also, with much work completed off-site, the few on-site functions can become an 'assembly' operation, leading to:

- ***Fewer on-site staff***: With structural elements produced in an off-site location, timber projects require just 5-8 installers (plus the crane crew) on site to complete the structural stage of a project. This significant reduction in on-site staff attracts reduced trade costs in addition to the many benefits discussed further below.
- ***Reduced on-site infrastructure***: Timber projects typically see a dramatically reduced reliance on common site infrastructure such as scaffolding, formwork, pumps, and props – the installation of which adds not only cost, but also time to assemble and remove. This benefit was reported for all projects in our database.
- ***Less waste***: The off-site manufacture of timber components has been proven to result in up to 90% less waste during the structure stage, and reduced waste in the finishes stage after. A benefit of prefabrication, this may result in significantly reduced bin hire and tipping costs, as reported for projects 7, 9, 13, 14, 15 and 18 in our database.
- ***A smaller crane***: The low density of timber elements results in floor and wall panels that weigh just 20% of their alternative in pre-cast concrete. This characteristic means that, subject to site constraints, projects can be completed without the use of high-capacity tower cranes. Instead, it is common for timber projects to utilise mobile cranes, self-erecting cranes and, where site constraints render it necessary, small tower cranes. Builders may also consider other lifting methodologies such as 'spider' cranes, mobile gantry cranes or other means that solve project-specific problems and increase productivity, thanks to the reduced weight of components.
- ***Improved site safety***: Significant timber projects have demonstrated several safety benefits associated with timber construction, including an increased ratio of supervisors to workers, cleaner and tidier sites, reduced acute joint strain associated with hammer drilling, the ability to pre-fit edge protection before lifting floor panels (essentially eliminating live edges), the absence of welding operations, etc. A 'zero lost time injury' result was reported for projects 10, 11, 12, 13, 14, 15, 17, 24, 25 and 26 in our database.

- ***Fewer deliveries***: With a typical delivery truck holding between 15 and 30 panels or structural elements, timber projects can experience up to 80% fewer deliveries than those utilising reinforced concrete as the main structure. This not only reduces disruption to the surrounding community, but also reduces costs associated with traffic control and permits. While all projects in our database experienced this benefit to different magnitudes, a reduction of 80% was reported in projects 5, 7, 9, 13, 14, 15, 16, 24, 25 and 26.
- ***Cheaper follow-on trades***: Services and finishes are typically installed faster in a timber structure than in concrete or brick due to easier fixing with smaller and lighter battery-operated tools, thus improving both the safety and the productivity of the workers. This benefit was reported for almost every project in our database, and has been suggested to result in competitive pricing when an experienced trade is quoting for a timber-based project.

3.6 Project Program

Timber projects can be faster to build on site than the alternative in concrete. While time-savings can often be explained by the pre-determined installation sequences and pre-planning of other on-site processes, evidence suggests that this increased site productivity is a result of the workers feeling safer. Subject to a number of site-specific factors (e.g. site conditions, number and size of loading docks, number and type of crane) and design specific factors (e.g. whether the design features load bearing walls, post and flat plate slab, or a post and beam typology) it has been observed that a typical timber project can be assembled on site at a rate of approximately 80-100 m^2 per standard working day, or 400-500 m^2 per five day working week. This rate reflects the average installation rate of the projects in the database (with outliers removed).

For example, Project #1 in Tale 2.1, a six storey timber structure with a floor area of approximately 1000 m^2 per level took 12 weeks to achieve structural completion. While it has been observed that the first floor can be quite slow to install (due to the interface between the concrete slab and the millimetre perfect timber elements), full speed is quickly achieved in the following floors.

3.7 Labour

A benefit of the dry, prefabricated nature of timber construction, timber projects often require a structural installation crew of just 5-8 people plus the crane crew. Using only battery-powered impact drives this crew can install columns, beams, walls, and floor panels at the rates identified above. Of this crew, it is necessary that just 3-4 of the installers are qualified carpenters as many tasks associated with timber installation are simple and highly repetitive. Typical installation times for off-site prefabricated timber panels are 16-20 lifts per day, allowing 15 minutes per panel for fixing and taping.

Both installation of the prefabricated timber elements and subsequent works are easier, quieter and safer, reducing or completely avoiding wet trades and reducing the number of personnel required to erect the superstructure by around 50-70%. Typically the following approximate time savings were found for various follow-on trades in the projects listed in our database:

- services (MEP) – about 30-50% faster
- dry liners – about 20-30% faster
- window & door installers – about 20-30% faster
- insulation installers – about 20-30% faster
- cladding installers – about 20-30% faster.

3.8 Foundations/consolidations

The natural light weight of timber typically means that projects with an engineered timber structure are 30-50% lighter (completed project weight) than the same design in concrete. Depending on the soil conditions on site, this may result in significant reductions in the size and depth of the footings and/or the consolidation works of the existing structures, in case of a vertical extension.

In some cases, the feasibility of a development has become positive only thanks to the lower weight of the timber structures, which has allowed to build a significantly higher volume over an existing structure, with minor consolidation works and much less disturbance to the existing tenants.

Figure 3.4: The short delivery time requirement for the Aveo Norwest building, completed in Sydney in 2018, made it an ideal project for the CLT design by Jackson Teece (architects and interior designers) and TTW (engineers), which enabled Strongbuild to complete it 13 weeks earlier than with the concrete program. The AVEO Norwest building is in a way the first of its kind, breaking the mould of the typical mass timber designs for residential buildings we have seen internationally over the past decade. In order to conform to the client's brief for this particular project there could be no obvious compromise in apartment layouts or building design in favour of specific prefabrication or mass timber construction requirements. The planning and the design of the building, including the curved and seemingly cantilevered balconies, required an innovative hybrid construction approach utilising CLT slabs and walls, Glulam beams and structural steel. The design had to achieve a balance between the desired architectural design outcome and construction rationale and had to push the boundaries of what was then perceived as possible in mass timber design and construction technology. It was a client decision to prioritise a specific desired architectural expression, through a specific budget allowance. Images: Brett Boardman and Strongbuild.

4 Procurement, Purchasing and the Supply Chain

The procurement routes and processes associated with timber construction are already commonplace within the industry, however it is important to note that some methodologies are better suited to it than others. This section discusses the most effective procurement and purchasing approaches and provides a brief overview of the main supply chains – both local and international.

4.1 Contracting Approach

Modern construction projects follow a wide variety of contracting approaches based on the project type, experience of the client and other factors. While all approaches can be suitable for timber projects, it is important to understand the potential benefits and drawbacks of each to ensure that the selected path is the right one. This guide discusses three commonly used approaches: traditional lump sum, early contractor involvement, and design and construct contracts. While they aren't discussed here, other forms of contract (e.g. construction management) can also be successful with timber projects.

4.1.1 Traditional Contracts

Traditional or lump sum contracts are common throughout the industry for projects of all sizes. Perhaps the simplest form of all contracting models, this approach sees the rigid separation of design and construction. In this process, the client appoints a team of consultants who complete the design of the project, generating all construction drawings, details, specifications, and often a Bill of Quantities. With this complete, the head contractor is selected through competitive tender and project is constructed based off the tender drawings.

This fragmented approach is well understood but is becoming less popular on large-scale and complex projects for a number of reasons ranging from the extended time frames to the reduced cost-efficiency compared to other types.

Timber construction can be paired with this contracting approach; however this is most successful where the design team is experienced with timber or works closely with a preferred supplier throughout the design phase as an inexperienced design team is likely to deliver a poorly optimised design. Once they are engaged, it is sometimes possible for the contractors to procure the timber structure while earthworks/basement works are underway, with the first timber elements typically available on site 'just-in-time' for their install.

4.1.2 Design and Construct Contracts

Perhaps the most popular form of construction contract, design and construct (D&C) contracts see the client engage a design team to complete 50-80% of the design at which point the responsibility for the design and construction of the project is transferred to a selected contractor. As part of this process it is common for the design team to be novated across to the contractor.

With the contractor in control of both the completion of the design and the construction of the project they are able to optimise the project for buildability and efficiency, ultimately delivering the same quality of project in a shorter duration, and often at a lower price.

This contracting approach is well suited to engineered timber construction as it allows for the engagement of a timber supplier before the design is complete, offering some potential to optimise the design for further efficiencies. Examples of this basic level of optimisation may include the selection of the most suitable mix of Engineered Wood Products and systems, varying the size and strength of selected elements, and the detailing of simple connections to improve on site productivity.

4.1.3 Early Contractor Involvement

While not a contracting approach per se, Early Contractor Involvement (ECI) can prove to be highly beneficial in large or complex timber projects. The first stage in what is typically a two-stage process, ECI sees the head contractor involved in the early design of the project. This input allows the contractor to offer design optimisation advice from the very start, ensuring the project is as efficient as possible. This input may involve the discussion of structural systems, spans, exposed finishes and much more. Perhaps the most valuable opportunity offered by the first stage of the ECI is to have a supplier involved from the start of the project. This allows for the design to be completed with the sizing, grading, pricing, and any limitations of the supplier in mind, generating a better outcome for all stakeholders.

With the ECI complete, the project can then proceed to the second stage and the appointment of the main works contractor. This process can either take place through competitive tender, however it is also common for this contract to be negotiated with the contractor in charge of the ECI.

4.2 Supplier Services

While the majority of suppliers specialise in the manufacture and delivery of a specific product, many are willing to add value where possible, often providing design support services or sourcing and even installing other complementary products. For example, the supplier may develop specific and optimised structural engineering calculations, shop drawings, provide all the accessory materials under one contract to optimise procurement and logistics, and may even be able to pre-install non-timber elements such as vapour membranes, windows, doors and so on. The addition of these services in a safe, clean, well-lit factory environment will often prove to be highly beneficial, minimising work on site, improving the standard of finish, reducing the number of contracts entered into, and ultimately reducing risk.

Regardless of the contract or procurement model, it is advisable for the client and design team to engage with potential suppliers of the timber superstructure at the earliest possible date. This will allow for valuable technical input to be offered at a time when it is easiest to implement. This early communication will also allow the supplier to ensure that they hold enough stock or product to supply the project, ensuring a positive experience for all.

4.3 The Supply Chain

The global supply chain for timber elements and connectors is well established and continues to grow at a significant rate. With almost all Engineered Wood Products sourced from the ever increasing area of sustainably farmed plantations, the international supply chain has enough fast-growing fibre to sustain the growth of the timber into the coming decades. This section discusses the state of the timber supply chain in Australia and overseas.

4.3.1 Australia

The Australian supply chain is well established, with plantations, mills, distributors and fabricators. Several of these businesses have been operating for more than 100 years, showing both environmental and financial sustainability. This mature supply chain is well placed to service both the traditional detached house market and the growing market of mid-rise stud frame structures, and has recently seen the emergence of several suppliers with the infrastructure to pre-install membranes, linings, floor coverings, windows and doors, thus delivering components enabling the builders to quickly achieve airtight building envelopes.

The Australian supply chain is also quickly growing to meet the needs of designs requiring mass timber construction. With established Glulam producers recently upgrading their facilities, mature LVL manufacturers gearing their product to the mid-rise market, and CLT manufacturers and fabricators already supplying significant projects, the Australian mass timber production capacity is growing quickly.

Purchasing from local suppliers has multiple benefits, ranging from the ease of inspection and Quality Assurance, to flexibility in design, to supporting the local economy and jobs in rural areas.

Australian produced Engineered Wood Products are commonly available in both softwoods and hardwoods. At the time of writing, the most common softwood used is *Pinus Radiata*, a fast-growing pine with a pale yellow tone. Engineered Timber suppliers specialising in hardwoods generally work with their closest resource but can also produce custom elements in a variety of timber species.

4.3.2 Overseas

It is now common practice for head contractors to consider suppliers established and producing in other countries for a variety of elements in a construction project (e.g. glazing, finishes). This approach is well known to any procurement manager, who consider financial costs, exchange rates, differences in legal terms, etc, however special consideration should be given when dealing with Wood Products:

- Always check the product’s performance specifications, sizes and dimensional tolerances, certification and testing documents, appearance, packaging, custom rules, etc, against the project specification (or the consultant’s brief) as it may be necessary to make different criteria compatible. Although there is a well-established set of trade and technical relationships (e.g. with New Zealand, North America and Europe) that make products compatible, sometimes little details may differ and the approval process may then become time consuming.
- If not buying from a local distributor, preferably adopt a ‘pull’ approach in logistics with the freight forwarder located in Australia, as they are experienced in importing products through local ports and customs. Buying ‘ex-works’ is sometimes attractive but the amount of associated work may result in unexpected difficulties and delays.

- Always remember that transporting a timber-based product on a ship exposes it to changing climatic conditions. Although there are plenty of positive experiences, the adequate protection and the prevention of unexpected movements is quite important to avoid defects in terms of dimensional stability and surface appearance. Typically, qualified overseas suppliers have suggestions that come from experience.
- Element sizing may be limited by the size of the transport vessel. While open top and special size containers and racks are available, the benefit of being able to transport larger elements does not always out-weight the cost premium associated with the specialised containers.
- Allow for a storage facility and labour to unload the containers, check the materials and let them reach the equilibrium moisture content with the local climate, before installing them.
- Fumigation may be required for all imports from certain regions at specific times of year. Confirm requirements with your supplier and local customs as early as possible, as the fumigation process must be allowed for in both program and cost estimates. This is now a routine operation and can be completed cost efficiently, but still must be considered.
- Loading containers takes time and wood elements have to be adequately protected and strapped to minimise damage during shipping.With all the right conditions in place, procurement times of 1-2 months from New Zealand or 2-3 months from Europe and North America are typical, including shop drawings, manufacturing and shipping.

Figure 4.1: The Green (Melbourne, 2014) is a 5-storey development designed by SJB Architects (planning) and Point Architects (documentation), scaling up the traditional stud frame design and adapting it to a new set of requirements. This 57-apartment project was approved with a Performance Solution and set an example for the Deemed-To-Satisfy rules that were approved in May 2016 in the National Construction Code. Developed and built by Australand, the project reported an overall 25% cost saving with respect to the alternative concrete-based program. The advantages of timber construction in this project, according to Irwin Consult (engineers) were: 1) lighter overall building loads on columns, foundations and ground floor transfer beams; 2) reduced building mass and stiffness resulting in lower lateral design earthquake loads in comparison to concrete buildings; 3) prefabrication of walls and floor elements to achieve a construction program equal to that of equivalent concrete buildings; and 4) use of a labour force experienced with this type of construction using materials that are commonly available and economical. Images: https://citta.com.au and WoodSolutions.

5 Risk Management

Risk management is an important facet of any construction project. The correct identification, assessment, contingency and control of project risks is key to ensuring the success of projects. While many risks are common across all building materials and systems, this section identifies where timber may be different and what the cost engineer or contractor should be aware of when assessing a project.

The risks associated with timber construction are generally similar to those encountered when purchasing prefabricated elements, such as glazed curtain wall units. First and foremost, it is important that design resolution and clash detection are completed before shop drawings and production. While minor on-site adjustments are very simple and easy to carry out with timber-based products, last minute, large-scale changes can be costly and inefficient.

5.1 Quality Risk

As with any product or material, it is important for the contractor to ensure that all elements produced are compliant with the specified design. Appendix 1 provides extended and more specific guidelines on how this should be planned and implemented.

Quality Assurance is a simple task with Engineered Wood Production and fabrication because these are normally highly automated processes in which all materials are tested, recorded and tracked throughout the production line.

Engineered Timber producers are required by the relevant Certification Body to engage in surveyed testing and quality assurance procedures to confirm the full compliance with the design requirements. This starts with strength grading of every single element and proceeds with controls on the bonding process, the dimensional tolerances and every other performance-related parameter. A copy of the track records of the activities and checks performed on a batch ready for delivery (or a summary document) can be requested from the supplier.

Tags, marks or other means of identification will assure the traceability of every element for QA and/or chain-of-custody purposes.

