Fire Design for Multi-Story Timber Structures

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Climate change impact seen in every continent.It is affecting every nation´s economies and human health.Climate getting warm (Warming of 1.5°over past century), so that ice is melting to rise sea levels. (united nation, n.d.). So to tackle and combat climate change involves the use of renewable materials such as wood, many researching has been conducted to get way to replace convention building materials (steel and concrete), that are the main the factor that contribute to acceleration of climate changing. Wood which is a carbon-sink, renewable, eco-friendly, and sustainable non-conventional construction material is solution to this problem. Now timber multi-story buildings are becoming common in Finland every year as national building code of Finland is modified to permit the construction of multi-story timber building when knowledge of timber design and progressive technology of timber allowed mass timber product to be used safely against fire.Using wood as a construction material found to have positive effects on well-being.The researchers aim to show that using wood for interior design, for example, increases well-being, creativity, and efficiency, which then produces measurable economic value. (Puutinfo, 21.9.2018.)

The aim of thesis is to discuss different codes and standards of different country that compares prescriptive and performance-based fire design of residential multi-story timber structures.

As the result it will be clear why we need to design multi-story timber building mixing perspective design approach and performance as both guarantee fire safety of tall timber building

Keywords Fire design, tall timber, prescriptive fire design, performance fire design.
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Contents

1 Introduction

From a fire safety perspective tall timber-structure is interesting topic that is being circulating among fire structural designer and design approving authorities. The main reason for this is timber building is being associated with fire hazardous events based on historical (happened history of disastrous and devastating timber building billowing-up in fire) and statistical parameters that engulf that fact that timbers fire resistance overwhelms its limitations regarding fire resistances. Timber as construction material has advantages and disadvantages when societies give priority to fire safety. By taking into consideration its advantageous side and mitigates the disadvantages, tall timber buildings can be designed to achieve equivalent or better levels of fire safety than concrete and steel such as intended by the prescriptive solution.It very well-known timber is a combustible material that contribute to fire load, though that, in construction it has significant insulating properties and burns in a slow, predictable, and measurable way.These factors see timber perform strongly against fire and give designers the ability to confidently create strong, durable, fire-resistant timber constructions .(Woodsolution.com, n.d.)

1.1 Background

According to ministry of the Environment of Finland, wood construction plays a vital role in the promotion of bioeconomy, and the promotion of the use of wood can help support sustainable and sensible tending of forests. Using wood reduces the carbon footprint of the construction industry when evaluating the entire life cycle of wood from the raw material through manufacturing, use and recycling. The carbon bound by trees is retained in structures and furnishings for a long time and affects the overall environmental impact of the construction industry positively. Increasing the amount of wood used in construction is also an efficient way of attaining the energy and climate targets laid down in the National Energy and Climate Strategy and to reduce Finland's carbon footprint by 2030 (ministry of the Environment of Finland).Tall multi-story timber building is uncommon in Finland like many European country but highly recommendable by many sectors of Finnish government for many purposes. There is strong political support for wood construction in Finland. The aim of increasing the share of long-term carbon-storage products and structures has been set in several national strategies and programmers in Finland.Finland also has a national Wood Building programme. Wood construction is promoted in the Government programme, the National Energy and Climate Strategy, National Forest Programme and Finnish Bioeconomy Strategy. Also, the Climate plan for the land use sector, which is drawn up in 2021, promotes the use of wood in long-term carbon binding structures .(ministry of agriculture and forestry of Finland, n.d.).So being timber future protentional building element using timber in multi-story building need more study to investigate its issue related to fire. In many countries designing timber building is mostly based on tradition way of designing but recently discovered way of designing that give priority to how timber building perform in fire rather than to prescriptive set of rules to follow blindly. Fire safety in multistory timber buildings has been covered in many recent studies, like *´´paloturvallinen puutalo ´´*by Finnish language written by T.Lahtela, 2021.

1.2 The purpose of my thesis

The purpose of my thesis is to compare prescriptive and performance fire design approach of multi-story timber building against fire and to discuss how these two approaches differ in different countries and to discuss different ways to meet fire performance requitement by complying with governmental and structural performance.

Important research questions answered based on my thesis objective

What is the difference between prescriptive and performance fire design approach?

What are the advantages and disadvantages of different fire design methods?

Is there a way to combine different methods (prescriptive vs. performance based)? use in the same multi-story timber building design in Finland?

How could we mitigate some problems of performance-based approach?

What should be done so the methods could be applied in Finland?

Why we need performance-based design approach if prescriptive based design is giving full safety.

Why these questions are important?

Knowing pros and cons of different fire design methods is good step in design selection judgment. Knowing the ways to combine different methods is mitigating some limitation of one another. Knowing the ways to use both methods in Finland would reduce rigidity of building code and will increase familiarity of performance-based design approach.

1.3 Literature review and methodology

Literature reviews summarized from the available knowledges and gained information from fire safety in tall timber buildings dedicated companies. Since fire designing needs experts, two (KK-Palokonsultti and Kauriala Oy) Finnish fire design companies were consulted, because these two companies are among leading companies for fire designing and they have highly competent and skilled designers (Satu Holopainen (Chief Fire Safety Expert at KK-Palokonsultti Oy), and Timo Jokinen, (Senior Fire Safety Specialist, at Kauriala Oy) was conducted for consultation .It because KK-Palokonsultti Oy(KK-Palokonsultti Oy is Finland's leading fire safety design agency) and Kauriala Oy are most fire design leading companies in Finland: so their staffs who was conducted are expert at fire designing in different fire design approach). The literature review consists of reports such as technical reports of WoodSolution (not for profit company that provides national research and development and promotional services to the Australian forest and wood products industry), given information and articles from Puuinfo oy which is the Finnish Timber Council. Standards and codes of Finland is used for refence and compared with other country's codes. IBC, NCC, NFPA Codes (Amrican national standrad institute) is referred. Books written by expert also referred. Literature Review meant to evaluate information available in literature that can be used to categorize fire safety design in tall timber buildings.

2 Wood as building material

Wood as construction material is as old as human civilization commenced but it is not used contently and constantly as other building material like concrete and steel throughout human civilization eras. At some point of human civilization, timber as construction material was limited by law up to 2-story building, this restriction comes as result of fire destruction of timber building. In 1904, the Norwegian city of Ålesund experienced a large fire which was allegedly caused by a cow kicking over a torch near the timber framed Ålesund Preserving Company's factory. Gale winds traveling over the village caused the fire to spread to the entire city, which mainly consisted of timber-framed houses. (Robert Gerard & David Barber,2013). Consequently, fire regulations started to appear in building industry. For example, For the former Ugrian region, Joseph II the Emperor signed the first fire protection order in 1788. There were 25 paragraphs in the order, where obligations were described for house owners, but also for chimney- sweepers, bricklayers, and other tradesmen. This order is the very first standard of firefighting measures in the region. (Stefko, & Osvald, 2021)