It is interesting to note that the Eurocodes associate a lower safety factor (meaning the materials are considered as having lower risks) to Engineered Wood Products than to other structural products, because:

- Every single element that goes into the building is strength graded with non-destructive and calibrated tools (not just a sample extracted from the batch and therefore not going to be installed, while the rest is considered equivalent).
- The sizes and the equations used in both the design checks and the laboratory tests are exactly the same.

5.1.1 Dimensions

Structural elements can be machined to their exact final dimensions using a CNC machine. At this stage, the CNC machine can also cut any penetrations, route channels for cables, and complete any other cutting to meet the design. The modern CNC machines run by timber element fabricators cut to within +/-1 mm tolerance, and so the accuracy of the element sizing and cuts is governed by the quality of the shop drawings. While timber suppliers have quality control procedures in place to ensure that their drawings accurately reflect the design they received, it is important that the contractor confirms this and regularly cross-checks their output.

5.1.2 Construction site

While timber projects typically have reduced exposure to the on-site risks commonly associated with construction, there are a number of risks that may have a greater impact for timber projects than others. With the fabrication of structural elements occurring in an off-site facility, on site activities centre around the assembly of the structure and the rate at which this can occur.

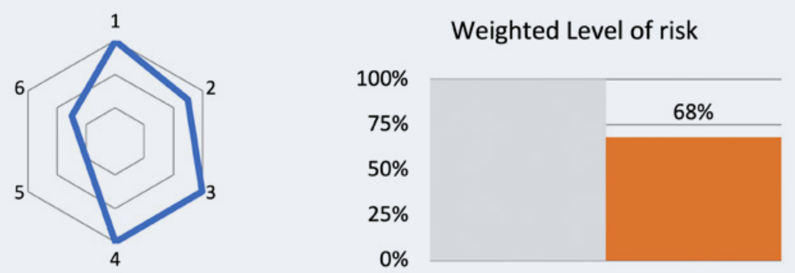
Analysis of the projects within our database shows that the most significant factors potentially affecting this key metric can be condensed into three categories: design (D), on-site access and activities (O), and environmental (E) factors. These categories each comprise several weighted parameters, for instance those identified in Table 5.1, which can each be scored in line with the notes in the 'guide' column to achieve an overall risk rating. Parameters and scores can be displayed and analysed with various stakeholders, for instance as shown in Figure 5.1.

Table 5.1: Example of risk parameters contributing to overall project installation rate

Code	Parameter	Weighting	Guide
D1	Gross Installation Area	0.3	Smaller means lower risk
D2	Number of Storeys	0.9	Less means lower risk
D3	Timber Volume (m^3)	0.8	Less means lower risk
D4	Steel Share Factor (kg steel/m^2 timber)	0.6	Less means lower risk
D5	Percentage of Visual Timber (%)	0.8	Less means lower risk
D6	Building Shape Complexity	0.85	Simpler is better
O1	Ease of Site Access	0.85	Larger entries are better
O2	Delivery Route	0.55	Less traffic is better
O3	Site Location	0.6	Less built up is better
O4	Trucks per Week	0.9	More is better
O5	Scaffolding and Building Access	0.7	Easier access is better
O6	Cranes	0.9	Less reliance is better
O7	Lay down area ratio (m^2 timber/m^2 lay down area)	0.7	Lower ratio is better
E1	Installation Season	0.5	Fewer rain days is better
E2	Geographical Location (Wind)	0.85	Less wind is better
E3	Wind Speed (m/s)	0.85	Lower speeds are better
E4	Protected Areas	0.2	More protected is better
E5	Flood Zone	0.1	Less flood zone is better

Figure 5.1: Example of risk assessment matrixes and graphs (http://www.eurban.co.uk/).

Building Risk Parameters							
	1	2	3	4	5	6	
	GIA (m2)	No. of Storeys	Timber Volume (m^3)	Steel Share Factor (kg/m^2)	Percentage of Visual Timber (%)	Building Shape Complexity	Weighted Building Risk
Weight	0.3	0.9	0.8	0.6	0.8	0.85	
Level of Risk	5	4	5	5	1	2	69%



5.1.3 Finishes

The client should seek and approve a physical sample of the desired finish before entering into a supply agreement, as finish grades may vary. Where a 'Visual Grade' finish has been specified, it is best practice to ensure that the face to be exposed is properly protected with an anti-mould and UV-resistant product until it has been installed and protected from UV exposure (e.g. the building envelope has been completed). Adequate detailing can be beneficial where visual grade surfaces interface with non-galvanised steelwork, as rust will stain the timber face in the event of rain.

On unprotected wood surfaces, a moisture content level that exceeds 15-16% for a significant period may start the appearance of blue stains from mould, which is significantly different from rot (no structural damage) and may have the following origin:

- surface moisture from high humidity in the air (windows open in foggy or rainy days, water spilled on the floor)
- excess of a waterborne surface finish, which has no anti-mould
- micro-particles from welding, sawing metal or plasterboard that could have happened close to the wood element.

The suppliers of coating systems will provide specific indications. As a general recommendation, it is advisable to:

- select a finish that has an anti-mould in it
- apply one coat of it either before shipping panels/beams from the factory or when individually de-stacking them from the truck or container on site (this will also protect the visual grade surfaces from dust and foggy days)
- apply a second coat after installation.

5.1.4 Weather exposure

While it is not a problem for non-visual grade elements to be exposed to the weather for short periods, it is important to prevent pooling of water for extended durations. It is best practice to protect the end grain of structural elements from water wherever possible, however if the timber structure is exposed to rain, it must be allowed to reach a moisture content of lower than 16-18% before encapsulating linings are installed. Slightly higher, localised moisture content levels are possible when breathable linings are used and adequate drying is foreseen over a short time. Measurements with a calibrated hygrometer are easy to perform and assure there is no risk of excess moisture being held behind the finishes.

Although protection methods will largely vary with location, period of installation and design, a typical mid-rise timber project in Australia would require the following actions, not significantly different from those considered when installing tilt-up concrete components:

- maintaining panelised elements dry as long as possible during transport and site storage
- taping of floor-wall joints as early as possible
- protection of the top edge of the walls with sarking
- use of vertical risers to promptly evacuate rainwater
- closing the window and similar openings as early as possible, eventually using temporary sarking
- use of tarpaulins on floor and roof elements during prolonged rainy periods or construction stops.

Appendix 1 provides extended and more specific guidelines on how to deal with temporary exposure to rainy weather during the construction period.

5.2 Logistical Risk

The selected supply route may affect the logistical risk associated with a project because international freight attracts a higher risk than road transport. Beyond this, other factors that may affect the success of the project include the following.

5.2.1 Supplier capacity

Regardless of the location of the supplier, it is important to confirm their capacity to produce, process, pack and deliver when required by the project's program. This is significant, as 'all up' deliveries, where all panels are sent in just a few batches will likely incur significant storage and sorting costs while waiting for installation on site. With this in mind, it is best practice to follow the 'just-in-time' philosophy, with each delivery of elements arriving on site when it is needed, with the right moisture content.

5.2.2 Packing order

The packing order of timber elements may influence on site productivity significantly, especially if elements are packed in a container (although this is also relevant for truck deliveries). Best practice is to ensure that when the elements are packed for the delivery on site, this is completed in the reverse order of installation, eliminating double handling and maximising productivity.

5.3 Financial Risk

When the level of off-site manufacturing increases, suppliers may require a substantial deposit well in advance of delivery. This should be evaluated and balanced with respect to the time saving in final delivery that, in most cases, mitigates the financial risk.

Where sourcing product from overseas, consider the stability of exchange rates and how their fluctuation may affect the supply contract.

Consider the required payment timeframes and the point at which the ownership (and therefore responsibility) of the goods transfers to the purchasing party.

5.4 Certification and Approval

Independent testing and/or certification often forms an important activity before materials are shipped or delivered them to the construction site. Their duration is not always predictable and may be considered within the risk analysis.

An efficient approach to reducing the risk is getting the certifier involved as early as possible and compiling a set of documents and drawings/information models that are consistent with the complexity of the project, in order to:

- define a set of technical requirements for the execution of a timber structure
- ensure that the designer gives the contractor all the relevant technical information for the execution of the structure, and that they are transferred to the contractor
- specify conditions to be fulfilled before the works begins
- list controls suggested at delivery, during and at the end of the execution, to assure that the specified quality is achieved.

A guideline for such an 'execution specification' is available in Appendix 1.

5.5 Delays and Variations

Building construction projects are often carefully planned. Despite this, some projects are completed late and/or generate unforeseen variations claims. If delays are compared to budget over-runs, the former play a much greater role in affecting the profitability of a construction project. A commercial construction project that overruns its budget by 50% but is finished in time earns only 4% less than the one that keeps both schedule and budget. In contrast, if a construction project stays in budget but exceeds its schedule by half a year, its earnings may drop as much as 33% [1]. Furthermore, time performance has been identified as the most important criteria for defining whether a construction project has been successful or not, surpassing both cost and quality performance [2].

Variations in timber construction are much like those in any other form of building. As experienced on most projects, decisions made at an early stage have the highest impact for the lowest cost; conversely later decisions attract a higher cost for a reduced impact.

While this theory holds true, some structural typologies can be seen to be more flexible than others. For example, post and beam or post and slab designs typically deliver large open spaces within which non-loadbearing partition walls can be altered as required with minimal concern of compromising the structure. In comparison, the honeycomb structure of projects utilising loadbearing wall panels (common in hotels, student accommodation and some multi residential buildings) can often be altered once built, however this can be a more complex process and require approval from the project's structural engineer prior to execution.

As wood-based projects require design to be largely resolved before the elements can be produced, projects often experience fewer variations than is common with other materials that have larger tolerances and require more site work.

Finally, in general terms, significant advantages can be found in a fast and predictable building process, like the one which arises from a well-planned and detailed design, where the accuracy of Engineered Wood Products can play a major role.

[1] O. Port, Z. Schiller, R. King, D. Woodruff, S. Phillips and J. Carey, A smarter way to manufacture, Business Week, no. 30, pp. 110-115, 1990.

[2] S. Khosravi and H. Afshari, A success measurement model for construction projects, in International Conference on Financial Management and Economics, Singapore, 2011.

6 Design Optimisation

A well-optimised project utilises the best material or system needed to deliver the level of performance required for a reduced price. This concept is common across all building materials and systems and, where applied correctly, can deliver high-performing, high-quality and cost-effective projects. This section details some common methods of design optimisation in timber structures followed by a case study in which several of these are applied.

The risks associated with timber construction are generally similar to those encountered when purchasing prefabricated elements, such as glazed curtain wall units. First and foremost, it is important that design resolution and clash detection are completed before shop drawings and production. While minor on-site adjustments are very simple and easy to carry out with timber-based products, last minute, large-scale changes can be costly and inefficient.

6.1 Structural Design Optimisation

6.1.1 Material and system

The first consideration when looking to optimise a timber project should always be the composition of the structure. While designers often may like to specify the same material for all the elements in timber construction, this isn't always the optimised solution. For example, a five-storey apartment block with few spans over 5 m is likely to be well suited to a lightweight frame solution (stud frames), with mass timber elements utilised where needed (e.g. in the core, some floors and potentially some structural walls at lower levels). An office building requiring large open floor spaces may be best suited to a Glulam or LVL column and beam structure, with CLT or LVL suspended floor plates. An optimised design typically uses a range of Engineered Wood Products, all to their specific best use.

The choice of the structural material and system is governed by a number of factors not limited to building use, required spans and the vertical load path through the building. Indeed, a well-optimised project may utilise a combination of materials and systems. Regardless of their form, all timber systems behave in a similar fashion under varying environmental conditions and therefore are simple to design, install and maintain together. This has been demonstrated around the world in projects that utilise mass timber elements (both panels, beams, and columns) in areas of significant loading, and lightweight wall and floor elements where lower loads are encountered.

The prefabricated nature and 'just-in-time' delivery of timber elements facilitates the installation. With all timber elements produced and machined off-site and delivered to the site in the order of their installation, concerns over the coordination of element install are effectively mitigated. This is particularly relevant where section sizing decreases or structural material changes (e.g. from mass timber panels to lightweight panels) as the building ascends, as all previous elements with a different size have already been installed.

Last but not least, Engineered Wood Products may be combined with other products within an optimised hybrid structure.

6.1.2 Load path and transfer

An optimised timber project should require minimal load transfer in the timber structure, with all vertical loadbearing elements 'stacked'. Where loadbearing wall panels or columns are required over a large span area (e.g. a loadbearing wall in the apartment above with a living room in the apartment below) this can typically be accounted for with the use of a high strength Glulam or LVL beam, however this may affect the ceiling height in this specific area.

Where timber structures are over a carpark, retail space or a building use requiring a specific grid, it is common for this load transfer to take place via a concrete slab. In practice, this has led to having the structure up to the most significant load transfer completed in concrete, with the timber structure above. This is common in multi-residential developments that feature retail and hospitality tenancies at the ground level, with the concrete transfer slab providing structural transfer, as well as fire and acoustic separation.

6.2 Fire Engineering

While the NCC provides a Deemed-to-Satisfy (DtS) solution for timber construction to an effective height of 25 metres, a DtS compliant design may not be the most cost-efficient design. Depending on a building's usage and risk profile, involvement of a fire engineer and the adoption of a performance solution can often result in simplified construction processes, and ultimately reduced costs.

Deemed-to-Satisfy requirements must allow for all buildings in all circumstances, and therefore consider the fire protection required for a 'worst case scenario' project. In contrast to this, a performance solution is able to consider a project in its own specific context and assess the real risk posed to its users.

Unlike a DtS solution, the fire engineering process considers the charring rate of timber – a natural and well-understood phenomenon where the surface of a timber element exposed to fire will char, ultimately insulating the structural core of the element for a period of time. Consideration of this factor in fire modelling has been seen to result in reductions to the number of layers, or extent of fire protective linings called for in mass timber projects. It is common for the savings made possible by this process to significantly outweigh the extra cost associated with engaging a fire engineer.

6.3 Acoustics

As discussed earlier in this guide, timber elements which separate residential units often require acoustic treatment to deliver high standard internal environments. This field is often over-complicated and can ultimately be simplified to two main requirements: (1) the addition of mass to a timber element to insulate against airborne noise, and (2) the introduction of a resilient layer or structural separation to minimise the transfer of vibration. With these principles in mind, this section will discuss floor and wall elements separately.

Acoustic modelling and testing can provide an effective opportunity for design optimisation or value management, limiting overdesign and time-consuming construction practices by, for example, using dry trades only and materials that can be immediately walked on by different trades.

6.3.1 Floor elements

The NCC 2016 requires that floor elements between Sole Occupancy Units (Class 2 and 3 buildings) achieve a minimum acoustic rating of 50 for airborne noise (R_w+C_{tr}), and a maximum rating of 62 for impact noise (L_{nw}). There is no minimum requirement for separation between commercial spaces (Class 5).

This requirement is easy to achieve where a suspended ceiling is utilised in the design, as a gap equal to or exceeding 100 mm and a resilient mounted suspended ceiling has been shown to greatly improve acoustic properties of a floor element. Where this is the case, a simple above floor build up including a resilient acoustic matting product topped with 30-40 mm of high-density material (e.g. a wet concrete screed, 2 x 15 mm compressed fibre cement boards, magnesium oxide board, particleboard, etc) has been shown to deliver a compliant system.

Where the design intends to expose the underside of a timber panel, the mass and resilience that would otherwise be on the underside of the element must be added to the top build up. In this circumstance, it is effective to specify a resilient batten (Figure 3.1) to maximise acoustic performance.

6.3.2 Wall elements

The NCC requires that wall elements between Sole Occupancy Units achieve a minimum acoustic rating of 50 for airborne noise (R_w+C_{tr}), with no requirement for impact rating (Class 2 and 3). Again, there is no minimum requirement for acoustic separation between commercial spaces (Class 5).

Similar to floor elements, the acoustic properties of timber walls are determined by both the mass of linings and the level of separation or discontinuity between the wall faces. The optimal wall design is commonly seen in timber frame, and comprises two wall frames aligned to parallel and separated by 20 mm. These frames are lined with a dense fire-protective lining on the external faces only, and offer complete discontinuity between faces (and therefore very good acoustic properties). This wall type can also be achieved with massive timber panels or a combination of both lightweight and mass timber.

While discontinuous walls deliver the highest standard of acoustics, a close second can be seen in staggered stud walls. Staggered stud walls achieve a moderate level of discontinuity within a single wall panel, resulting in a faster install than experienced with discontinuous walls. This wall type is not suitable for all sections of a party wall (the NCC requires complete discontinuity in some areas between Sole Occupancy Units), but its proper specification and use can result in savings to both program and cost.

6.4 Finishes

Ever popular within the design community, exposed structural timber elements are indeed beautiful. While many look to expose as much of the structure as possible, it is important to consider the costs that this may add to the project, and potentially look to alternatives to achieve a similar finish.

Visual grade timber elements require higher levels of processing, and therefore attract a higher cost out of the factory. The exposed faces may also require special protection in transport and installation, adding to the total building cost, and attract additional maintenance costs.

While not always practicable, structural elements with visual grade finishes can be substituted with an 'industrial grade' structural component to which a non-structural 'visual grade' element like plywood or a solid wood panel is attached during the finishes stage of construction.

6.5 Design for Assembly

It is important to consider the buildability of a structure and whether the construction sequence can be simplified to improve on-site processes and productivity. For example, while a loadbearing wall 'honeycomb' structure may seem logical for a short span project, this may experience a slower install rate than if a short span post and slab design were utilised. Typically, early contractor Involvement is used to collaboratively define the best option.

Where large lay down areas are available, both the designer and construction team should consider the opportunity to pre-assemble certain groups of elements at ground level before they are lifted and secured into their final position. This on-site prefabrication process is well suited to complex, repetitive, or 'box' sections such as bracing or core elements, and has proven to significantly reduce the total number of crane lifts in a project, resulting a reduced build time over all.

Figure 6.2 - Blackdale Residences (Norwich, UK, 2016) designed by LSI Architects and Ramboll (engineers) for the University of West Anglia, comprises 514 apartments built to BREEAM Excellent standards. With a tight build program, offsite construction techniques ensured on-time delivery and high quality, also through BIM level 2 with full 6D asset information incorporating time, cost, virtual modelling and all aspects of life-cycle facility management. The Senior Project Manager described it as his 'best project ever'. Images: https://ramboll.com and https://b4ed.com

7 Feasibility

While the feasibility process for a timber project is similar to that for a traditionally built structure, there are some key contrasts that must be considered. Differences between these systems range from familiar factors of prefabrication such as varied payment structures, to potential benefits such as increased Gross Floor Area and the 'unlocking' of previously unviable sites.

7.1 Payment Structures

Modern timber construction involves the on-site assembly of engineered timber elements that have been produced and fabricated off site. This process sees much of the work typically performed on site moved to safe, well lit, well supervised, indoor locations, and so much of the expense is incurred off site. Depending on the scope of their contract, Engineered Wood Product suppliers and fabricators typically request 50-100% payment before elements are installed on site. While no different to the delivery of a unitised curtain wall from overseas, this is an expense that must be expected early in a project.

7.2 Reduced Interest Expenditure

As identified in this guide, projects featuring timber structural elements typically experience a reduced on-site program. This expedited process has many benefits, including the significant amount of cost savings afforded by the reduced number of interest payments required before settlement. Timber projects can vary in productivity depending on the complexity of the design, however it is common in Europe and North America for timber projects to proceed up to 30% faster than an alternative in concrete. These savings will increasingly be seen also in Australia, as the use of Engineered Wood Products matures in the market.

7.3 Payback Periods

The payback period associated with a major construction project is determined by many factors, including the site, the size and type of building, the condition of the market, and the standard of finish achieved by the building. While highly finished timber buildings may attract a similar if not slightly higher cost than the alternative in traditional systems, the many benefits of timber workplaces have seen higher rentals than would have otherwise been the case.

Conversely, compliant standard timber buildings can be cheaper to build than the concrete or steel alternative of the same standard while achieving a similar rental income. Ultimately, payback periods associated with a timber building can be slightly shorter than experienced in the traditionally built alternative, however this can vary depending on the factors identified above.

7.4 Opportunities

The use of Engineered Wood Products can have a significant impact on the overall success of a project, when there is an early and shared understanding and what it may enable the developer, designer, builder, agent and, ultimately, the owner to do. The following is a non-exhaustive list of considerations and suggestions from those who have experienced it first hand and contributed to our Database of successful projects.

7.4.1 Optimised design

When considering the use of Engineered Wood Products as the primary structural frame, the architect and structural engineer need to carefully evaluate the product capability, referring to their consultants, suppliers and advisers as required. A lot of information is usually available from the product manufacturers. For an experienced designer, one of the major strengths of timber structures is the possibility to combine the solution to the structural, fire, thermal, acoustic and aesthetic requirements within a single material or assembly.

A pure conversion of a concrete frame to a timber frame, without any variation of geometries and depths is normally possible, but it will often prove to be inefficient. Therefore, specific tools for optimising the design are freely available, including WoodSolutions Technical Design Guides (notably Guide #46 – Timber Construction Systems) and commercially available structural design software.

Aiming for a repetition of vertical penetrations in the walls will optimise the flow of the service installations and reduce material off-cuts, with significant time and cost benefits.

Adopting clear spans that do not exceed the material's optimum capabilities (9 m for commercial buildings and 6 m for multi-residential buildings) will result in a design which is not only optimised for structural performances, but also from the point of view of supply and logistics.

Using the highest possible number of timber panels as load-bearing walls will reduce the need for long spanning joists or primary beams (however this may affect installation times).

Deviation from the line loading of the walls floor to floor should be avoided, as any off-sets or eccentricity of the line loads will require thicker wall panels and/or stiffening in the floor in localised areas, thus creating inefficiency in both frame design, the procurement and the installation.

Stacking wet areas, among many other advantages, offers the opportunity to use them as additional cores, when their walls are load-bearing timber panels that can be easily connected to each other, rather than being dead load over the floors. Also, a reduced floor depth is possible in this case, with the additional benefits of easily achieving a set-down in the wet area and a reduction in the materials needed because of a reduced span.

These and other opportunities are most likely to arise when a project proceeds with a timber structure in mind from the early draft design. Experienced architects and engineers typically report significant savings from their growing skills and the evolution of a dynamic sector.

7.4.2 New sites

As a raw material, timber is considerably lighter than both steel and concrete, typically 20% of the weight for equivalent structural components. Once completed with all fire rating, acoustic build ups, services, finishes, furniture, and all other components required to deliver them, timber buildings are still significantly lighter than their concrete counterparts, with a rule of thumb suggesting the completed timber building will weigh 40-50% less than the equivalent concrete alternative.

This is significant in that is opens up new possibilities. The light weight of timber structures means that they can be built in locations previously deemed unviable with traditional systems. Whether above an existing building, on poor or contaminated soil, or over a subway tunnel, timber projects pose the answer to many difficult sites.

Figure 7.1: A 10-storey vertical extension to an existing six-storey office, this Melbourne hotel designed by BatesSmart for Hume Partners Property would not have been possible without timber. With the existing office building only capable of accommodating an extra six storeys in concrete, the project team turned to a CLT and Glulam solution, finding the lighter weight system allowed an extra four storeys for a total height of 16 storeys. Images: http://atelierprojects.com.au/

7.4.3 Increased net saleable area

An outcome of the highly efficient and high-performing 'honeycomb' structural typology, projects featuring load bearing wall elements have been observed to achieve a higher floor plate efficiency than their traditional alternatives. With floors spanning 4-7 m and floor-to-floor heights rarely exceeding 3.1 m, multi-residential, student accommodation, and hotel projects are perfectly suited to the 'honeycomb' structure of panelised timber construction.

Panelised timber construction utilises wall panels as load-bearing elements, eliminating the need for columns. In a well-optimised design, party walls – being either discontinuous or staggered stud walls – are utilised as load bearing. These wall types are structurally efficient, and are often at least 40 mm thinner than the non-load-bearing alternative utilised in traditional projects (these are often up to 300 mm thick to allow for columns), with the same or superior acoustic and fire performance.

While 40 mm doesn't sound much, when multiplied by the hundreds of metres of party wall typically found in a multi-residential, student accommodation or hotel project, this can total tens of square metres, and potentially hundreds of thousands of dollars of extra revenue.

Figure 7.2: Dalston Works by Waugh Thistleton Architects (London, UK, 2017) is a landmark project in the use of timber construction in high-density urban housing. The 10-storey, 121-unit development is made entirely of CLT, weighing a fifth of a concrete building of this size, and reducing the number of deliveries during construction by 80%. Due to its reduced weight, the building is taller than was ever thought feasible using the same sub-structure on the site, the difference being very significant: 35 additional flats were made possible by using wood structures. Images: http://waughthistleton.com

7.4.4 Rental yields

Timber projects featuring exposed structural elements have been seen to achieve higher rental yields than traditionally built structures. While there are many potential reasons for this, tenants have been attracted by several proven benefits of exposed timber in office environments (see 8.6 Biophilic design), as well as the branding opportunity as an organisation that cares about the environment.

7.4.5 Goodwill and branding

Timber projects are widely identified as having a smaller impact on the environment than those using steel or reinforced concrete. With certified Engineered Wood Products manufactured from sustainably farmed, highly efficient plantations grown specifically for harvesting, timber construction can be confidently labelled as a sustainable practice.

Not only does the production of timber elements require significantly less power generation than other materials (and most of what is needed is provided by the sun), but trees absorb carbon dioxide, locking it up in the timber itself. This means that timber elements ultimately remove more CO_2 from the environment than their fabrication produces, making it the only truly green and sustainable construction material. This title is not lost on the informed public, and through popular media outlets has seen timber buildings earn a reputation as being beneficial for the environment.

Organisations seeking to differentiate themselves and transparently demonstrate their investment in the environment have been some of the first to both develop, and move into significant timber structures, and this trend is expected to continue for the foreseeable future.

More information about how to integrate sustainability features into costing and feasibility is presented in Chapter 8.

8 Life Cycle Costing

Timber projects can be simple and potentially cost effective to build but how much maintenance do they require and how do they perform in operation? And, can the carbon sequestration benefit be quantified and costed?

While there are still relatively few local examples to answer these questions, this section draws on the available local data as well as relevant evidence from international projects to do so. The list of international projects is significant and every-growing, with Engineered Wood Products established in markets around the world. This popularity is documented well in Waugh Thistleton Architects' 100 UK CLT Projects – showcasing 100 significant buildings in the United Kingdom alone.

8.1 Operation

Engineered timber elements are typically cut to a tolerance of 1 mm and sealed with tape during their assembly, meaning that, where used as external walls, they can deliver an airtight envelope to the building (subject to good window and door fittings). While just 20% the weight of reinforced concrete, timber elements have a very low thermal conductivity, good thermal inertia and high water vapour permeability. Combined, these are the properties explain why timber construction is the first choice for a 'passive house' design. While this means a significant reduction in the need for heating and cooling energy requirements, it requires a mechanical and automated means of providing the requested air exchange or an 'active' behaviour from the occupants operating its openings.

8.2 Durability

If designed and built correctly, timber projects can stand for hundreds of years. While this has been well demonstrated by religious structures overseas, it is also the case in Australia with a nine-storey timber frame structure standing in central Brisbane since 1913 (Figure 8.1).

To ensure the long-term durability of a timber structure it is vital to consider the location and the way to which it will be exposed to the weather. While it has been shown that internal and weather protected elements are stable without maintenance, structural members exposed to the outdoor environment require regular inspection and re-application of any finishes.

Internally, timber finishes exposed to UV rays may discolour over time however this has no impact on the structural performance of the element.

WoodSolutions *Technical Design Guide #5 Timber service life design - design guide for durability* is a useful tool for anyone seeking to understand the better way to minimise risk and associated costs in a given project.

Figure 8.1: Perry House in Brisbane, a semi-tropical climate, was built in 1913 with a timber structure and masonry cladding. It was then the tallest building in Brisbane. An extra storey was added in 1923. Perry House is still believed to be the tallest timber structure in the Southern Hemisphere that's built on wooden foundations. Its timber structures were kept in the 1996 renovation and are still efficient and beautiful in its new life as the Royal Albert Hotel. Its contemporary equivalent (Figure 8.2) adopts a CNC-machined GLT and CLT structure and is clad with a glazed curtain wall, but shares with Perry House the same care in design and constructions, for a wonderful and future-proof result that makes it a valuable asset. Images: https://www.royalalbert.com.au/

Figure 8.2: Aurecon (engineers) sought to create a world-class working environment when searching for new office space in Brisbane. The timber option they designed with BatesSmart (architects), built by Lendlease in 2018, created a 10-storey office environment that supports the health and wellbeing of its users and has met high rating standards from the Green Building Council, NABERS and WELL. Images: https://www.aurecongroup.com and WoodSolutions.

8.3 Maintenance

After an initial settling period where gravity loads, construction tolerances and moisture-related shrinkage or swelling act to different extents according to each project's specific conditions, engineered timber buildings are known to experience minimal seasonal movement in their service conditions, generating very little cracking in the finishes and virtually no disruption to vertically reticulated services. This is attributed to the high dimensional stability of timber at different temperatures, with very minimal expansion and contraction occurring parallel to the grain. Also, the lower weight and higher ductility of timber structures provide a better behaviour with respect to any wind loads, or seismic and soil movement events that are within the expected range of design actions.

Mid-rise Australian projects have been observed to require equal to lower maintenance when compared to similar buildings in the same vicinity constructed of heavier and/or more brittle materials. Remarkable examples are Melbourne's Forte' Living and the Library at the Dock, both of which have reported reduced maintenance requirements compared to a typical building of their class.

In-situ water damage repairs during building use, for instance after a leak from the hydraulic systems or appliances, as well as other repairs and modifications due to changes in the installations or the fit out, can be easily achieved with minimum disruption, noise and execution times.

Moreover, timber buildings can easily be designed for 'zero structural damage' and/or high levels of robustness with respect to actions beyond the codes and the project specifications, so it is possible, fast and economical to provide structural consolidation and repair after a fire, quake or high wind has caused some significant effects. This is an often underestimated quality of timber construction, that is nonetheless very interesting for a Cost Engineer able to use it to provide a significant benefit to the building owners and occupants.

8.4 Demolition and Disposal

At the end of a building's operational life, timber elements can be reclaimed and reused for other purposes. Where the timber structure is carefully dismantled, its elements may be re-used in another structure. Where not usable for a structural purpose, timber elements can be re-purposed in engineered timber board products, or at a later stage as fuel in a biomass burner.

8.5 Carbon Credits

Many organisations are managing their greenhouse gas emissions in order to:

- gain a competitive advantage in a rapidly evolving low-emissions context that is already rewarding energy efficiency and will soon need to extend to reducing emissions
- demonstrate corporate responsibility by becoming carbon neutral (e.g. reduce emissions as much as possible and compensate for the remainder by investing in carbon offset projects).

Buildings owned or occupied by an organisation are a primary tool to achieve cost savings from improved energy productivity or other operational efficiencies, while responding to the demand from investors and tenants for sustainable and energy-efficient accommodation. Increasing the use of wood products in a building is generally acknowledged as a significant contribution towards these targets by almost every rating scheme. As operational energy emissions are decreasing through improved energy efficiency and use of renewable energy, the embodied impacts of structural materials is increasing proportionally to a buildings impacts.

In Australia, at the time of writing, NABERS and the Green Building Council provide some rating benefits for timber construction systems, although not directly related to quantified greenhouse gas emissions or embodied energyand are in the process of making substantial changes in addition to the points in the star rating tool, especially for embodied carbon. The Federal Government has developed the voluntary National Carbon Offset Standard for Buildings with best-practice guidance on how to measure, reduce, offset, report and audit emissions that occur as a result of the operations of a building (i.e. emissions generated from the day-to-day running of the building) to target carbon neutrality. Emissions from energy (including energy embodied in construction materials) are not considered part of a building's operational carbon account and are therefore not covered by the current version of the Standard, which already foresees that "Embodied energy from construction materials and processes may be considered for future versions of the standard."