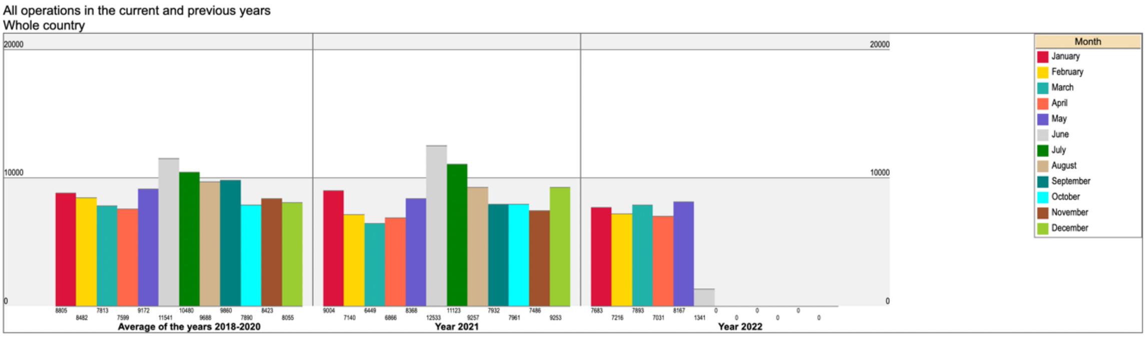
In Finland, the fire code was modified in 2011 to enable the construction of multi-Story wooden buildings up to eight Stores, although there are special regulations for wooden buildings, including sprinkler requirements. However, the wooden the construction products are regarded very fire safe. In a case of fire, the steady charring of wood material makes the endurance and behavior of the structure easy to predict. In addition to the sprinkler system, there are ways to structurally protect the wood. Most commonly, the material is covered with a drywall, which keeps the temperature low and keeps the fire away from the wood material for a certain amount of time. (Puuinfo, n.d.)

Fire is never leaving unwanted phenomena that accompanied and will accompany any form of human civilization. The relevant fire incident from statistics Finland for 2018-2021 is shown in Fig. 1. According to statistic from Finland website there is great deal of accident related to fire of building. As it can be seen in figure 1. about450 building at fire risk of fire every month in Finland if risk of fire increased. Every building material will be negatively impacted by exposure to fire. Steel buckles by high temperature, concrete will deteriorate and wood burns to ash. The idea of building with larger pieces of wood is to allow the outside of the wood to char before the internal wood structure is compromised. This process typically takes two to three hours, with a single plank of wood. Therefore, it will take longer with a double plank, or one covered with a heavy building material. Each Authorities having jurisdiction will rule on a case-by-case basis if wood construction should be permitted.

Due the advancement of technology (usage of Sprinklers, Fire retardative painting, specification of cavity barriers, detection, and alarm systems) and the extensive research in the field of fire safety of timber buildings (Charing of wood showed wood resist fire, fire rating can be improved by using adequate cladding and correct sizing, encapsulation) restriction of timber usage in constructions of multi-story timber structures is relaxed.

Figure 1.Statistic of fire incidents in Finland

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
Average of the years 2018-2020	8805	8482	7813	7599	9172	11541	10480	9688	9860	7890	8423	8055	**107808**
Year 2021	9004	7140	6449	6866	8368	12533	11123	9257	7932	7961	7486	9253	**103372**
Year 2022	7683	7216	7893	7031	8167	1341	0	0	0	0	0	0	**39331**



2.1 Property of wood

Like any construction materials, timber has properties that demonstrate how timber reacts with fire and other property related to strength and stiffness. Wood as building material has many essential properties ranging from simple to complex propert.

2.1.1 Strength and stiffness properties of wood

The Strength of wood directly proportional to density and Density is an important material parameter since it affects other properties such as thermal conductivity and mechanical properties. And density depends on moisture content that in turn will affect both mass and volume!. Most commonly the density of wood is given as dry air density, whereby the mass and volume of the wood are measured with its level of moisture at 15 % (or 12 %). Pine and spruce are the most common in construction.in Finland. The density of Finnish pine is 370 – 550 kg/m3, spruce 300 – 470 kg/m3 and birch 590 – 740 kg/m3. In the main Finnish trees, the density and strength of the wood decreases as you go from the base to the top. In pine, the longitudinal change in density is greater than in spruce. The density of the wood increases with age in species of tree in which the density increases from the core out towards the surface. The strength of the wood is fundamentally affected by the direction in which it is loaded in relation to the grain. In the direction of the grain, the bending strength is directly proportional to the density of the wood. In uniform, flawless wood, the bending strength is as great as the tensile strength. Tensile strength in the direction of the grain is usually 10-20 times more than its strength perpendicular to the grain. Tensile strength also depends on the density of the wood: for example, the tensile strength of the spring wood in a pine is only 1/6 of that of summer wood. The compression strength of air-dry wood is about half of the corresponding tensile strength. The shearing strength of wood is 10-15 % of its tensile strength in the direction of the grain. Shearing strength is weakened by knots and faults and cracks that appear in the wood. The elasticity and durability of wood increase as its density increases. The modulus of elasticity of wood in the direction of the grain may be up to a hundred times more than the same parameter perpendicular to the grain. In the radial direction, the modulus of elasticity is about twice as great as the same parameter in a tangential direction. (Puuinfo.fi,2020)

2.1.2 Fire property of wood

When the temperature of wood rises to 100 ºC, chemically unbound water begins to evaporate from it. The thermal softening of dry wood begins at a temperature of about 180 ºC and reaches its maximum between 320 ºC and 380 ºC. Then the lignin, cellulose and hemicellulose in the wood begin to disintegrate. The softening of moist wood begins earlier, at about 100 ºC. The ignition temperature of wood is affected by how long itis exposed to heat. Wood usually ignites at 250 – 300 ºC. After ignition, the wood begins to carbonize at a rate of 0.8 mm per minute. Fire progresses slowly in a solid wood product, as the layer of carbon created protects the wood, and slows down the increase in temperature of the wood's inner parts and thus the progress of the fire. For example, at a distance of 15 mm from the carbonization limit, the temperature of the wood is under 100 ºC. This property is utilized in dimensioning load-bearing structures, among other things. In glued laminated wood, the speed of carbonization is less at 0.7 mm/min. The ignition sensitivity of wood increases as its density and moisture content decrease, and as the thickness of an individual piece of wood decreases. The sharp corners, rough surface, flaws and cracks of timber also increase the impact of fire. (puuinfo, 2020)

2.1.3 Timber products

Wood's potential from a carbon footprint perspective is much broader than many thought possible. Worldwide, mass timber buildings are now surpassing 20 stories, and the International Code Council (ICC) has approved changes to the 2021 IBC that will allow up to 18 stories in the U.S. While innovative systems continue to be developed within the mass timber category, common products currently include:

Cross-laminated timber

CLT consists of layers of dimension lumber (typically three, five, or seven plies) oriented at right angles to one another and then glued to form structural panels with exceptional strength, dimensional stability, and rigidity. CLT can be used for walls, floors, and roofs—as a stand-alone system or with other structural products (e.g., post and beam) and is often left exposed on the interior of buildings. Because of the cross-lamination, CLT offers two-way span capabilities.

Glued-laminated timber

(glulam or, when used as panels, GLT) – Glulam is composed of individual wood laminations (dimension lumber), selected and positioned based on their performance characteristics and bonded together with durable, moisture-resistant adhesives. These adhesives are applied to the wide face of each lamination. Glulam has excellent strength and stiffness properties, and is available in a range of appearance grades. It is typically used as beams and columns, but can be used in the plank orientation for floor or roof decking. It can also be curved and bent, lending itself to the creation of unique structural forms.

Nail-laminated timber (NLT) – NLT is created from individual dimension lumber members (5cm-by-4cm, 5cm-by-15cm, etc.), stacked on edge and fastened with nails or screws to create a larger structural panel. Commonly used in floors and roofs, it offers the potential for a variety of textured appearances in exposed applications. Like glulam, NLT lends itself to the creation of unique forms, and wood structural panels (WSPs) can be added to provide a structural diaphragm.