In Europe, the EN 16449 standard *Wood and wood-based products. Calculation of the biogenic carbon content of wood and conversion to carbon dioxide* provides a reference for different tools used in design, rating and procurement schemes. The standard specifies that the calculation method can be used in building design and Environmental Product Declarations. The calculation is based on the atomic weights of carbon (12) and carbon dioxide (44):

$$P_{CO2} = \frac{44}{12} \cdot cf \cdot \frac{\rho\omega \cdot V\omega}{1 + \frac{\omega}{100}}$$

With:

P_{CO2} The energy use at the end-of-life of the product (kg). In scientific terms, it's the biogenic carbon oxidiszed as carbon dioxide emitted by the product into the atmosphere

cf The carbon fraction of the wood-based products (0.5 is the default value).

ω Tthe wood moisture content (12% is the typical value).

$\rho\omega$ The density of the wood-based products at the above moisture content (kg/m^3).

$V\omega$ The volume of wood-based products at the above moisture content (m^3).

From a cost engineering perspective, being able to correctly quantify the carbon amount, embodied energy and emission reduction of a project is therefore already very important and may become critical in the near future. Next to the 'direct' effects proportional to the amount of wood used, the 'indirect' effects (e.g. the reduction of foundations and emissions from truck deliveries) will allow a project to reap the full potential from the applicable schemes and benefits.

To support designers and specifiers, WoodSolutions has made available a series of environmental product declarations (EPDs), developed through an extensive stakeholder consultation process (https://www.woodsolutions.com.au/articles/environmental-product-declarations).

Software tools for integrated life-cycle analysis (i.e. https://legep.de/?lang=en or https://www.oneclicklca.com/)support the project teams in the design, construction, quantity surveying and evaluation of new or existing buildings. Their databases contain the description of all elements of a building, their life cycle costs based on standard references and the calculation rules of the applicable certification schemes. All information is structured along life cycle phases (construction, maintenance, operation, cleaning, refurbishment and demolition). The environmental assessment comprises the material flows (input and waste) as well as an effect-oriented evaluation. The database is hierarchically organised, starting with the LCI-data at the bottom, building material data, work-process description, simple elements for material layers, composed elements like windows, and ends with macro-elements like building objects. The data can be used either bottom up or top down. Elements at each level contain all necessary data for cost, energy and mass-flow and affect evaluation.

8.6 Biophilic Design

The health and happiness benefits associated with biophilic design are well known and demonstrated, as summarised in a report from Planet Ark (Wood – Nature Inspired Design – freely available from www.makeitwood.org/healthandwellbeing). Surveyed Australians appear to be innately drawn towards wood. The results indicate that wood elicits feelings of warmth, comfort and relaxation and creates a link to nature.

Multiple physiological, psychological and environmental benefits have been identified for wooden interiors and how they provide a healthier, happier environment:

- ***Offices***: Productivity can be increased, and sick leave decreased, thanks to improvements to a person's emotional state and level of self-expression, resulting in significant benefits in concentration and efficiency.
- ***Education***: Reduced blood pressure, heart rate and stress levels result in increased rates of learning, improved test results, concentration levels and attendance, reduced impacts of ADHD (Attention Deficit Hyperactivity Disorder).
- ***Healthcare***: In a clinical study, the physiological effects described above resulted in post-operative rates of recovery improved by 8.5%, while pain medication was reduced by 22%.
- ***Retail***: The presence of vegetation and landscaping has been found to increase average rental rates on retail spaces with customers indicating they were willing to pay 8-12% more for goods and services.
- ***Residential***: Research in North America found that 7-8 % less crime is attributed to areas with access to nature and can command an increase of 4-5% in property prices.

In Australia, these benefits have already been shown to translate into higher rental returns and selling prices, in a growing number of cases.

Indoor environment quality not only benefits the current occupants but also enhances the value of a property in the long term and reduces the costs of ordinary maintenance, as occupants tend to keep what they appreciate and change what they don't.

The wellness advantages are being progressively reflected in the evolution of building standards and rating organisations, both in Australia and internationally, e.g. by the GBCA, WELL, Living Future and several other rating systems and networks.

<20%	Visibility of wood in the working environment	>60%
47%	Physical workplace satisfaction	81%
56%	Satifaction with working life	81%
44%	Optimistic about the future - most of the time	61%
49%	Confident - most of the time	68%
42%	Stress levels - low	65%
65%	Ability to Concentrate	83%
	Productivity	

Figure 8.3: Results from an independent survey of 1,000 office workers in Australia show a clear relationship between visible wood and workplace satisfaction and productivity.

9 Case Studies

The case studies illustrate the principles discussed in this guide through examples which, although realistic, state of the art and referring to real projects, cannot represent the variety of cases and conditions that are found in practice. However, their value is in guiding through the different steps and activities that are typical of Cost Engineering and explaining their interdependence through the resulting numbers. In particular:

- ***9.1 Design Optimisation*** describes a value management activity on an existing timber-based design, with reference to updated objectives. It illustrates the costing of individual Engineered Wood components, based on few EWP inputs and simple % or parametric (/m^2, /m^3) rates for connectors, labour, CNC machining, transport.
- ***9.2 Estimating of a Whole Construction Cost*** shows how to take into account all the variables that can have an influence, and their relationship, into analysing the feasibility of a proposed development precinct.

Considering that numbers vary with time and location, and that some of what is reported in the case studies is subject to confidentiality, percentages are a better indicator that actual dollar values. Once the method is clear, the result will be as accurate as needed.

Considering that numbers vary with time and location, and that some of what is reported in the case studies is subject to confidentiality, percentages are a better indicator that actual dollar values. Once the method is clear, the result will be as accurate as needed.

9.1 Design

This case study aims to apply the concepts discussed in Sections 3 (Estimating) and 6 (Design Optimisation) to a typical residential mid-rise project, like the one which was first developed for use in *WoodSolutions Technical Design Guide #27 Rethinking Apartment Building Construction* (TDG#27) and later served as a basis for other initiatives such as our Demo Building at Holmesglen TAFE, and the worked examples in *WoodSolutions Technical Design Guide #50 Structural Engineering Timber Buildings*. Developed in collaboration with a group of consultants, with a typical floor plan featuring a variety of spans and in-set balconies, TDG#27 compares the costs of building an 8 storey multi-residential structure constructed entirely in one of three main structural systems: lightweight frame (stud frame), mass timber (CLT) and reinforced concrete.

This case study optimises the TDG#27 design approach a step further as per a typical value management process, in search of more cost savings, easier construction, and improved acoustic and fire performance. The most efficient way to achieve these targets is to apply the design optimisation concepts discussed in Section 6, specifying different Engineered Wood Products where they are best utilised. As shown hereafter, an efficient residential mid-rise timber design typically would feature lightweight framing for the top 3-4 levels, with massive timber components below.

9.1.1 Initial design

TDG#27 presents two timber designs, each of which demonstrates an efficient way to build using a single structural system (stud frames or CLT) within a platform frame approach (e.g. a ‘load bearing wall’ construction, with most walls aligning vertically to achieve an efficient load path and the floors sitting on top of each wall).

Where walls are required to be discontinuous for acoustic compliance this is achieved through the use of two wall panels separated by a 20 mm gap (while it is common for both panels to be loadbearing in stud frame construction, CLT construction typically requires just one of these panels to be load bearing while the other can be installed off the critical path of the program). Compliant acoustic separation of floors is achieved through the use of a wet 40 mm screed over a 10 mm rubber mat on the floor surface, and an underside comprising one layer of 16 mm fire-rated plasterboard, plus a 13 mm layer of standard grade plasterboard mounted on furring channels for mass timber, or alternatively two layers of resiliently mounted 16 mm fire-rated plasterboard for lightweight systems. Graphic representations of these two systems can be seen in Table 9.3 in Section 9.1.3.2.

The initial design of this structure is compliant with Deemed-to-Satisfy requirements of the National Construction Code, meaning that:

1. All structural timber is enclosed in fire-protective layers to achieve the required FRL.
2. All insulation within fire-protected cavities is non-combustible.
3. There are sprinklers throughout the project.
4. Cavity barriers are installed as required in areas.

With all loadbearing timber elements encapsulated by fire-protective linings, it is assumed that any mass timber within the structure features an industrial non-visual finish.

9.1.2 Areas for improvement

The first and most significant optimisation is, in this case, a revision of the structural design, optimised for its overall installed cost and not just for the material cost. While it is found that CLT provides the optimal solution for the higher loads experienced in the lower floors, the loadbearing function on the top four floors can be efficiently performed by stud framing. Therefore, the 105 mm and 85 mm thick CLT loadbearing walls found on the top three levels of the mass timber design were redesigned as stud frames, and all the panel sizes were optimised for transport and lifting.

Conversely, in the stud frame design it is commonly observed that the use of more and/or larger dimensioned studs at lower levels can be cost efficient than simply specifying a mass timber panel. This optimisation can have flow on effects, with the more structurally efficient mass timber panels resulting in a thinner wall panel than high-capacity load-bearing studs (plus fire-protective linings), and therefore more net sellable area.

This concept of designing for the installed condition can also be applied to floor panels, designed for their effective spans where unaffected by sizing constraints and adopting continuous spans wherever possible, rather than making all floor panels equal throughout the structure. While it isn't common to mix lightweight and mass timber floor elements on a single floor (although this is possible, e.g. if an exposed ceiling is requested for the lounge or bedroom), floor depth variance within single level allows the designer to maximise the available space for services reticulation and increased ceiling heights. This flexibility in appearance and structural floor depth may be expensive to achieve with concrete, but timber allows for high levels of design variance with very little penalty on cost and installation time.

While this cost balance between stud and mass timber elements is directly influenced by the timber and fabrication costs, it is also affected by the fire-rating requirements of the two systems (e.g. where lightweight elements may require two layers of fire-rated plasterboard for each fire-protected side, mass timber elements typically only require one).

Again, the 'installed cost' concept can be applied to the connectors utilised in a project. Connector costs and installation times can vary significantly, and as such it is valuable to optimise their design while this is being done for the structural elements.

With reference to acoustics, while the wall systems specified in the initial design are best practice, the floor systems offered an opportunity for further optimisation, as it features the same acoustic system for both mass and lightweight timber, with a 50 mm build up on top of the floor and furring channel mounted ceiling underneath. The build-up includes a 10 mm acoustic mat and 40 mm screed, providing both mass and resilience to the floor system. This design provides compliant acoustic ratings with modelling suggesting airborne ratings (R_w+C_{tr}) of 51, and an impact rating (L_{nw}) of 55 for both systems. These ratings render both the mass and lightweight systems compliant, however a value management approach is possible and was implemented.

There is also an opportunity to engage a fire engineer to model the behaviour of a fire in the building and identify areas for further design optimisation utilising a Performance Solution. While this will not be applicable to all buildings in all locations, this step often results in a simplified construction process and cost savings which typically far exceed the consultant's fees.

9.1.3 Optimised design

Structural optimisation

As shown in Table 9.1, a review of the structural design has resulted in an optimised mix of Engineered Wood products, with the structure made up of massive timber elements in the lower floors and stud-framed walls and cassette floors in the higher floors. In this case, the core remains as mass timber throughout the structure. To find the point at which it is most cost effective for the structure to transition from lightweight frame to massive timber we analysed the structural design and costing rates in conjunction, through a series of iterations.

Table 9.2 illustrates a case in which when using stud frame at lower floors (Level 5 here) the total costs to fabricate and fire rate may exceed the total costs associated with the CLT system, while the reverse is true from Level 6 up. The use of stud framing at higher levels is often an effective design optimisation, as panels with simple offsite fabrication, open on one side for the installation of services, can be transported and erected in the same manner as mass timber panels, providing equivalent performances and typically attracting a lower cost.

Table 9.1: Structural Optimisation Process (note that only one party wall type is shown here for illustrative purposes, but the value management was run on all the wall types).

Code	Element	Initial Design (Stud Frame)	Initial Design (CLT)	Optimised Design (mixed EWPs)
8	Wall	MGP10 90 x 35 @ 600 crs	CL3-85	MGP10 90 x 35 @ 600 crs
	Floor	499 mm deep cassette	CL5-225	412mm deep cassette
7	Wall	LVL 90 x 35 @ 600 crs	CL3-105	LVL 90x35 @ 600 crs
	Floor	499 mm deep cassette	CL5-225	412mm deep cassette
6	Wall	LVL 90 x 45 @ 600 crs	CL3 - 105	LVL 90 x 45 @ 600 crs
	Floor	499 mm deep cassette	CL5-225	412mm deep cassette
5	Wall	LVL 2 x 90 x 45 @ 600 crs	CL3 - 105	CL3 - 105
	Floor	499 mm deep cassette	CL5-225	CL5-225 (CL3-145 where applicable)
4	Wall	LVL 2 x 90 x 45 @ 600 crs	CL3 - 125	CL3 - 125
	Floor	499 mm deep cassette	CL5-225	CL5-225 (CL3-145 where applicable)
3	Wall	LVL 2 x 90 x 45 @ 600 crs	CL3 - 145	CL3 - 145
	Floor	499 mm deep cassette	CL5-225	CL5-225 (CL3-145 where applicable)
2	Wall	LVL 3 x 90 x 45 @ 600 crs	CL3 - 150	CL3 - 150
	Floor	499 mm deep cassette	CL5-225	CL5-225 (CL3-145 where applicable)

Table 9.2: Rate Comparison for two wall types at Levels 5 and 6, where the structural design requirements could be achieved with both options (Note: values applied for Melbourne in April 2019, ask the suppliers for an update).

Wall Type	Lightweight	Massive	Lightweight	Massive
Level	5	5	6	6
Wall Type	LVL 2 x 90 x 45 x 2 @ 600 crs	CL3-105	LVL 2 x 90 x 45 @ 600 crs	CL3-105
Bracing (one side only)	17 mm plywood		12mm plywood	
Costs ($/m²)				
Loadbearing Element (stud frame or CLT panel)	$104	$157.50	$80	$157.50
Bracing	$50	-	$30	-
Insulation between studs	$10		$10	
Acoustic stud wall		$60		$60
Fire-rated plasterboard				
2 x 13mm FRPB (each side)	$120		$120	
1 x 16mm FRBP (each side)		$60		$60
Total Rate ($/m²)	**$284.00**	**$277.50**	**$240.00**	**$277.50**
Selected for use?	×	✓	✓	×

To optimise the floor elements, cassette depths have been re-assessed, with a thinner floor cassette possible on multiple spans and depths further reduced where shorter spans are encountered.

Finally, all connectors have been reviewed and optimised based on availability, buildability and productivity (e.g. preferring connectors with fewer nails or screws to reduce the time spent installing each item).

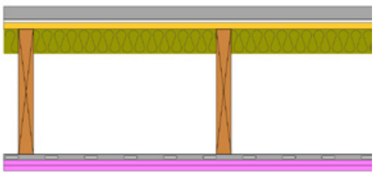
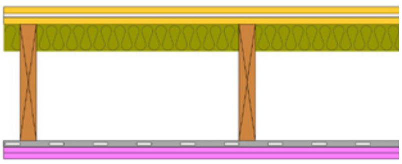
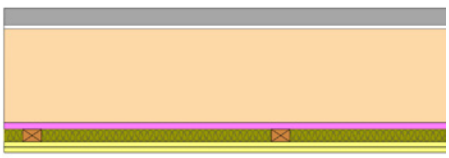
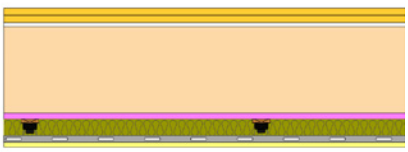
Acoustic optimisation

With wall systems already maximally optimised, we can focus on the optimisation of floor systems. The floor solution provided in the initial design has historically been a popular one, with builders correctly identifying a wet screed as an inexpensive way to add the required mass to timber floors.