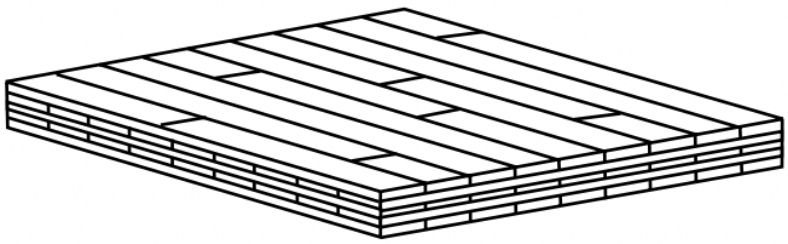
Dowel-laminated timber (DLT) – Common in Europe and gaining popularity in the U.S., DLT panels are made from softwood lumber boards (5cm-by-4cm, 5cm-by-15cm, etc.) stacked like the boards of NLT but friction-fit with hardwood dowels. The dowels hold each board side-by-side, while the friction fit adds dimensional stability.

Structural composite lumber (SCL) – SCL is a family of wood products created by layering dried and graded wood veneers, strands, or flakes with moisture-resistant adhesive into blocks of material, which are subsequently re-sawn into specified sizes. Two SCL products—laminated veneer lumber **(LVL**) and laminated strand lumber (LSL)—are relevant to the mass timber category as they can be manufactured as panels in sizes up to 243.84cmwide, with varying thicknesses and lengths. Parallel strand lumber (PSL) columns are also commonly used in conjunction with other mass timber products.

Tongue and groove decking (T&G) – Structural T&G decking is made from lumber at least 2.5-3.8cm thick, with the flat (wide) face laid over supports such as beams or purlins for floors and roofs. Available in a variety of species, thicknesses and lengths, it is used where the appearance of exposed wood decking is desired for aesthetics or where its mass is desired for fire resistance.(McLain, & Breneman ,2019)

CLT is made from sawn timber boards glued together in layers at 90° to each other as shown in Figure 2 , rather like thick plywood. CLT is manufactured in large panels several metres in each direction. The individual board thickness is usually between 10mm and 40mm, sometimes with different thicknesses in one panel. The most common layups are three-ply, five-ply, or seven-ply, so the finished thickness of typical panels is from about 40mm (three thin layers) to 300mm (seven thicker layers) or more. Some manufacturers glue the edges of the boards together, whereas others leave the edges with no adhesive. Most CLT is used for prefabricated building systems, with pre-assembled panels for walls or floors. Most CLT panels are glued with one-component polyurethane adhesive, although some manufacturers offer other adhesives or even non-glued panels where the boards held together with nails or hardwood dowels. If no delamination of layers occurs, CLT has roughly similar fire properties to solid timber or glulam, but the effect of gluelines and the influence of layers in the weak direction must both be allowed .CLT panels with the best fire performance will be those with thick layers of wood, especially the layer on the fire-exposed face. (Buchanan & Abu, 2017)

Figure 2.Typical cross laminated timber panel(Buchanan & Abu, 2017)



2.2 Example tall Building project in Finland and abroad

The tallest wooden building in Finland so far is the Joensuu Lighthouse student dormitory, which has 14 floors. The fire safety design for the building is based on functional fire design, as the standard E1 tables only cover wood buildings up to 8 Stores high. The fire protection for the structures is based on gypsum board cladding and the charring rate of the underlying wood structure. There are sprinklers throughout the building (OH1 level, two-way water supply), but functional fire design has shown that the building can withstand a design fire even if the sprinklers do not work. VTT inspected the ventilation system by modelling the building. The title of the world's tallest timber-framed house is the 18-storey Mjøstårnet Hotel, built in Brumunddal, Norway.(PUUINFO OY, n.d.)

Even tall buildings could be built of wood. From the fire regulations point of view, they belong to fire category P0, that is they require the demonstration of fire safety by means of performance based functional fire design.

Figure 3. Jonsulight house. This photo is from Puuinfo OY

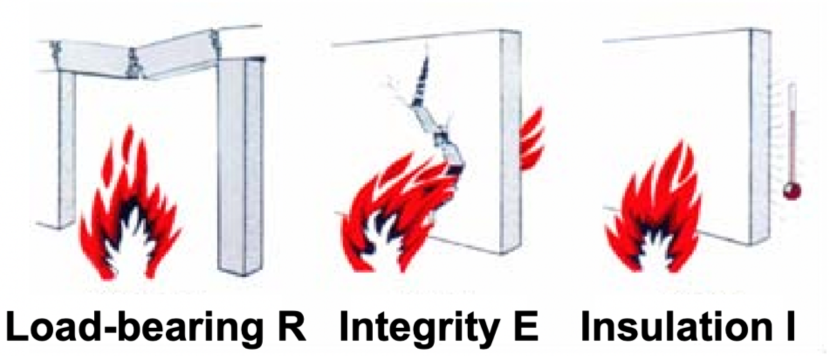
3 Wood reaction to fire

Fire resistance refers to the ability of a building item, or element, to fulfil specific requirements during a fire test for a given amount of time and (David Trujillo, ,2021). The ability of structural elements to continue to function when subjected to the effects of heat is defined as its fire resistance and this is normally measured in terms of time. It is the fire resistance of the assemblies, not just components, which must be evaluated. The fire resistance of a component, or assembly of components, is measured by the ability to resist fire by retaining its loadbearing capacity, integrity and insulating properties. The loadbearing capacity of the assembly is its dimensional stability. The integrity of the assembly is its ability to resist thermal shock and cracking and to retain its adhesion and cohesion. The insulation offered by the material is related to its level of thermal conductivity. Fire resistance is normally defined under these three characteristics (loadbearing capacity, integrity and insulation) and given in minutes or hours of resistance. (Douglas, 2001)

Fire resistance means the ability of a structural element to maintain its performance during a specified period during a fully developed fire. Fire resistance consists of three main performance abilities R, E and I :

The load-carrying capacity of the structure (Requirement on Mechanical Resistance ,R) .The load-bearing capacity of the construction can be assumed for a specific period of time – Protective coverings and sprinklers can be utilized).The separating function of walls and floors (Requirement on Insulation I and Integrity E . The generation and spread of fire and smoke within the construction works are limited Compartmentation is essential independent of structural material .The spread of fire to neighbouring construction works is limited distance, compartmentation, fire wall).The load bearing ability, R, of the structure is examined during the fire test and after the test. The load, which the structure is exposed to, is usually not specified in the test method, but decided by the sponsor of the test. The integrity, E, of the structure can be observed visually during the fire test. The integrity ceases when flames or smoke are penetrating the structure. The insulation, I, of the structure is measured with thermocouples on the unexposed side of the structure. The allowed temperature rise is limited by the test method, usually to maximum 140°C on average.These three abilities can be combined in any way and are used together with a time demand in minutes for example REI 30, EI 60. The abilities are tested according to a national or European test method following the standard fire curve according to ISO 834 or equivalent. (Östman &Rydholm, 2002)

Figure 4.Taken from Eurocode 5



3.1 How fire resistance ratings wood is measured

According to NordTreat (Vantaa based company which promotes sustainable wood construction by developing and producing translucent, environmentally friendly flame retardants for wood products), type of wood products are usually tested regarding their tendency to spread fire (SBI, EN 13823) as well as non-combustibility (EN ISO 1182), calorific value (EN ISO 1716) or ignitability (EN ISO 11925-2). When timber is submitted for evaluation, timber must meet certain minimum acceptance criteria before it is granted a fire resistance rating. The Standard Time-Temperature Curve is used to evaluate fire resistance ratings of different assemblies. To measure hourly fire-resistance rating of wood, wood undergo testing under controlled laboratory manipulation.

To establish their hourly ratings, wood is installed in a temperature-controlled propane gas-fired furnace, and the temperature is increased over a prescribed period in accordance with the criteria established in the American Society for Testing and materials standard E119 “test Methods for Fire tests of Building construction and materials. If timber endure the fire test for a specific period of time, timber is rated as meeting that hourly rating. For example, if wall stud endures the increasing temperature fire test for 3hour, it is rated to be equivalent to a “three-hour stud.” This stud would be installed in building where prescriptive codes require the installation of a three-hour fire resistance. (NordTreat, n.d.)

3.2 Fire ratings improvement for timber

According to Woodsolution website guide Fire ratings can be improved by:Protecting timber by covering it with a good insulator such as fire-rated plasterboard. The surface of a material can be protected with a layer that delays the temperature rise and reduces the evaporation of pyrolysis gases and the access of oxygen on the surface, this means that the timber takes longer to get to ignition temperature and can remain functional for a longer period while the fire is burning. Using oversized timber - this will allow for loss of material charring throughout the burn period, and there will still be enough timber remaining in the cross-section to give it the required strength. When wood structures are exposed to high temperatures, they will decompose to provide a char layer and pyrolysis zone, an insulating material that inhibits further degradation. Char layer protects the residual cross-section from high temperatures. Treating timber with fire-retardant chemicals - this delays the initiation of combustion and can prevent the spread of flame.

4 Fire design of multi-story timber building

Part E1, Finnish Fire safety of buildings, of the National Building Code of Finland (NBCF) accepts two different approaches to show that a building satisfies the fire safety requirements. The fire safety requirement is deemed to be met if the building is designed and executed by applying the fire classes and numerical criteria provided by the regulations and guidelines of the part E1 of the NBCF (the prescriptive approach), or, alternatively, by designing and executing the building based on design fire scenarios covering the conditions likely to occur in the building (the performance-based approach). and NBCF doesn’t not recommend the combination of both methods to achieve the compliance with NBCF fire safety requirement as it the case in Australian building code (NCC-National construction code of an Australia) but according to Timo Jokinen (Senior Fire Safety Specialist, Markku Kauriala Oy), the performance-based fire design is always a combination of prescriptive design and performance-based design.

According to national Construction Code (NCC) which is the regulatory framework for determining minimum construction requirements for all types of buildings in Australia, Compliance with the NCC is achieved by satisfying the Performance Requirements and the supporting ‘Governing Requirements’. ‘Compliance Solutions’ are either. Performance Solutions or Deemed-to-Satisfy Solutions. or Compliance with the NCC is achieved by combining both methods.

According to International building code IBC Section 703.2 methods to Demonstrate Fire-Resistance Ratings of Mass Timber are rating to be determined by testing in accordance with ASTM E 119 (or UL 263) or via one of six alternatives listed in IBC Section 703.3:

1. Fire-resistance designs documented in approved sources

2. Prescriptive designs of fire resistance-rated building elements, components or assemblies as prescribed in Section 721

3. Calculations in accordance with Section 722

4. Engineering analysis based on a comparison of building element, component or assemblies’ designs having fire- resistance ratings as determined by the test procedures set forth in ASTM E119

or UL 263

5. Alternative protection methods as allowed by Section 104.11

6. Fire-resistance designs certified by an approved agency

These alternatives are options when the exact assembly has not been tested per ASTM E 119 and a test report is therefore not available. They are all founded on ASTM E 119 testing

4.1 The fire safety goals

The principles of fire safety remain same weather prescriptive design approach or performance design approach is used in multi-story timber building. Therefore, there is general agreement that the goals of structural design against fire are to limit risks to the individual and society, to directly exposed or neighboring property, and to the environment. To meet these goals, fire protection requirements use the prescriptive format, e.g., they specify the permissible materials for buildings, the thickness of insulation, or the minimum acceptable spacing between buildings. This is the traditional approach that continues to this day. In the early 1970s, performance-based approaches were developed, following an evolution in the understanding of fire and building performance in fire. Performance-based methods allow the designers to account for the unique features and uses of buildings and promote a better understanding of how buildings perform in fire. Compared to prescriptive methods, performance-based approaches have a greater potential to promote innovation and cost savings but require more expertise. (Dat Duthinh, 2014)

Fire Safety Goal is overall outcome to be achieved with regard to fire. Goals are nonspecific and are measured on a qualitative basis. They should be stated in terms of conditions that are intrinsically desirable and do not rely on any assumptions. Goals should be stated in terms that are potentially measurable, even if the precise measurement scale is not specified. Thus, goals may be expressed in terms of impact on people, property, or the environment, or in terms of mission continuity. (NFPA, 1997)

4.2 Prescriptive design approach

Although tall timber building getting ground on the mind of many designers as it is renewable source of building material, designers are currently limited by prescriptive provision. These provisions restrict the potential for tall timber buildings based on the issues of structural and fire safety, as height and area limitations restrict use. Timber building is designed with regard to fire classes and criteria provided by regulations and guidelines. According to prescriptive regulation multi-story timber residential building is classified as P2 with the height less than 28m For example, the evacuation safety can be based on both active and passive elements. Greatest distance to the nearest exit, number of exits and dimensions of exits are regulated in prescriptive codes. are rules for doors, locks and exit lights. Active fire detection and alarm or sprinkler may lower the level of requirements. (Rasmus, 2021)

So majority of buildings in the world are designed in accordance with prescriptive regulations. In such prescriptive regulatory environments, fire safety is recognized as being achieved by a structure that is designed to meet the prescriptive requirements of the code. As knowledge and understanding of fire and timber buildings develops, the potential for regulatory change becomes increasingly possible (Gerard & Barber, 2013). Prescriptive fire design is what is designed as fire safety for building, which is, based on national and international standards and codes and that building comes under code compliance, so it is acceptable by legal authorities/authorities having jurisdiction and from other aspects that is: as this building is designed as per codes and standards, so it is a safe building, having less fire risk. (VMS, n.d.)

The timber fire performance requirements (life safety ,property and environmental safety) are considered to be met whenever the building is designed according to prescriptive provision. In the case performance measurement, compliance with the essential requirements shall be demonstrated on a case-by-case basis, taking into account the characteristics and use of the building.The most important factors in the fire engineering design of a timber building frame are the fire resistance of the load-bearing frame and the compartmentalizing building components.