While this system is indeed cheap to install, there are downsides associated with adding a wet trade to what is otherwise a dry site. First and foremost, the use of a wet screed calls for stringent moisture control to ensure that any moisture affecting the timber is able to escape (rather than pooling and causing durability issues). In addition to this, however, the use of wet screeds limits access to the screeded area while curing, limiting on-site productivity for this duration. With these issues in mind, a number of builders have moved toward achieving a similar effect with the use of dry boards. Whether compressed fibre cement, magnesium oxide, or even particleboard, the application of dry board products to the top of the timber floor (typically sitting on top of an acoustic mat) has been shown to deliver both the extra mass and resilience required to achieve acoustic ratings beyond compliance. What's more, other works can continue as these dry boards are installed, ensuring that the builder can take full advantage of timber's 'no-prop' characteristic.

To illustrate this, in this case study we replaced the 40 mm concrete screed on 10 mm of acoustic matting with one layer of 19 mm particleboard on 10 mm of acoustic matting (or 12 mm softboard) on the lightweight cassette, and two layers of 19 mm particleboard on 10 mm of acoustic matting on the mass timber panel. As shown in Table 9.3, this change provides a modest improvement in acoustic performance of the floors, even providing a decrease in floor depth for the cassette option. Note that while this floor system is effective in multi-residential projects, commercial projects can achieve similar ratings with the use of access floors.

Table 9.3: comparing acoustics and depth of system.

System	System Depth	Rw+Ctr	Lnw
Initial Design (cassette) 	50 mm (acoustics) + 382 mm (structure) + 32 mm (fire) + 35 mm (acoustics) = **499 mm**	51*	40-55 (depends on floor covering)
Optimised Design (cassette) 	29 mm (acoustics) + 319 mm (structure) + 32 mm (fire) + 32 mm (acoustics) = **412 mm**	55*	49* (no floor covering)
Initial Design (mass) 	50 mm (acoustics) + 225 mm (structure) + 16 mm (fire) + 50 mm (acoustics) = **341 mm**	51	55 (no floor covering)
Optimised Design (mass) 	48 mm (dry acoustic solution) + 225 mm (structure) + 16 mm (fire) + 50 mm (acoustics) = **339 mm**	51*	54* (no floor covering)

*INSUL Prediction **Based on Auckland Uni CLT Acoustic Test (with 140 mm CLT)

Fire engineering

The high level of this case study makes it difficult to develop a fire design different than using the DtS provisions and standard details, however if a site was specified and the design developed a little further it is likely that fire-protective linings and fire rating details for penetrations would be simplified.

9.1.4 Impact of optimisations

While direct factors such as reducing the volume of timber used or the number of connectors specified are easily quantified, less tangible factors such as the increase in productivity due to the use of dry boards rather than a wet screed or the simplification of fire rating details cannot be ascertained until the project is completed. In many cases this process may render the project more buildable, ultimately improving construction efficiency and reducing the total build time.

The structural optimisation has delivered thinner, lighter panels that may allow the builder to utilise a smaller crane. Finally, while the wall design of the base case is well optimised, it is common for a review of this design to result in a thinner wall panel with similar acoustic performance. This reduced area results in a variety of benefits, ranging from reduced loads on footings to the delivery of larger rooms and a higher quality product than otherwise achievable. These findings, and the overall impact of this optimisation, are displayed in Table 9.4 and Figure 9.1.

Table 9.4: Estimated impact of optimisation process in comparison to base CLT design. Cost savings identified in this case study relate to a design and layout completed with timber systems in mind, and a requirement for multiple building use classes. This is distinct from the second case study which refers to a building with the design initially completed for concrete and adapted to timber, and no transfer slab required.

Category	Estimated impact
Total Project Cost	-2% compared to initial CLT design
Comparison to concrete cost as estimated in WoodSolutions Technical Design Guide #27	-8% (formerly 6%)

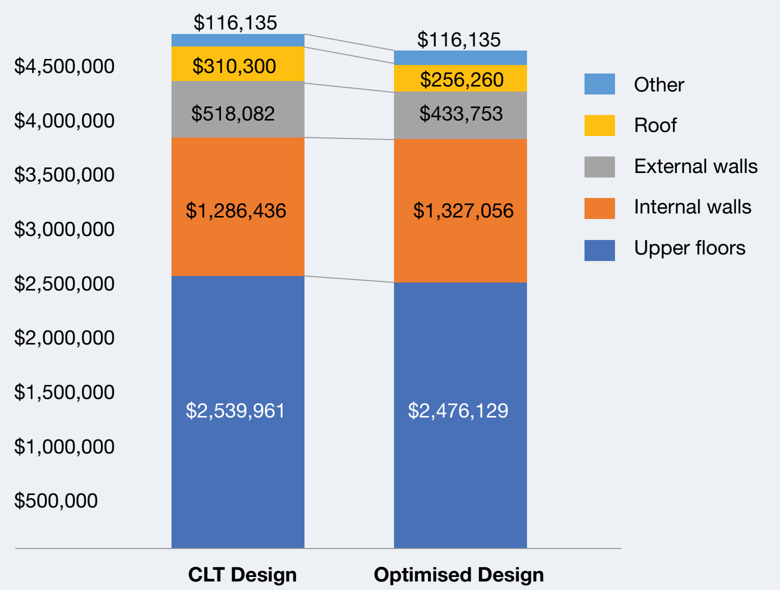


Figure 9.1: Graphical representation of the cost impact of design optimisation ('other' refers to costs not affected by the optimisation such as staircases and columns).

9.1.5 Estimating for design optimisation

Integral to the design optimisation process is the repeated checking for cost efficiency and viability. This section demonstrates how this checking was undertaken for this case study project with focus on how the prices for the walls, floors, and preliminaries were developed.

Before beginning the take-off it is important to ensure that the required level of design detail is available or that adequate assumptions are reported. For timber elements, this information may include the type of Engineered Wood product to be used, dimensional sizing, strength grade, level of treatment (if any), and quality of finish, and for connectors may include type of connector, and where required number of screws or nails required for compliance with certified structural design. Section 3 provides more information on each of these details. In this case study, we are aware of the type and strength of timber products required, and as the design is intended to be compliant with the Deemed-to-Satisfy requirements we can assume that the industrial non-visual finish is specified to any engineered products.

To illustrate the estimating procedure for a floor element in this case study, consider a section of the lightweight floor. The total installed cost of this element can be broken into two categories: supply costs and installation costs. The supply cost is best determined through the acquisition of quotes that allow for material and fabrication, however, where fabrication isn't possible this can be allowed for separately. For example, a cassette fabricator may be willing to quote for the supply and fabrication of the joists and floor membrane, but may be unwilling or unable to quote for the installation of the acoustic floor build-up. In this case, the floor build-up can be added on site, with the costing process proceeding as identified in Table 9.5.

Table 9.5: Supply cost for optimised lightweight cassette. (Values applied for Melbourne in April 2019, ask the suppliers for an update).

Detail	Quantity	Unit	Rate	Total
Floor cassette (including 300 deep, MGP10 chord floor joists and particleboard flooring)	1	m^2	$135	$135
Acoustic underlay (S&I)	1	m^2	$15	$15
19 mm particleboard (S&I)	1	m^2	$25	$25
2 x 16 mm fire-rated plasterboard installed on furring channel (installed on site)	1	m^2	$81	$81
Supply and fabrication cost for cassette:				**$256**

With the off-site fabrication of the cassette already allowed for,, it is important that only the cost for the transport and site installation of the cassette is added. Installation rates can vary, depending on the complexity and efficiency of the project's design, however start by applying the installation rate of about 500 m^2/week observed from the database of completed projects identified in Section 1. This rate also allows for the installation of the walls within this floor area. We can simply divide the installed floor area by the approximate installation rate and multiply this by the expected number of workers, their working hours and their hourly rate. To this total number, add an allowance for contingency, overheads and margin, and this can be used to represent an approximate installation cost for the structure.

For example, if we assume this structure is 4,500 m^2 in area we can calculate an approximate installation program of nine weeks. Assuming that the installation of this structure will require seven workers (as observed from the database), working for eight hours a day, five days per week for this duration, we can calculate a net cost for installation. To this number we may choose to add 15% for contingency, overheads and margin, giving the gross installation cost for the structure (excluding any temporary works, propping or other project specific requirements). This number can then be divided by the installed floor area to give us a unit rate for install.

9.2 Estimating a Whole Construction Cost

In 2018, Rider Levett Bucknall undertook a benchmarking case study of a well-optimised project (Caulfield Village Precinct 1 Building 2A) developed by Beck Property Group, Melbourne. Completed in August 2016 by Probuild, the five-storey project comprises 65 apartments. Its initial specifications included a concrete flat plate slab with concrete columns and precast concrete core walls and stairs, and a façade featuring glazing, brick veneer and lightweight cladding.

Rider Levett Bucknall undertook costings based on the following revised specifications: in situ concrete podium; suspended slabs and roof comprised of a lightweight cassette system; Cross Laminated Timber (CLT) lift, stairs and stair shaft walls; and load bearing intertenancy and corridor walls comprised of timber stud. The revised specifications reduced the construction program by five weeks. An additional two weeks were eradicated as the curing process was eliminated, allowing finishing trades to follow on more quickly. In addition, the columns in the basement and the size of the pad footings were reduced, and columns throughout the upper levels were eradicated.

This benchmarking case study demonstrated that a switch to timber construction could have resulted in an overall saving of 2.2% and motivated Beck Property Group to request an estimate on one of the buildings designed for Caulfield Village Precinct 2, currently under development. The procedure and results are described hereafter.

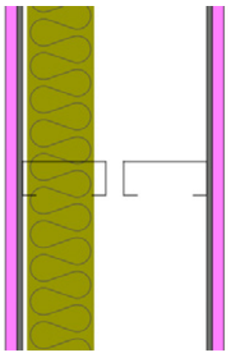
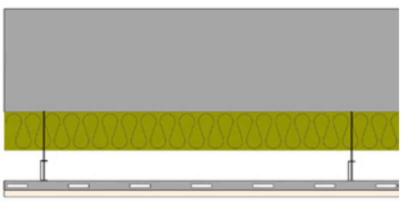
9.2.1 Case study project

This case study was an eight-storey apartment building with a total of 98 apartments and a Gross Floor Area of 7,817 m^2. The structure features a tight floor to floor height of 3,050 mm, with finished ceiling heights set at 2,700 mm above floor level. Originally designed in reinforced concrete, the project's façade includes large areas of exposed precast concrete, as well as areas of both glazing and lightweight cladding. The design features large balconies on each level, with most floor spans measuring around 5 m.

9.2.2 Initial concrete design

First designed for traditional concrete systems, the structure involved post tensioned flat plate slabs and in-situ columns, with an in situ concrete core. The significant dead load of the superstructure is transferred to an alternative column grid at the first floor via a 400 mm deep transfer slab with 500 mm deep in situ concrete beams (giving a total transfer slab depth of 900 mm). The design features non-loadbearing lightweight steel frame partitions and a lightweight dropped ceiling, with acoustic performances as identified in Table 9.6.

Table 9.6: Acoustic ratings of baseline floor and wall systems.

System	Build-up	Rw+Ctr	Lnw
Lightweight Steel Party Wall 	13 mm fire-rated plasterboard 6 mm cemintel wallboard 93 mm steel stud 20 mm gap 93 mm steel stud 6 mm cemintel wallboard 13 mm fire-rated plasterboard	51*	-
Lightweight Steel Dropped Ceiling 	200 mm concrete slab Rondo suspended ceiling systems w/ resilient mounts 11 kg/m^3 insulation Furring channel 13 mm plasterboard	56*	55-60 (no floor covering)

*CSR Redbook

9.2.3 Optimised timber design

An optimised timber design was developed, following the fundamental optimisation principles outlined in Section 7 and discussed further in Section 10. This design involved a massive timber structure to the fourth level, above which lightweight floors and walls extended to the full height of the building. As in the design of the case study project in Section 10, the central cores of the project are to remain as massive timber throughout. A massing of the project can be seen Figure 9.2.

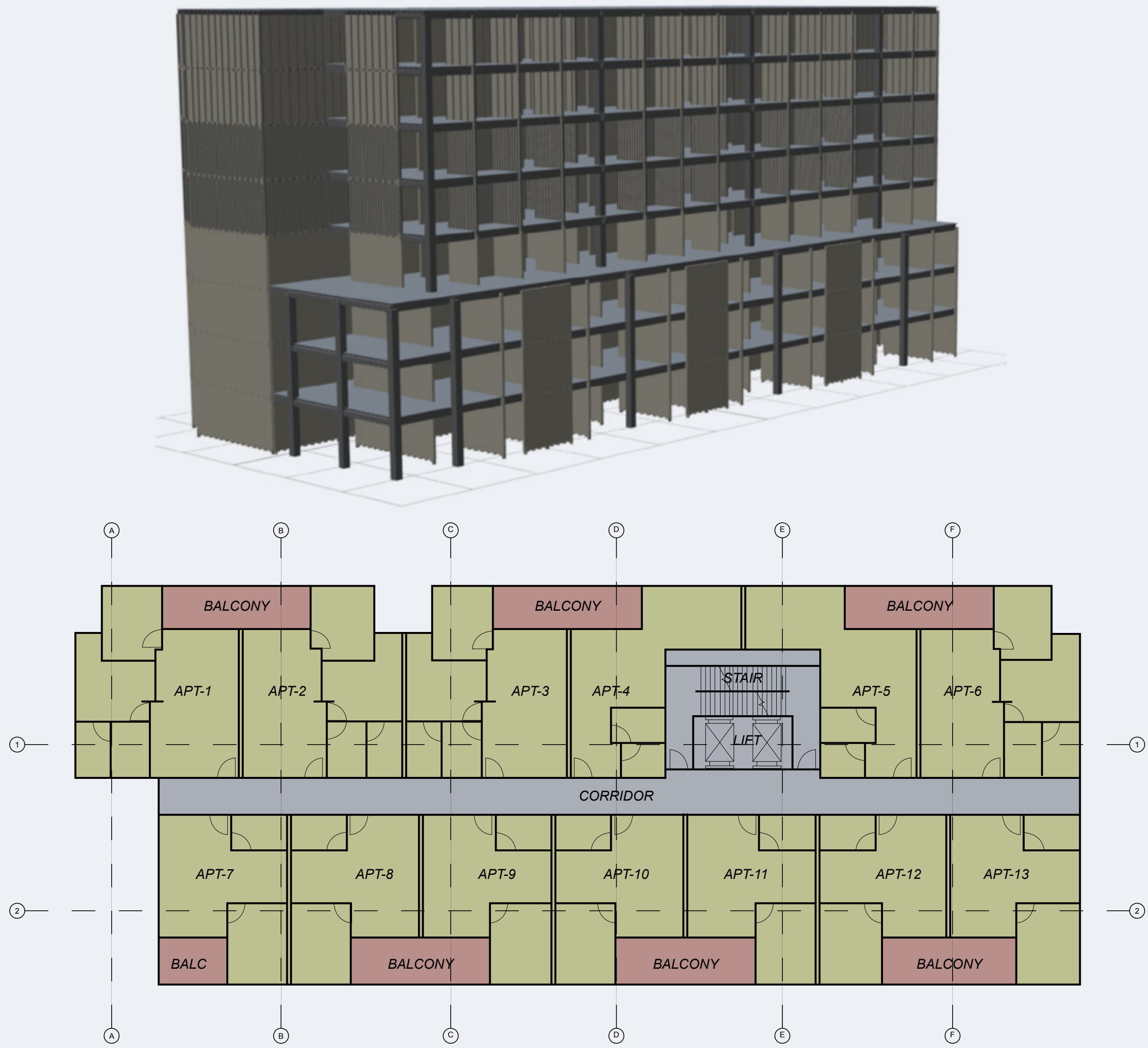
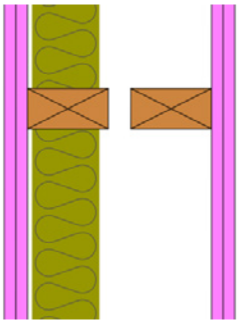
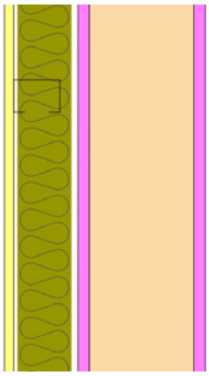


Figure 9.2: Massing and typical plan of case study project.