4.2.1 Fire class of timber multi-stories timber building

According to the National Building Code of Finland, 2017 (regulations on fire safety in buildings, E1,2017), In Finland, buildings are divided into four fire classes: P0, P1, P2 and P3. Three to eight story timber buildings are classified as fire class P2 and two-story houses as fire class P3. The muti-story-timber build lies in P2 category classificationwhen building is designed based on prescriptive regulation and also muti-story-timber build can be classified as P0 if building is designed based only performance design approach

Fire class of a building In the regulations on fire safety in buildings, E1 , the fire classes of buildings are P1, P2 and P3. In the explanatory memorandum to the regulations, fire classes are defined as follows:

´The load-bearing structures of a building belonging to fire class P1 are generally assumed to withstand fire without collapse. There is no limit to the size of the building and the number of people. The requirements for load-bearing structures in a building belonging to fire class P2 may be lower than in the previous class. An adequate level of safety is achieved by setting requirements, in particular for the properties of the surface parts and the devices for improving fire safety. In addition, the size of the building and the number of people are limited depending on the use. No special fire resistance requirements are imposed on the load-bearing structures of a building belonging to fire category P3´.

An adequate level of security is achieved by limiting the size and number of people in the building, depending on the use.In Finland fire class are specified in the Decree of the Ministry of the Environment on the Fire Safety of Buildings (848/2017). The fire classification of building materials is carried out in accordance with the classification standard SFS-EN 13501-1 + A1. The European standard is based on three fire testing methods that are used to divide products into so-called Euro-classes. In addition to the seven main classes (A1-F), there are additional classes to describe smoke production (classes s1, s2 and s3) and the formation of flaming droplets (classes d1, d2 and d3).

4.2.2 Mass timber & construction type

Before demonstrating fire-resistance ratings of exposed mass timber elements, it’s important to understand under what circumstances the code currently allows the use of mass timber in multi-family residential timber building. A building’s assigned construction type is the main indicator of where and when all wood systems can be used. IBC Section 602 defines five main options (Type I through V) with all but Type IV having subcategories A and B. Types III and V permit the use of wood framing throughout much of the structure and both are used extensively for modern mass timber buildings.

Type III (IBC 602.3) – Timber elements can be used in floors, roofs, and interior walls. Fire-retardant-treated wood (FRTW) framing is permitted in exterior walls with a fire-resistance rating of 2 hours or less.

Type V (IBC 602.5) – Timber elements can be used throughout the structure, including floors, roofs and both interior and exterior walls.

Type IV (IBC 602.4) – Commonly referred to as 'Heavy Timber' construction, this option has been in the building code for over a hundred years in one form or another, but its use has increased along with renewed interest in exposed wood buildings. This construction type is unique in that fire-resistive behavior is based in part on the inherent and long-demonstrated fire resistance of large solid wood framing. Structural wood components are permitted in floors, roofs, and interior walls when they meet minimum cross-section sizes. Per IBC Sections 602.4.1 and 602.4.2, exterior walls required to have a fire-resistance rating of 2 hours or less are also permitted to use FRTW framing, or CLT when covered with FRTW sheathing or noncombustible materials. In general, heavy timber components used in Type IV construction (called Type IV-HT in the 2021 IBC) can be exposed. (R. McLain, & S. Breneman 2019)

4.2.3 Fire class properties based on Euroclasses

A1, Products do not contribute to a fire at any point

A2, Products contribute to a fire to an extremely small extent

B, Products contribute to a fire to a very small extent

C, Products contribute to a fire to a small extent

D, Products contribute to a fire to a limited extent

E, Products contribute to a fire to a moderate extent

F, Reaction to fire performance has not been determined

s1, Smoke production is very limited

s2, Smoke production is limited

s3, Smoke production is not limited

d0, No flaming droplets or particles

d1, Limited quantity of flaming droplets or particles

d2, flaming droplets or particles are not limited (Nordtreat, n.d.)

4.2.4 Purpose of the building and fire load

Multi-story timber building considered in this thesis residential premises used as dwellings multi-story timber building. Premises belonging to the fire load group not less than 600 MJ / m 2 but not more than 1,200 MJ / m 2 include fire compartments containing furniture storage in residential building.Restrictions on the size of the building Table 3.2.1 of the Fire Regulations E1 shows the restrictions on the size of buildings with different fire classes when using design based on fire classes and numerical values (Table 1).The following apply to wooden apartment buildings (category P2, 3 to 8 storeys): - More than two storeys are only possible for residential and workplace buildings and there can be a maximum of 8 storeys. A 3-4 storey building can be up to 14 m high .

Table 1.Restrictions on the size of buildings and on the number of occupants (Decree of the Ministry of the Environment of Finland on fire safety of buildings,2002)

TABLE 3.2.1	RESTRICTIONS ON THE SIZE OF A BUILDING		
Characteristic of the building	**Fire class of the building**		
	P1	**P2**	**P3**
NUMBER OF STOREYS			
– in general	no restriction	maximum 2	maximum 2
– residential building, office premises	no restriction	maximum 4	maximum 2
– production or storage premises, garages	no restriction	maximum 2	maximum 1
HEIGHT			
– in general	no restriction	maximum 9 m	maximum 9 m
– residential building, office premises	no restriction	maximum 14 m	maximum 9 m
– 1-storey production or storage premises	no restriction	no restriction	maximum 14 m
GROSS FLOOR AREA			
In general			
– 1-storey	no restriction	no restriction	max 2400 m^2
– 2-storey	no restriction	no restriction	max 1600 m^2
Gross floor area in production and storage premises and garages			
– 1-storey	no restriction	no restriction	no restriction
– 2-storey	no restriction	no restriction	*not permitted*

4.2.5 Compartmentalizing room space

Comprising rooms in building is constructed to stop the spread of fire to or from another part of the same so that life and property damage is prevented. Fire compartmentation should be analyzed during each Fire Risk Assessment done by Fire Risk expert. To facilitate the prevention fire spread from compartment to other or vice versa, fire resisting walls and floors that offering between half hour and one and half hour fire resistance must be installed or constructed considering any openings in the compartment like service penetrations. The wall and floor should operate as intended for the duration of the designed fire resistance period. The compartment wall and floor must work to stop fir spreading by avoiding cracks and holes from which flame and smoke might escape to other room. And it should reduce temperature increase to other side of structure. For example, escape corridors, rooms, and stair. Fire compartmentation is important to confine fire in its original place for long time and give chance for evacuation and provides the building additional time to evacuate before escape routes are potentially compromised by the spread of smoke and fire. Compartmentation also help fir-fighter.

Fire safety of buildings E1, of the National Building Code of Finland (, The maximum area of a fire compartment is set out in Table 5.2.1 is shown in table 2 and the class requirements for fire-separating and partitioning building elements are set out in Table 7.2.1 in Fire safety of buildings Regulations and guidelines 2002 is shown in table 3. Provide detailed information regarding the minimum periods of fire resistance required in buildings for different purpose groups and maximum permitted compartment sizes. In some instances, automatic fire suppression systems such as a sprinkler system may be provided where necessary to reduce the rate and growth of fire which may also impact on permitted maximum compartment sizes.

According to the Fire Protection Association Fire compartmentation can be achieved as follow

Fire resisting construction and cavity barriers, with any fire stopping if necessary.

Fire safety of buildings E1, of the National Building Code of Finland refers to a cavity as any concealed space and states that cavity barriers should be provided in the following situations.

To divide cavities at junctions and cavity closures.

To close the edges of cavities at junctions and cavity closures, and.

To protected escape routes.