This new design was calculated to impart about 30% less dead load on the basement carpark and footings than the comparison in concrete, allowing for the significant transfer slab to be re-designed and simplified, and carpark columns and pad footings to be reduced in size by 25%.

The design of the acoustic systems also followed a similar path to what was observed in Section 10.1 of this report. A high standard of acoustic separation was achieved through the use of discontinuous wall construction for all party walls. Where the structure is timber framed, this is easily achieved via two parallel load bearing timber frames, with fire-rated linings applied to the outside faces. This system is effective as it delivers the required loadbearing capacity, a high standard of acoustic insulation, and the necessary fire protection within a single system. Where the structure is massive timber, acoustic discontinuity is achieved via a single load bearing mass timber panel, and a separate non-loadbearing frame. In this system, fire-rated plasterboard is directly applied to the massive timber element, with the stud frame available for the easy reticulation of electrical services. Examples of these systems can be seen in Table 9.7.

Table 9.7: Acoustic ratings of optimised wall systems.

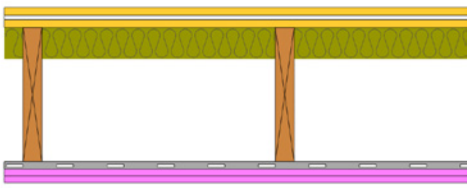
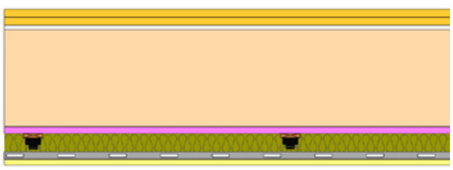
System	Build-up	Rw+Ctr
Lightweight 	2 x 13 mm fire-rated plasterboard 90 mm stud 20 mm gap 90 mm stud 2 x 13 mm fire-rated plasterboard	53*
Massive 	13 mm acoustic plasterboard 64 mm steel stud 20 mm gap 16 mm fire-rated plasterboard CLT element 16 mm fire-rated plasterboard	56**

*CSR Redbook ****WoodSolutions Technical Design Guide #44***

Similar to the walls, the acoustic system utilised for the floors varies slightly between lightweight and massive flooring systems. A strict limit of 350 mm is applied to all floor depths (inclusive of structure, fire rating and any acoustic treatment), requiring special attention to achieve this while delivering a high standard of acoustic performance. For the lightweight cassettes, acoustic compliance is achieved through the addition of an acoustic mat and one layer of 19 mm particleboard to the top of the system, and ensuring that the required two layers of 16 mm fire-rated plasterboard are fixed to the floor joists via acoustic isolation mounts. Mass timber floors feature a slightly more robust acoustic topping of two layers of 19 mm particleboard on top of a 10 mm acoustic mat (or 12 mm softboard), with the required layer of fire-rated lining direct fixed below, and a dropped ceiling of varying depths (dependent on the structural depth) below this. Examples of these systems can be seen in Table 9.8.

Note that while further efficiencies could likely be identified through a fire engineering process, this case study considers it under Deemed-to-Satisfy conditions.

Table 9.8: Acoustic ratings and depths of optimised floor systems.

System	System Depth	Rw+Ctr	Lnw
Lightweight 	29 mm (acoustics) + 257 mm (structure) + 32 mm (acoustics) + 32 mm (fire) = **350 mm**	54*	55* (no floor covering)
Massive 	248mm (dry acoustic solution) + 160mm (structure) + 16mm (fire) + 100mm (dropped ceiling) + 13mm (plasterboard) = **337 mm**	52*	53* (no floor covering)

*INSUL Prediction

9.2.4 Results

The results of this case study are as determined by Rider Levett Bucknall in consultation with the industry. In the completion of this exercise the cost consultant identified several main areas of cost variance, including both reductions and increases to certain cost categories. The following section interrogates each of these categories, noting the true value of timber construction in larger mid-rise developments.

Substructure

In this case study, the light weight of the timber superstructure has been shown to result in needing fewer and smaller footings. Beyond this, the reduced dead load also allows for all basement columns to be reduced in dimension by about 25%. This reduction in size not only saves material, but also saves labour hours, with smaller footings requiring less time in excavation, lining, steel fixing, and concrete placement. On the other hand, for this specific project, it was not possible to extend the benefits to the transfer slab, as there is no transfer grid. In mixed-used project where the residential part is above a commercial tenancy, this would have been possible.

Structure

This case study reveals that by using an optimised structural system, the cost associated with the structure can be comparable to, or less than, the initial design. Both allowances for internal and external walls increased in the timber design, as in this scenario many of the walls are loadbearing and therefore must be robust, with a higher degree of fire protection. Note that with all loads now transferred via the loadbearing wall elements, the structural columns initially specified throughout the project can be avoided, resulting in a significant cost impact.

Program and preliminaries

In consultation with major contractors and with reference to the database of timber projects in this guide, Rider Levett Bucknall developed a conservative indicative program for the construction of this case study project in both concrete and timber construction systems. In comparison, the timber design is expected to be delivered two weeks earlier than the concrete alternative, resulting in reduced time-related costs. The main impact of this reduction can be seen in the reduced preliminary costs. While this faster delivery has many other benefits (e.g. reduced interest expenditure, faster settlement times, etc), these have not been allowed for in this comparison.

Wall and ceiling finishes

In this estimate, the cost categories of both wall and ceiling finishes saw a reduction in total cost. This variance can be attributed to an allowance for these costs in the 'Internal Walls' and 'Upper Floors' cost categories, and therefore doesn't represent a true reduction in the cost of finishes.

Summary of results

With these areas of cost variance in mind, an indexed comparison has been provided for the two designs in Table 9.9. All costs that remained the same across the comparison have been grouped in the 'Other Costs' category for simplicity. This cost exercise has identified a positive impact in the move to an optimised timber design, suggesting a total construction cost reduction of 2.51% could be achieved if this change were to occur. This cost saving does not allow for other potential savings associated with interest or holding costs.

Table 9.9: Indexed cost comparison of concrete and timber designs.

Element Category with cost difference	Indexed cost in initial design	Indexed cost in revised design	Percentage change in indexed cost
Preliminaries	10.63	9.92	-6.67%
Substructure	2.23	1.68	-24.86%
Columns	2.14	0.00	-100.00%
Upper Floors	11.14	9.16	-17.75%
Staircases	0.76	0.55	-28.26%
Roof	3.07	2.78	-9.66%
External Walls	15.48	16.78	8.35%
Internal Walls	9.46	12.35	30.50%
Wall Finishes	2.81	2.15	-23.45%
Ceiling Finishes	3.11	2.78	-10.60%
DD Contingency	2.44	2.36	-3.06%
Builder’s Margin	2.92	2.84	-2.86%
Other Costs *	33.80	33.80	0%
Total	**100.00**	**97.14**	**-2.86%**

* Note: ‘Other Costs’ category includes all fields unchanged by varying the structure including external doors, internal screens, internal doors, floor finishes, special equipment, sanitary fixtures, sanitary plumbing, gas, ventilation, AC, fire protection, electrical, communications, transport systems, BWIC, ex storm and drain, and special provisions.

9.2.5 Feasibility and Sensitivity Analysis

The WoodSolutions Mid-rise Advisory Program has developed a discounted cash flow modelling tool to assess the potential financial viability of projects and model their sensitivity to movements in financial measures. For this case study, this sensitivity analysis was performed to determine the impact of project program on gross profit. With ancillary costs, approval timeframes, and sales values assumed, this feasibility analysis suggests that if this building were to be constructed at the full estimated cost and sold at a price estimated based on current market conditions, the profit realised would exceed typical developer requirements.

Furthermore, the sensitivity analysis identified that variance of construction cost and sales revenue are highly influential on the total profit margin, with any savings in construction costs or increases in revenue directly resulting in extra profit for the project. This is important when considering whether to pursue further design optimisation, as smart design using the right elements in the right locations may lead to further profits for the project.

10 Appendix 1: Guideline for the execution of timber structures

Contents

Introduction

This Guideline applies to the execution of timber structures to achieve the intended level of quality, safety and serviceability during their whole Life Cycle. Its main goals are to:

- define a set of technical requirements for the execution of a timber structure
- ensure that the designer transfers to the contractor all the relevant technical information for the execution of the structure
- specify conditions to be fulfilled before the works begins
- list controls suggested at delivery, during and at the end of the execution to ensure that the specified quality is achieved.

Before the work begins, make available for the contractor a set of documents and drawings/information models giving all the information required for the execution of the work, which includes the appropriate references to applicable Codes and Standards. This set of documents is referred to as the Execution Specification.

1 Scope

This Guideline contains provisions for the execution of load-bearing timber structures and applies to:

- timber structures built fully on site from individual components (e.g. stud frames)
- timber structures assembled with elements and modules prefabricated off site
- manufacture of timber elements and modules where no applicable product standard exists
- permanent and temporary timber structures.

This Guideline does not apply to:

- temporary parts of timber used only for equipment or construction aids for the execution (e.g. formwork and scaffolding)
- specification, production and conformity of the timber components
- safety and health aspects of execution or safety claim against third parties.

This Guideline does not regulate contractual and responsibility matters related to the construction work.

2 Terms and Definitions

Structure: Everything that is constructed or results from construction operations. It is a combination of connected parts designed to carry loads and provide adequate rigidity.

Connection: The point at which two or more structural members meet and are joined to transfer load effects.

Connector: Connecting element that transfers forces between two or more structural components.

Anchoring length: The depth of penetration of the portion where the tip is:

- the depth of penetration into the part that receives the tip (single section connection) or
- the thickness of the centre part (double section connection).

Critical moisture level: The predetermined level that, if exceeded, could cause damage associated with microbial growth.

Control: Evaluation of compliance by observation and assessment on the production site supported by measurement, testing or interpretation where appropriate.

Quality plan: Specification of the procedures and associated resources to be applied when and by whom to a specific object within a quality management process.

Temporary structure: Structure designed for a short design working life.

Assembly plan: Documents including drawings/information models, technical data, tolerances, weather protection measures, the order of work, execution methods, assembly procedures and other requirements necessary for assembly.

Assembly tolerance: Geometrical tolerances relating to location, verticality, horizontality or other characteristics of the assembly of a structure.

Prefabricated timber element/module: Timber element or module that is built on a place other than the final location of use, either at the factory or on site.

Manufacturing tolerance: Permissible deviation for the dimensions of a timber component, timber element or timber module arising from the production of the component, element or module.

Execution Specification: Documents that include all drawings/information models, technical data and requirements necessary for the execution of a specific project.

Compound construction tolerance (the 'box principle'): The sum of the tolerances for the actual position of a point, line or surface of the component and its basic position on the construction site.

Permitted deviation: Permitted algebraic differences between the limits of size and the corresponding reference size.

Tolerance: Difference between the upper and lower limits of size.

Note: Geometrical tolerances for prefabricated timber components, elements and modules are:

- manufacturing tolerances as defined in the relevant product standards
- assembly tolerances.

Tolerance is an absolute value without designation. It is expressed, however, usually by "sum of ± permitted deviations", so the value of tolerance is implied.

Timber component: Part of a timber structure that itself may be composed of several components.

Execution: All activities in the physical implementation of the work, including procurement, storage, gluing, mechanical fastening, transportation, stabilising measures, assembly of prefabricated timber elements/modules and control and documentation.

Execution Class: Classified set of requirements specified for the execution of the works as a whole or an individual component.

Note: Execution Classes differentiates requirements based on varying reliability expectations, complexity of the project and degree of new technology being used.

Consequence Class and Reliability Class: A classification of structures based on the risk associated with a collapse, referring to potential consequences. The Consequence Class of a structure determines its Reliability Class, which influences the design assumptions but also the levels of supervision, inspection and execution.

As an example, the following are the definitions adopted in the Eurocodes:

Class	Description	Examples
CC1 and RC1	Low consequence for loss of human life, and economic, social or environmental consequences small or negligible	Agricultural buildings that people do not normally enter (e.g. for storage), greenhouses
CC2 and RC2	Medium consequence for loss of human life, economic, social or environmental consequences considerable	Residential and office buildings, public buildings where consequences of failure are medium
CC3 and RC3	High consequence for loss of human life, or economic, social or environmental consequences very great	Grandstands, bridges, public buildings where consequences of failure are high (e.g. a concert hall)

3 Documentation and Quality Management

3.1 Assumptions

Before the execution begins, meet the following:

a) Accurately design the structure or the structural part, including prefabricated timber elements and modules.

b) Make the Execution Specification for the works available at the construction site.

c) For work that builds on previously performed work, ensure documentation showing that the work is within the permitted deviation, e.g. for foundations.

3.2 Execution Classes

Specify the Execution Class to be used in the Execution Specification, on the basis of the expected reliability requirements, the complexity of the work and the degree of new technology being used. Execution Classes differentiate requirements for documentation, competence and control of execution and may refer to the whole structure, to structural parts or to specific materials and technologies used in the execution.

Table 1: Guidance on the selection of the Execution Class.

Consequence Class, Reliability Class / and other associated requirements	Execution Class[a]
CC1/RC1 (low)	1
CC2/RC2 (medium)	2
CC3/RC3 (high)	3
[a] A more stringent Execution Class than the CC/RC would indicate may be selected, for example, because of a high degree of complexity and the use of new technology.	

3.3 Documentation

3.3.1 Execution Specification

The Execution Specification received for the works includes the following elements:

- project specification that contains information and requirements for the specific project with reference to this Guideline, relevant standards and regulations
- Execution Classes for the work
- any special control requirements
- tolerance classes for the work
- drawings/information models and other technical documents necessary for the execution including which products are to be used
- requirements for handling and storage, including weather protection during storage and execution
- assembly plan for prefabricated timber elements and modules, and where appropriate for other wood components
- moisture control plans.

3.3.2 Documentation of execution

Perform registrations and documentation in accordance with Tables 2, 3 and 4.

Measurements showing that the performed work meet the tolerance requirements of clause 8, should normally be recorded and documented, even when it is not required. The timing of control should be considered, especially if control is difficult at a later stage.

Where special documentation of the execution is required, specify the nature and extent of the documentation in the Execution Specification.

3.4 Quality Management

3.4.1 General

Where a quality plan is required in the Execution Specification, make it available on site. There may be one quality plan that covers all activities or one ‘high level’ plan complemented by separate plans for the various phases and activities to be performed.

To ensure compliance with the requirements of the Execution Specification and the requirements of regulations and agreed standards, the work should be performed with:

- the necessary competence and qualifications of the personnel
- suitable equipment
- adequate resources (e.g. staff number and time).

It is assumed that the execution will follow regulations and standards such as those involving all the mandatory OH&S and environmental aspects of the construction work.

The project and site management are responsible for organising the work to ensure:

- correct and safe use of equipment and machinery
- satisfactory quality of materials
- the execution of the structure meets the requirements
- coordinated assembly of prefabricated elements and modules according to the assembly plan
- safeguarding of structure until the handover of the works.

3.4.2 Execution Control

General

The requirements for control are set using one of three Execution Classes (Table 2).

An execution control involves checking that the execution, products and materials are according to the Execution Specification.

This Guideline does not define any provisions related to the degree of independence of the personnel performing the control.

The Execution Specification may specify additional provisions for the control.

Weather protection measures

The weather protection measures can be preventive or corrective. The higher the possible impact of moisture damage, the higher the level of preventive measures that is needed.

Moisture control plans should cover the entire construction process for timber structure and conform to building material manufacturers' instructions. Quality procedures may be established where moisture control plans are included.

Unless otherwise agreed, the contractor is responsible for the preparation and follow-up of moisture control plans, including their documentation.

The Execution Specification should specify the matters of significance for the moisture control.

The supplier(s) of all the moisture-sensitive building components specify the moisture level in the components at delivery and necessary weather protection measures in order to avoid exceedance of the critical moisture level.

Moisture Control plans

Make moisture control plans where:

- relevant moisture sources are considered
- the possible consequences of moisture damage are assessed
- moisture level in the different phases of the construction work is specified
- measurement methods are specified
- weather protection and necessary protection measures are indicated
- measures to limit moisture damage in the structure are specified.

Moisture control plans may include the following:

1) Basic information of the project such as:

- address and coordinates of the construction site
- name of the construction site manager
- the name of the person responsible for follow-up of the moisture control plan.

2) Overview of wood materials and products to be used on the construction site.

3) Limit of moisture content in wood upon delivery to the construction site, during erection and at completion.

4) Inspections on site and name of the person(s) who perform the inspections.

5) Possible moisture sources at the construction site (rain, snow, groundwater, etc).

6) Weather protection measures chosen for the construction phase and an estimate of the necessary duration of protection.

7) Protection of timber components on site:

- during storage
- during assembly (as given by the level of protection)
- drying methods for wood above critical moisture level.

8) Controlled drying of structures down to the level of use of the building:

- risk assessment and prevention of wetting, including rain
- the project's vulnerability to unfavorable weather and exceptional circumstances
- determination of moisture level in the wood, drying methods, drying times and suitable drying conditions
- organisation of drying conditions
- effects on the building site's time schedule (alternative plans).

9) Moisture measurement plan:

- measurement method; perform moisture controls with a calibrated instrument and preferably following a standard measurement method
- time schedule
- documentation
  - type of measuring instrument
  - air temperature
  - measurement points and positions
  - measurement date
  - measurements values, any corrections and final values
  - assessments and conclusions
- the responsible person.

Control of materials and products at delivery and after storage

At delivery, check the identification of received materials and products against the specification in the Execution Specification. It should also be checked at delivery and after any storage for any damage. Control requirements at delivery, for compliance with the Execution Specification, are given in Table 2.

Table 2: Control of materials and product on construction site at delivery and after storage.

Subject	Execution class 1	Execution class 2	Execution class 3
Materials for temporary stabilizing and corrective measures	Spot checks of compliance with the requirements of 7.1	Systematic control of compliance with the requirements of 7.1	
Fittings and connectors	Spot checks	Systematic control	
Timber components	Spot checks of compliance with the requirements of 5.1 and 5.2	Systematic control of compliance with the requirements of 5.1 and 5.2.	
Other components	Spot checks	Systematic control	
Handling and storage on site	Spot checks of compliance with the requirements of 5.3 and 5.4	Systematic control of compliance with the requirements of 5.3 and 5.4	
Documentation	Not required	Required	

At an initial inspection, verify and document that the materials and products delivered to the construction site are according to the Execution Specification. If the order or the order confirmation is controlled and found to be in accordance with the Execution Specification, the delivery may be checked against the order or order confirmation.

A control at delivery should include the following checklist:

- amount and quality of the products according to the Execution Specification
- assembly instructions are provided, clear and sufficient
- there is no visible damage
- the moisture content of wood-based and other moisture-sensitive products is correct.

Errors, defects and damage should be documented and signed by both parties before the delivery ticket is signed, and reported to the responsible manager for the follow-up of deviations.

Control of execution

Control requirements for compliance with execution specifications are given in Table 3 and Table 4.

Table 3: Subjects for control of execution.

Subject	Execution class 1	Execution class 2	Execution class 3
Control of the manufacturing and erection	Control of compliance with requirements in 5.2.2 and Chapters 6, 7 and 8 that are important for further execution.	Control of compliance with requirements in 5.2.2 and Chapters 6, 7 and 8.	
Control upon completion[a]	Control of compliance with requirements in 5.2.2 and Chapters 6 and 8.		
Assembly of prefabricated timber components, timber elements and timber modules	Control of compliance with the requirements of 7.2.		
[a] If control upon completion is not possible, the structure or structural part should be controlled during erection. This applies for instance when the structure is enclosed.			

Table 4: Type of control and documentation of control.

Subject	Execution class 1	Execution class 2	Execution class 3
Scope	Visual inspection of all works. Random control measurements	Visual inspection of all works. Systematic and regular control measurements of important works. Possible additional requirements for control according to the Execution Specification.	Visual inspection of all works. Detailed control of all works of importance for the bearing capacity and durability of the structure. Additional requirements for control as specified in the Execution Specification
Type of control	Self-inspection	Self-inspection. Internal systematic control.	Self-inspection. Internal systematic control. Extended control.
Documentation of performed control	Not required	Required	
Documentation of as-built structure	Not required	Control of compliance with Execution Specification required	

Control of execution verifies and documents that the execution is in accordance with the Execution Specification.

Record, document and resolve deviations in accordance with 4.3.3.

A control of the execution should include the following checklist:

1) Control that the work done by others is sufficient and within tolerances so that it is ready for further work, such as:
   - correct position of the building (map references, position of the corners)
   - casted slabs, floors and foundations (height, position, diagonal measures and any surface deviations).
2) Control of supports.
3) Control of temporary bracing.
4) Control of external walls.
5) Control of roof.
6) Control of the assembly of prefabricated elements or modules.
7) Moisture control.

3.4.3 Measures in case of deviations

Handle deviations according to the quality system of the contractor (or their client, if applicable).

Where the control reveals deviations, take appropriate measures to ensure that the structure is suitable for the purpose.

Examine the following conditions in the order listed:

a) the significance of the deviation on further execution and appropriateness to the designed purpose

b) measures necessary to make the component acceptable

c) the necessity of replacement of a non-repairable component.

When required in the Execution Specification, the deviation should be corrected in accordance with a procedure specified in that specification or as agreed.

3.4.4 Competence requirements

General

Requirements for competence are specified in the following points:

- project leaders
- construction site manager, where relevant
- assembly manager for prefabricated timber components, elements and modules, where relevant
- carpenter
- inspection manager of internal systematic control, where relevant
- inspector for internal systematic control, where relevant.

The project leader, inspection manager for internal systematic inspection and assembly manager for prefabricated timber components, elements and modules are to be be present and available where the work is performed, to the extent found necessary.

The same person can cover multiple management tasks if competence requirements are met and documented.

Project leader

The project leader has the top professional supervision of all parts of the works, including scaffolding, element assembly, transport, erection and finishing operations, depending on what is relevant for the specific project, also when done by subcontractors, hired workers or chartered business enterprises.

The project leader needs to have:

- understanding of loads and structural behaviour during the construction period and in the final state
- thorough knowledge of building technology, choice of construction methods and equipment
- understanding of how moisture and weather conditions affect execution
- understanding of the necessary requirements for timber properties
- understanding of required control of the works.

The project manager needs to understand the principles of the performed work operations, and have knowledge of critical aspects of the execution. For assembly of elements, the project leader will have undergone training in the relevant technological field.

When working in Execution Class 1 and 2, the project leader needs to have, at least:

- relevant craft certificate or equivalent qualifications
- necessary relevant supplementary education
- the experience necessary for the work.

When working in Execution Class 3, the project leader needs to:

- be an engineer with special qualifications for leadership of execution of timber structures or have equivalent knowledge
- have necessary relevant supplementary education
- have documented relevant experience in execution of timber structures in execution class 3.

Construction site manager

The daily work is carried out under the management of construction site manager with:

- relevant craft certificate or equivalent qualifications
- necessary relevant supplementary education
- work experience in similar type of work.

Assembly manager for prefabricated timber components, elements and timber modules

The assembly manager will lead the assembly work at the construction site according to the assembly plan.

The assembly manager needs:

- proven skills on structural behaviour, materials used, required weather protection, securing of elements and requirements for working at heights
- necessary knowledge of stability, stays, mooring and lifting
- proven experience of similar work.

Carpenter

The carpenter needs to:

- have craft certificate or equivalent qualifications
- know the requirements, rules and regulations applicable to assembly work
- have a basic understanding of concepts such as stability, stays, mooring and lifting.

Control manager for internal systematic control

The internal systematic control of the execution will be carried under an overall supervision of the Control Manager with experience in technical control, good insight into what is critical work operations and good insight into what is critical for the structural functionality.

The qualification requirements to the Control Manager of a work are corresponding to the requirements of the project leader. Experience both from the construction site, as a designer and with control work is relevant practice.

Where the Inspection Manager delegates parts of their tasks, the person delegated needs to have equivalent qualifications for the particular field.

Where a subcontractor performs parts of the works, the qualification requirements for the control manager of the subcontractor's control manager are equivalent to the one that leads the subcontractor's work.

Inspector for internal systematic control

The Inspector for internal systematic control needs to have adequate theoretical and practical knowledge to perform the allocated tasks, and a good understanding of the work to be performed.

4 Timber Materials

4.1 General

4.1.1 Product properties

Mark products for identification and, where required in the Execution Specification, the planned position in the structure.

Products must be in accordance with the Execution Specification and satisfy relevant product standards. Any surface treatment and structural protection must be in accordance with the Execution Specification and the manufacturer's instructions. Surfaces visible in the completed structure should not be exposed to sun and moisture, which would lead to an unattractive appearance.

4.1.2 Prefabricated elements and modules

Elements and modules manufactured in a factory are, until the delivery at the construction site, covered by the relevant product standards (prefabricated products). If the elements or modules are built on the construction site, the requirements in the relevant product standards apply, but from the time these are transported away from the place of production, the requirements of this standard apply. For prefabricated elements and modules not covered by any product standard, the provisions for manufacturing in this standard apply.

4.2 Moisture

4.2.1 Moisture level upon delivery on site

Where the Execution Specification contains requirements for moisture content upon delivery, control the moisture level of the delivered materials using the measurement methods referred to in the quality plan.

Control materials on delivery according to the execution class (see Table 2).

Unless otherwise agreed, the following moisture level is normally assumed upon delivery:

- solid timber for studs, plates, joists and trusses (non-pressure-treated): 10 to 16%
- solid timber for studs, plates, joists and trusses (pressure-treated): 16 to 24%
- glulam and Cross-laminated timber: 10 to 16%
- LVL, OSB, plywood and particleboard: 8 to 14%.

4.2.2 Moisture level during execution and upon completion

During transport, storage and erection at the construction site, keep the moisture level in the materials under control with weather protection and by controlling the moisture level in accordance with the moisture control plan. Make measurements where the humidity is highest or in areas with the highest risk of biological growth. It may be necessary to measure the moisture in the timber several times during the execution. Upon completion, control and document the moisture level.

Closure of timber structure (establishment of barrier layers) is not allowed until the desired moisture level is achieved, typically lower than 18%. It is assumed that other materials enclosed inside the structure are sufficiently dry.

For structures that dry very slowly after the closure, such as walls below ground level, compact timber roofs and sleeper floors with an impermeable coating, the critical moisture level may be lower than 18%. For such structures, a separate risk assessment with regard to critical moisture level should be provided in the Execution Specification.

At high moisture levels, assess what measures will be taken, such as further moisture measurements, drying measures or replacement of wood. Where there is visible mould growth, implement measures before closure of the structure.

Moisture control plans may differ from the Execution Specification where well justified, for example by changes in conditions on the construction site. Document the deviation. Such deviations must not reduce the quality of the completed structure.

4.3 Handling

Upon delivery and before installation, control handling so that there are no defects or malfunctions of materials or products (scratches, distortion from incorrect stacking, dirt, grease…).

Plan handling and carry out risk assessments in order to prevent damage.

Make available a lifting plan for heavy or complex lifting operations.

4.4 Storage and Weather Protection

Store products in accordance with the manufacturer's instructions.

In storage, keep the base flat and stable. Have at least 100 mm clearance from the terrain. On moist terrain, establish a barrier layer with necessary fall for runoff to protect against evaporation from the ground. Ensure good air circulation. Stack timber materials in such a way that damage does not occur at the bearings and there is no danger of overturning.

Cover the structures as follows, depending on the specified weather protection requirements, to avoid undue wetting:

a) No protection required

- relevant for only short periods (e.g. during erection and before sealing the roof) with no requirement to the appearance or where surface protection or other means provide protection
- structures with effective runoff (such as vertical structural surfaces).

b) Shielded and ventilated

- structures with required wood moisture to be to under 18%
- relevant for storage at the construction site
- structures erected over a longer period in areas with the risk of heavy rainfall
- the base does not contribute to wetting by capillary action.

c) Protection with tents or a temporary roof built over the roof

- structures with required wood moisture to be to under 12%
- relevant for structures with special requirements for moisture level and appearance.

Select weather protection during storage based on an assessment of the risk of wetting.

5 Connections

5.1 General

Follow the Execution Specification and the manufacturer's instructions during installation of fasteners.

Perform connections according to the Execution Specification.

Generally, the moisture level in the wood during assembly should not differ significantly from the moisture level in the connection as a whole.

Make connections so that the surfaces are planar, congruent and get good rest. Do not place connections on active faults, such as cracks, knots and dull edges, where this has an impact on the capacity or function of the connection.

Assemble structures in such a way that connections are not overloaded. Replace connections that have been skewed, cracked or that are poorly fitted.

Do not allow dirt and water collecting pockets in connections caused by the execution.

Where pre-drilling for mounting of fasteners is necessary, but not specified in the Execution Specification or in this standard, report the deviation to the designer in order to ensure that the strength and rigidity of the connection are achieved.

Ensure the connection is corrosion-resistant and fire-protected as specified in the Execution Specification.

Fasteners must be in accordance with the Execution Specification, which complies with relevant product standards.

5.2 Nail Connections

Connections require at least two nails.

Unless otherwise specified in the Execution Specification:

a) Perform skew nailing and skew screwing with approximately 45° angle with a minimum distance equal to 10x nail diameter *d* to the end (see Figure 2).

b) Nails are normally nailed perpendicular to the fibre direction and in a depth so that the nail head is flush with the surface of the wood.

c) Cross-loaded nails require a minimum anchoring length of 8x nail diameter *d*.

d) The diameter of the pre-drilled hole should not exceed 0.8x nail diameter *d*.

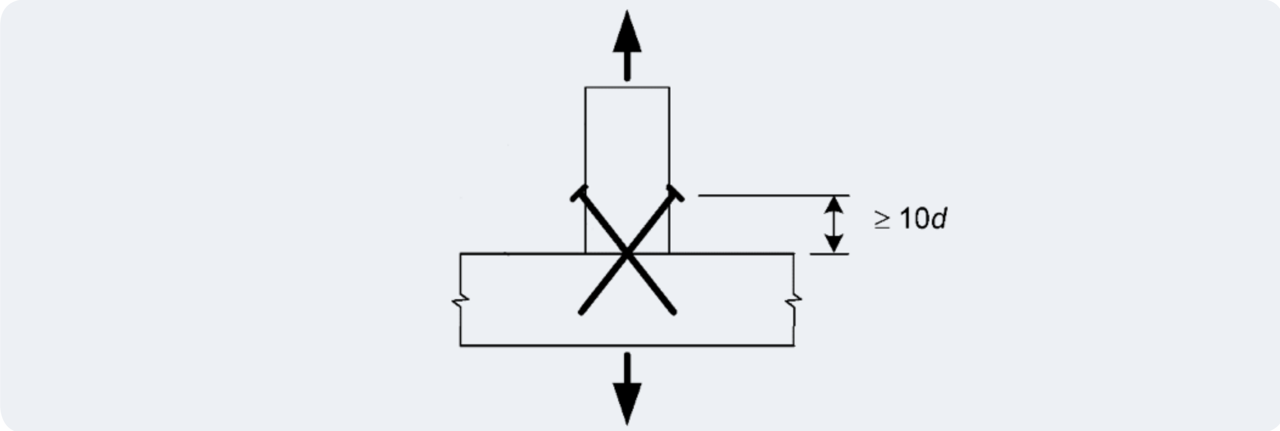


Figure 2: Skew nailing of connections.