To cavities affecting alternative escape routes

Table 2.The maximum area of a fire compartment. (Decree of the Ministry of the Environment of Finland on fire safety of buildings)

TABLE 5.2.1	**MAXIMUM AREA OF FIRE COMPARTMENTS**		
Use of building	**Fire class of the building**		
	P1	**P2**	**P3**
FLOORS			
Residential buildings	fire separation by apartments	fire separation by apartments	fire separation by apartments
Accommodation premises and institutions			
– premises for staying overnight	800 m^2	800 m^2	400 m^2
– other premises	1600 m^2	1600 m^2	400 m^2
Assembly and business premises and offices	2400 m^2	2400 m^2	400 m^2
Production and storage premises and garages	after consideration[1)]	after consideration[1)]	after consideration[1)]
ATTICS AND VOIDS OF THE UPPERMOST FLOOR	1600 m^2	1600 m^2	according to the compartments underneath [2)]
BASEMENTS	800 m^2	800 m^2	400 m^2

According to EI regulation a fire compartment can be enlarged by providing the compartment with an automatic fire alarm installation, an automatic smoke extraction installation or an automatic fire-extinguishing system and the big compartment area, the high fire risk. This because big timber compartment area has more fuel load as it is from timber itself.

Table 3.Class requirements for fire-separating building elements (Decree of the Ministry of the Environment of Finland on fire safety of buildings)

TABLE 7.2.1 CLASS REQUIREMENTS FOR FIRE-SEPARATING BUILDING ELEMENTS

	Fire class of the building					
	P1			**P2**		**P3**
	Fire load MJ/m^2			Number of storeys		
	over 1200	600–1200	under 600	3–4	1–2	
Column	**1**	**2**	**3**	**4**	**5**	**6**
Fire-separating building elements in storeys	EI 120	EI 90	EI 60	EI 60	EI 30	EI 30
– partitioning building elements (walls and doors of accommodation rooms)	EI 15	EI 15	EI 15	■	EI 15	EI 15
Fire-separating building elements in attics	EI 30	EI 30	EI 30	EI 30	EI 30	EI 30
– partitioning building elements	EI 15	EI 15	EI 15	EI 15	EI 15	EI 15
Fire-separating building elements in basements	EI 120	EI 90	EI 60	EI 120	EI 60	EI 30

Note to the Table: Class requirements for fire-separating building elements implementing fire-separation by area of production and storage buildings according to guidelines E2 of the National Building Code of Finland, those of garages according to guidelines E4 and the class requirements of fire-separating building elements of boiler rooms and fuel storages according to guidelines E9.

Symbol in the Table: ■ = not possible

4.2.6 Maintaining the load-bearing capacity of constructions

In a timber residential building, the load-bearing and partitioning structures can be made of wood products, A load-bearing construction is designed to correspond with the class requirement with reference to the standard temperature/time curve. Conformity with the requirement is attested by: Testing, calculation, combining the results of testing and calculation or using an acceptable design method based on use of tables.

The class requirements for the load-bearing capacity of constructions is according E1 in Table 6.2.1 are in table 4 below., As shown by the requirements in the table, timber structures are allowed in residential buildings up to eight storeys. The requirement R60/EI30(nbb) or EI60/EI30(nbb) means that the load-bearing and separating building elements shall have fire protective, non-combustible cladding, with a fire resistance (R value) of the cladding itself of 30 minutes. If sprinklers are present, the requirements are relaxed. External walls shall be constructed so that a fire will not spread from one fire compartment to another through them for a specified period of time.

Table 4.Class requirements for the load-bearing capacity of constructions. (Decree of the Ministry of the Environment of Finland on fire safety of buildings)

TABLE 6.2.1	CLASS REQUIREMENTS FOR LOAD-BEARING CONSTRUCTIONS				
	Fire class of the building				
	P1			P2	P3
	Fire load MJ/m²				
	over 1200	600–1200	under 600		
Column	1	2	3	4	5
Buildings with not more than 2 storeys, in general	R 120*	R 90*	R 60*	R 30	—
– if the insulation materials in the building are not at least of class A2–s1, d0	R 120	R 90	R 60	R 30	—
– institutions, accommodation premises, basements	R 120	R 90	R 60	R 30	—
Buildings with 3-8 storeys, in general	R 180	R 120	R 60	■	■
Residential or office buildings with 3-4 storeys					
– storeys	R 180	R 120	R 60	R 60*	■
– basement storeys	R 180	R 120	R 60	R 120	■
Buildings with more than 8 storeys	R 240	R 180	R 120	■	■
Basement storeys located below the uppermost underground storey	R 240	R 180	R 120	R 120	R 60

4.2.7 Internal surfaces of exterior walls and interior walls Protective coverings

The fire resistance for wall and floor constructions is determined by testing and/or calculations. The capacity of a load bearing structure is calculated according to National Building Code o f Finland Part BIO or Eurocode 5. The structures are designed at normal temperature according to National Building Code o f Finland Part BIO. The height o f the walls is limited from 2,0 to 3,8 metres with separating walls and from 3,6 to 8,5 with load bearing and separating walls or only load bearing walls.(Birgit Östman & Daniel Rydholm.2002). External walls and roofs must be constructed to avoid vertical and horizontal fire spread.

The external wall frame of a P2-class 3- to 8-storey building must be made of at least D-s2, d2-class material and the thermal insulation and other filling must be at least A2-s1, d0. The basic requirement for the inner surface of the ventilation gap is B-s1, d0 (Table 5) and it can be applied in wooden residential building when the inner surface of the ventilation gap becomes K2 30 with a protective cladding and it is made with EI 30 structure. In this case, the product to be protected is a product of class A2-s1, d0 and the ventilation towards the gap is a product of class B-s1, d0. The product of class B-s1, d0 also can be used for the inner surface of the ventilation gap when the frame structure (and thermal insulation) of the outer wall is at least class A2-s1, d0 or it is an outer wall of an additional layer built afterwards. The inner surfaces of a building of fire class P2 and more than two storeys, apart from exit and exit enclosure surfaces, must be fitted with a protective covering of K2 30 class, made of at least A2-s1, d0-class building materials.

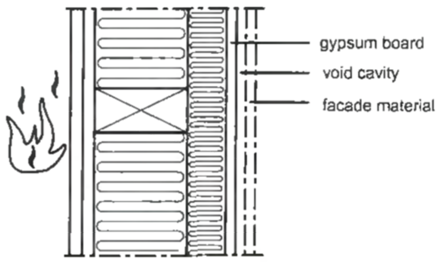
The basic requirement for the outer surface of the outer wall and the outer surface of the ventilation gap is B- s2, d0 and the internal wall and roof surfaces of a building of fire class P2 and of one to two storeys must be fitted with a protective covering of K2 10 class, made of at least B-s1, d0-class building materials (Table 5), but wood products meeting the class D-s2, d2 may be used instead, subject to the limits and conditions in the table below (Table 5).

Table 5.Class requirements for surfaces of external and ventilation gaps. (Decree of the Ministry of the Environment of Finland on fire safety of buildings)

TABLE 8.3.4 CLASS REQUIREMENTS FOR SURFACES OF EXTERNAL WALLS AND VENTILATION GAPS

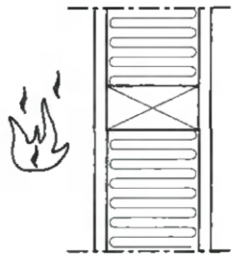
	Fire class and use of the building					
	P1		P2			P3
	Buildings of class P1 in general	Residential and office premises with not more than 4 storeys	Institutions	Residential and office premises with 3–4 storeys	Other buildings of class P2	
External surface of external wall	B-s1, d0 1)	B-s1, d0 2)	B-s1, d0 2)	B-s1, d0 2)	D-s2, d2	D-s2, d2
External surface of ventilation gap	B-s1, d0 1)	B-s1, d0 2)	B-s1, d0 2)	B-s1, d0 2)	D-s2, d2	D-s2, d2
Internal surface of ventilation gap	B-s1, d0	B-s1, d0	B-s1, d0	B-s1, d0	D-s2, d2	—

The multi-storey timber building have either timber frame or solid timber construction. Some examples of constructions being used are shown below in Finland(Östman and Rydhokn 2002).Load bearing and separating external walls with one or two insulation layers. Timber vertical and lateral load-resisting elements are designed to achieve a 90-minute fire resisting rating, which is achieved by encapsulating them in two layers of gypsum plasterboard. In addition to this passive fire protection in the form of gypsum, the primary buildings are equipped with automated fire detection and sprinkler systems. For multi-story timber buildings, particularly frame buildings (post and beam construction), several tests have considered multiple load ratios to evaluate the fire performance of specific timber elements .(O'Neill, 2009) . Generally the greater the load ratio, the worse the fire performance. Multi-story timber buildings in which timber is a main construction material should be designed in ways that occupants will survive full burn-out of the fire compartment(s) in which a fire starts, whereas other parts of the building remain undamaged.



Load bearing wall, external				
	Studs	Insulation	Lining (inside)	Lining (outside)
R 60	According to design at normal temperature but at least 45x95 mm cc= 600 mm	Rock wool (30 kg/m^3)	2x15 mm Fire rated gypsum board	9 mm gypsum board, void cavity and facade material

Table 6.Load bearing external wall with two inside and two outside layers. (Östman and Rydhokn 2002)



Load bearing and separating walls, internal			
	Studs	**Insulation**	**Lining (each side)**
REI 30	According to design at normal temperature but at least 45x95 mm cc= 600 mm	Rock wool (30 kg/m^3)	13 mm gypsum board
	Dubble separated studs according to design at normal temperature but at least 45x95 mm cc= 600 mm	Rock wool (30 kg/m^3)	13 mm gypsum board
REI 60	According to design at normal temperature but at least 45x95 mm cc= 600 mm	Rock wool (30 kg/m^3)	2x15 mm Fire rated gypsum board
	Dubble separated studs according to design at normal temperature but at least 45x95 mm cc= 600 mm	Rock wool (30 kg/m^3)	2x15 mm Fire rated gypsum board

Load bearing external wall with two inside and two outside layers.(Östman and Rydhokn 2002)

Figure 5.Floor with three ceiling layers.(Östman and Rydhokn 2002)

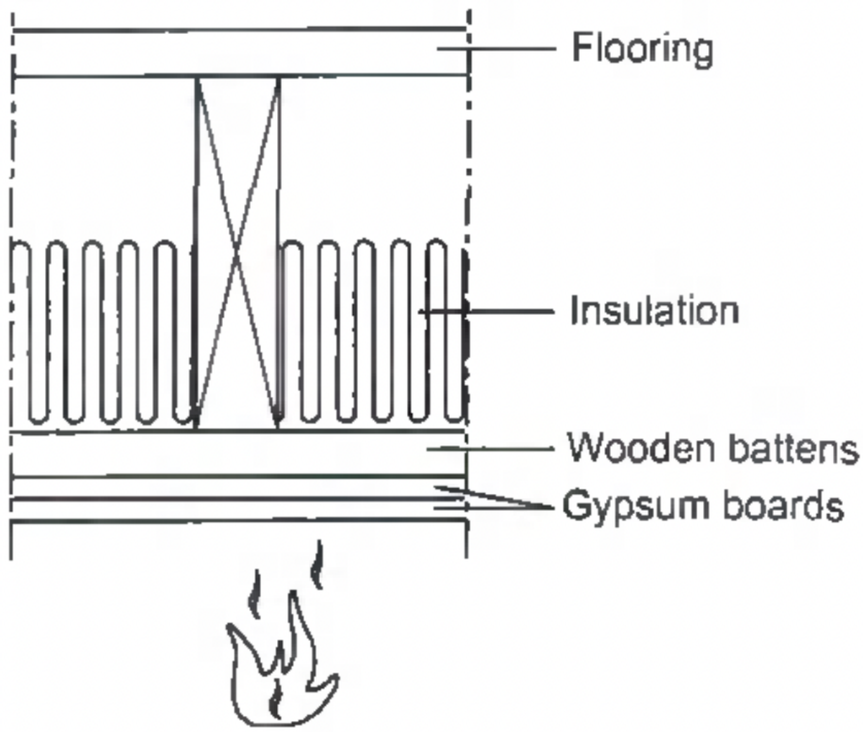


Table 7.Floor with three ceiling layers.(Östman and Rydhokn 2002)

Floors			
Class	**Flooring**	**Wood joists + Insulation**	**Ceiling side**
REI 30	With (floors) or without (roofs) flooring	According to design at normal temperature, cc= 600 mm + 100 mm Rock wool (30 kg/m^3)	45x45 mm wooden battens or acoustic steel profiles + 2x13 mm gypsum board

4.2.8 Fire wall

A building must be provided with a fire wall if it near to a neighbouring building or so close to a neighbouring building that the spread of fire is evident. The fire wall in a P0 and P1 fire class building and in a P2 fire class building whose height exceeds 14 metres must be made of A1-class building materials, and the doors in it must be made of at least A2-s1, d0-class building materials. The fire resistance time of the door in a fire wall or similar building element must be at least the same as the fire resistance time that the fire wall is required to have.

Table 8.Class requirment for fire wall.(Decree of the Ministry of the Environment of Finland on fire safety of buildings)

Fire class of building	P0 and P1			P2	P3
Fire load MJ/m²	more than 1,200	600-1,200	less than 600	-	-
	EI-M 240	EI-M 180	EI-M 120	EI-M 120	EI-M 60 [1]
[1] The EI-M 60 requirement may be replaced by fire compartmentation if the facing external walls of the buildings meet the EI 60-class requirement against internal fire.					

4.2.9 Evacuation

It should be ensured that every occupant escape safely in case of fire. A building shall be provided with an adequate number of appropriately located exits that are sufficiently spacious and passable, so that the time to leave the building will not be so long as to cause danger. Length of a passageway should be short and safe exits should be provided in case of a fire. The building must have enough exits that are appropriately located, spacious enough and easy to access in a way that the evacuation time is as short as possible (M.kauriala oy,n.d.) . There should be at least 2 number of exits in multi-story timber building. The minimum width of an exit should be at least 1,200 millimetres and its free height must be at least 2,100 millimetres.

Table 9.Maximum length of passageway to nearest exit (metres) (Decree of the Ministry of the Environment of Finland on fire safety of buildings)

Use of evacuation area	General	The evacuation area is equipped with a fire alarm system based on smoke detection or with an automatic fire-extinguishing system	The evacuation area is equipped with a fire alarm system based on smoke detection and with an automatic fire-extinguishing system
Evacuation area from which there is only one exit	30 m [1) 2)]	30 m [1)]	30 m [1)]
Sleeping premises at an institution	30 m	30 m	30 m
Accommodation premises, other premises of institutions, and shops	30 m	40–50 m [3)]	45–60 m [3)]
Other premises	45 m [2)]	50–60 m [3)]	60–70 m [3)]

[1)] Distances may be exceeded by 20 per cent in a ground-level storey if emergency evacuation is possible through easily opened windows.
[2)] The building inspection authority may, where this is justified, require shorter maximum passageway lengths when an exceptional risk of rapid ignition and spread of fire due to the special use of the premises may jeopardise safe evacuation.
[3)] The lower limit corresponds to a (maximum) 3 metre average room height, and an upper limit to an average room height of over 10 metres. In-between values are obtained by linear interpolation.