5.3 Screw Connections

Pre-drill according to the manufacturer's instructions. Where instructions are not available, the holes may normally be pre-drilled with the following requirements:

- the hole for the shaft should have the same diameter as the shaft and the same depth as the length of the shaft
- the hole for the threaded part should have a diameter equal to 0.70x the shaft diameter
- guiding holes and pre-drilling holes for self-tapping screws require a diameter less than the internal thread diameter of the screw.

Pre-drilling can prevent cracking and injuries during execution. Pre-drilled holes may be appropriate to ensure proper placement and orientation of the screw. Test drilling may be used to check the suitability of the selected technical solution.

Unless otherwise specified in the Execution Specification, the anchoring length of screws needs to be at least 6x the screw diameter *d*.

Avoid overpulling of screws.

5.4 Bolt Connections

Select the bolt length so that at least one full thread round is above the nut, measured from the nut outer surface to the end of the bolt after tightening.

Ensure the diameter of the bolt hole in the wood is not any more than 1 mm larger than the bolt diameter *d*.

Washers against wood need a side length or diameter of at least 3x bolt diameter d and a thickness of at least 0.3x bolt diameter *d*. Mount washers under the bolt head and nut with complete contact surface.

Screw nuts on the corresponding bolt and tightened them so that the parts fit tightly. Repeat the tightening if necessary when the timber has reached its equilibrium moisture to ensure the structure's capacity and rigidness.

Avoid overpulling of bolts.

5.5 Dowels

Pre-drilled holes in the timber require have a diameter smaller than the dowel.

5.6 Glued Connections

Glued connections, where the adhesive bond strength is a precondition for the capacity in the ultimate limit state, need to be in accordance with the Execution Specification and controlled in order to ensure that the reliability and quality of the connection are consistent with the technical specification.

Follow the adhesive manufacturer's recommendations with regard to composition, environmental conditions for application and curing, the moisture content of the components and other factors relevant for the proper application of the adhesive.

For adhesives that require post-curing in order to secure full strength to be achieved, postpone the application of load on the connection until full strength is achieved.

Use adhesives that are not corrosive and are chemically neutral in relation to the base materials.

Adhesives should not be hygroscopic and be durable in the environment in which they are used. Ensure they are resistant to ageing, and adapt the curing temperature to the properties of base materials.

6 Special Provisions for Execution

6.1 Temporary Stabilising and Correcting Measures

6.1.1 Basic requirements

Safeguard elements and structural parts before and during construction. Ensure temporary support and bracing. Before commencing the work, agree which measures are to be implemented and who is responsible. Carry out measures in such a way that the structure or structural part:

- can withstand all foreseeable loads it can be exposed to during the construction process
- is rigid enough to ensure compliance with the specified geometrical tolerances
- does not get defects.

Treat the form, function, appearance and durability of the permanent timber structure with caution during assembly, use and disposal of temporarily stabilising and correcting measures.

Where the Execution Specification specifies stabilising measures, report deviations to the designer and document the divergent measures.

Ensure materials for temporary stabilising and correcting measures comply with the relevant product standard and are fit for the purpose to ensure the safety and requirements of the structure are met. Where there is no such product standard, take into account the properties of the material.

6.1.2 Design and assembly

Consider whether it is necessary to develop a description of methods for the assembly and dismantling of temporary supports and bracings.

Unless otherwise agreed, the contractor is responsible for the design of temporary stabilising and correcting measures. In the design of temporary supports and bracings, consider deformations that may occur during the execution of the permanent timber structures.

Where the design of the final permanent structure assumes support, bracing or other measures to the structure before other parts are in place, state this in the Execution Specification.

Do not remove temporary stabilising and corrective measures before the permanent timber structures are sufficiently secured to:

- prevent damage during demolition, e.g. to people, equipment or structures
- carry the loads applied to the timber structure at this stage
- avoid damage due to climatic effects.

Where the order for the removal of temporary stabilising and corrective measures are important, methods should be described and included in the Execution Specification.

6.2 Assembly of Prefabricated Timber Components, Elements and Timber Modules

The assembly plan specifies the execution of the connections, necessary stabilising and bracing measures, tolerances for the execution, safety measures, requirements for weather protection, any sequence of work and other necessary measures in the assembly phase.

Make the assembly plan available on site.

The assembly may be initiated when the previous works are adequately controlled.

Where relevant, perform a control of the assembly before the further works make control difficult.

Make available assembly plans showing element positions, as well as the reach and capacity of the building cranes. When required, access and working scaffolds should appear in the assembly plan.

Carry out measures to ensure the stability of the supports during construction and to reduce the risk of damage to such supports, with special considerations to achieving a safe installation and avoiding accidents and injuries. For beams and floors, minimum edge distance and support width should be specified in a way that facilitates both installation and control.

Ensure assembly of prefabricated elements and modules conform with the assembly plan, the Execution Specification and the order of work in the work program.

During assembly, control the positions of the prefabricated elements, the accuracy of the geometry and the position of the supports, the joints and the total formation of the structure and make any necessary adjustments.

The completed structure must be within the maximum permissible deviations to avoid detrimental effects in terms of:

- load-bearing capacity and stability in transient and service stages
- service performance during the use of the structure
- placing compatibility for the erection of the structure and its non-structural components.

The compound construction tolerance (the box principle) requires that all points of the structure are within the specified theoretical position with a margin in any direction corresponding to the permitted deviation.

Specify Tolerance Classes for the assembly in the Execution Specification, and when selecting tolerance classes, consider the production tolerances and requirements for the finished surface.

Production tolerances for timber components, elements and modules must be in accordance with the permitted deviations specified in the relevant product standard. For prefabricated elements and modules where production tolerances are not given in a product standard, the values for permitted deviation for Tolerance Class 3 given in Table 5 and 7 may be used as production tolerances.

Assembly tolerances must comply with permitted deviations given in Tables 5, 6 and 7. Unless otherwise stated in the Execution Specification, Tolerance Class 1 applies. During the design phase, consider the assembly tolerances.

This Guideline does not specify requirements for the combination of geometrical tolerances and deformations in the structure due to the applied actions. Permitted deviations apply to the situation prior to the occurrence of deformations due to loads and time-dependent deflections, unless otherwise stated in the Execution Specification.

Long-term effects resulting from normal creep, dimensional changes due to moisture, assumed use or settings, should have been taken into consideration during the design and are not covered by the permitted deviations.

If the requirements of this Guidelines are to be applied beyond the conditions defined above, this must be described in the Execution Specification.

Specify any requirements for special tolerances in the Execution Specification and give the following information:

- any amendments to the permitted deviations given in this Guideline
- any further type of deviations to be controlled, together with defined parameters and permitted values
- whether these special tolerances apply to all relevant components or to particular components which are identified.

If using more lenient permitted deviations than Tolerance Class 1, it should be documented that the design assumptions are met for the completed structure.

If a certain geometrical deviation is covered by different requirements, the strictest requirement to permitted deviation applies. Where components are incorporated in a structure, requirements for permitted geometrical deviations for such components will be subordinate to the requirements of the completed structure.

The specified permitted deviations of beamlines and floor levels also apply to other horizontal and sloping structural parts.

Permitted deviations for the support width of prefabricated beams and floors are not specified in this standard. They should be specified in the assembly plan or as technical information for the prefabricated element.

Permitted deviations for surfaces between components where forces are intended to be transmitted by full contact bearing between the surfaces are not specified in this Guideline. State any requirements for such surfaces in the Execution Specification.

The requirements for tolerances refer to the dimensions given in the Execution Specification. Position tolerances in plane refer to the construction axis grid (or secondary lines) in the plane. Position tolerances in height refer to the construction axis grid in height, e.g. a transferred height benchmark. Specify any requirements for the construction axis grid in the Execution Specification.

Handle deviations from the specified tolerance range in accordance with 4.4.3. Deviations that have no significant consequence on the performance of the completed structure may, by agreement, be ignored.

Tolerance Class 1

- Normal tolerances for the primary structure.
- Primary structures where a secondary structure with more stringent requirements for permitted deviations is built on site allowing adaptation, for example filling in timber framework and joists.
- Structures or structural parts where there are no strict requirements for the properties in use, for example roof structures, garages, warehouses and agricultural buildings.
- Secondary structures without strict requirements for surface deviations, such as floors in agricultural buildings, warehouses and garages.

Tolerance Class 2

- Load-bearing elements.
- Primary structures to be adapted to prefabricated elements and modules, such as wall elements.
- Normal tolerances for secondary structures.

Tolerance Class 3

- When strict requirements are necessary.

Table 5: Geometrical assembly tolerances for structural components such as walls, columns, beams and roof trusses/rafters.

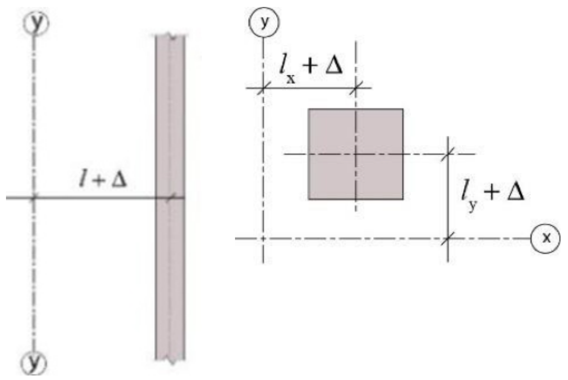
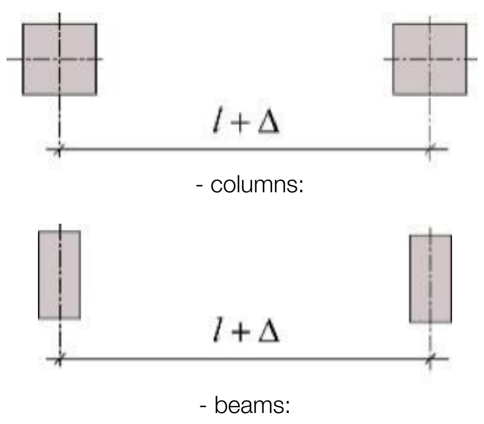
Type of deviation	Description	Permitted deviation		
		Tolerance Class 1	Tolerance Class 2	Tolerance Class 3
Position in plane relative to secondary lines		± 15 mm	± 10 mm	± 5 mm
Distance between individual beams, distance between individual columns and walls		± 30 mm	± 20 mm	± 10 mm

Table 5 (continued): Geometrical assembly tolerances for structural components such as walls, columns, beams and roof trusses/rafters.

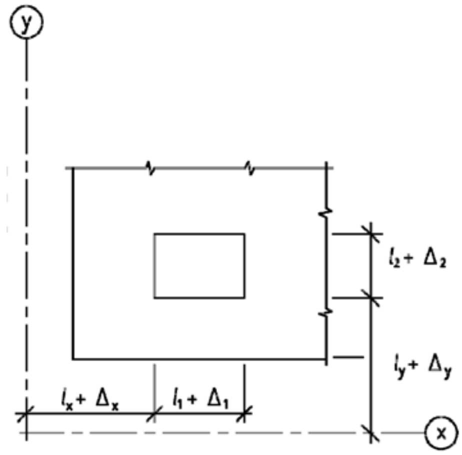
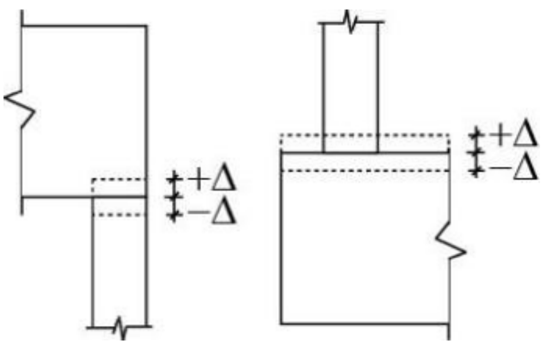
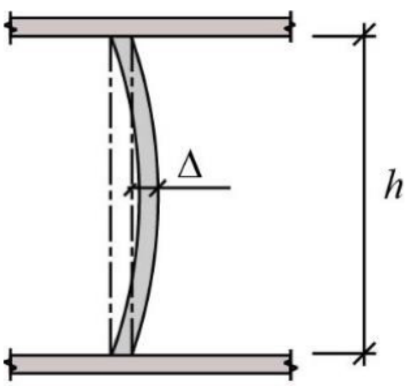
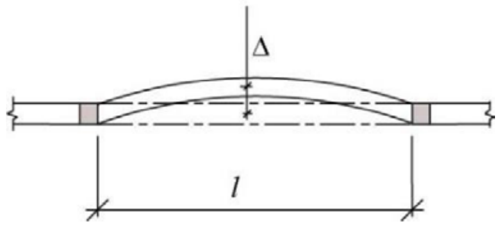
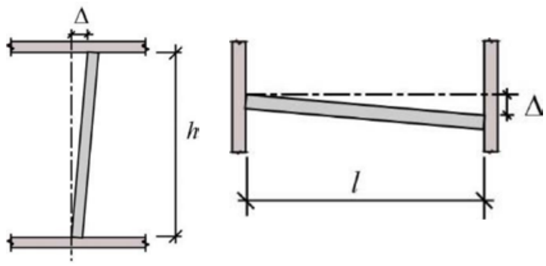
Type of deviation	Description	Permitted deviation		
		Tolerance Class 1	Tolerance Class 2	Tolerance Class 3
Distance between beams in frames, distance between roof trusses, distance between studs		± 15 mm	± 10 mm	± 5 mm
Dimensions of recesses for doors, windows or stairs etc. (Δ1). Position of recesses for doors, windows and stairs etc. (Δ2) [a]		± 15 mm	± 10 mm	± 5 mm
Vertical position of the support of beams, columns or roof trusses/rafters	- beam supports - column supports 	± 15 mm	± 10 mm	± 5 mm
Curvature/ straightness of walls and columns		Minimum of ± 20 mm and 2 ‰ /3,3 ‰ of the height for glulam and solid timber, respectively	Minimum of ± 10 mm and 2 ‰ /3,3 ‰ of the height for glulam and solid timber, respectively	Minimum of ± 5 mm and 2 ‰ /3,3 ‰ of the height for glulam and solid timber, respectively

Table 5 (continued): Geometrical assembly tolerances for structural components such as walls, columns, beams and roof trusses/rafters.

Type of deviation	Description	Permitted deviation		
		Tolerance Class 1	Tolerance Class 2	Tolerance Class 3
Horizontal curvature/ straightness of beams or top/ bottom girders	 l = length between braced points	Minimum of ± 20 mm and 2 ‰ /3,3 ‰ of the length for glulam and solid timber, respectively	Minimum of ± 10 mm and 2 ‰ /3,3 ‰ of the length for glulam and solid timber, respectively	Minimum of ± 3 mm and 2 ‰ /3,3 ‰ of the length for glulam and solid timber, respectively
Total inclination from the designed plane for walls, columns, beams and floors.		Minimum of ± 15 mm and 5 ‰ of the height/ length	Minimum of ± 10 mm and 3 ‰ of the height/ length	Minimum of ± 5 mm and 1,5 ‰ of the height/ length

[a] The requirements in the table do not apply when the manufacturer of doors and windows specifies other tolerances.

Table 6: Type of control and documentation of control.

Type of deviation	Description	Permitted deviation
Connections	Gravity centre of connections	± 10 mm
	Position in plane for fasteners	± 10 mm
	Distance between fasteners	± 10 mm
	Inclination of fasteners	± 5°
	Edge distance	-5 / +10 mm
	Side distance	-5 / +10 mm

Table 7: Other geometrical assembly tolerances.

Type of deviation	Description	Permitted deviation		
		Tolerance Class 1	Tolerance Class 2	Tolerance Class 3
Compound construction tolerance (the box principle)	See other requirements in clause 8	± 50 mm	± 30 mm	± 15 mm
Joint between structural parts or elements	Discontinuities at laps etc.	± 10 mm	± 6 mm	± 3 mm
	The thickness of joints etc. Deviation from nominal value	± 10 mm	± 6 mm	± 3 mm