4.3 Performance design approach

Any building is designed to meet some needs. Any building must have specific size, hold specific number of occupants, and has specific usage. Multi-story timber building can be design using Performance design approach. According to performance design approach Fire safety planning is based on assumed fire development and fire scenario. Functional fire design shall take into account the fire situations likely to occur during the design life of the building and the resulting fire loads and the actual locations of the fire loads. In addition, functional fire planning takes into account the fire safety systems selected for the site, such as automatic fire detectors and extinguishing systems. Functional sizing always means an exceptionally demanding level of fire safety planning, for which our office is provided by sufficiently qualified and experienced designers (KK-PALOKONSULTTI OY, n.d.). Performance-based fire design is being adopted as a rational means of providing efficient and effective fire safety in buildings. Some prescriptive building codes give the opportunity for performance-based selection of structural assemblies. For example, if a code specifies a floor with a fire resistance rating of two hours, the designer has the freedom to select from a wide range of approved floor systems which have sufficient fire resistance(Buchanan & Anthony .2017)

2012 NFPA 5000 provides guidance for a performance based fire solution. The document suggests that an alternative method shall be approved where the building official agrees that a performance based design has met the required safety goals (See Section 1.4) (NFPA, 2012).

Performance design process whose fire safety solutions are designed to achieve a specified goal for a specified use. This process allows performance-based documents to be used and make sure that their goals are achieved as it is intended.

The following describes a performance-based design approach:

a) Set safety goals.
b) Evaluate the condition of the occupants, building contents, or part of building being considered regarding fire safety.

c) Set performance objectives with performance criteria.
d) Figure out potential hazards to be protected against.
e) Establish suitable fire scenarios.
f) Based on fire scenarios, select suitable calculation methods.
g) Check proposed solution.
h) Prepare document for proposed solution with every information needed.
i) The proposed solution must be approved by authority having jurisdiction. (National Fire Protection Association, 1997)

Performance design approach is mainly used when prescriptive provision is insufficient or unsuitable for the building so timber building more than eight story can be designed by performance design regulation.

4.3.1 Demonstration and reporting of compliance

Performance design is based on section 1.3.2 of the Fire Safety Regulations E1, which provides an alternative and equivalent procedure for the use of fire classes and numerical values (section 1.3.1 of E1) with instructions as follows: The fire safety requirement is also considered to be met if the building is designed and constructed on the basis of an assumed fire development that covers the situations likely to occur in that building. Compliance shall be verified on a case-by-case basis, taking into account the characteristics and use of the building. Evidence of Suitability can be showed by verification method, expert judgement and comparison with the prescriptive Provisions.

Purpose of the building and fire load. The fire loads on which the dimensioning of a P0 fire class building is based must be determined.

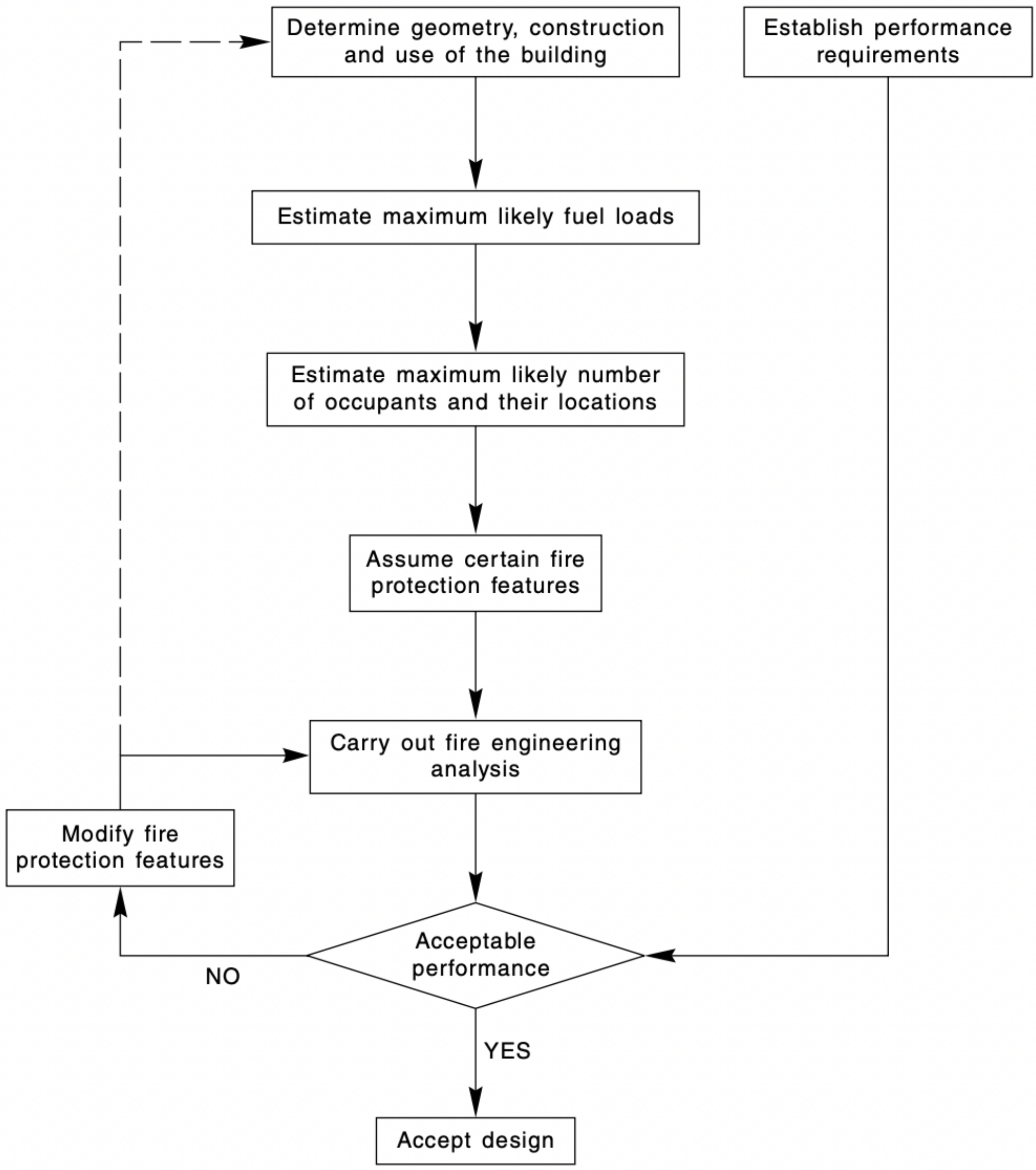
4.3.2 Fire Scenario

Specification of fire conditions under which a proposed solution is expected to meet the fire safety goals. The fire scenario describes factors critical to the outcome of the fire such as ignition sources, nature and configuration of the fuel, ventilation, characteristics and locations of occupants, condition of the supporting structure, applicable operating equipment (e.g., reliability and/or effectiveness). Determining realistic fire loads also involves many challenges. The possible arrangements of fire loads in most buildings are so numerous that no design could account for all of them. Fire protection engineers often address this difficulty by determining worst case fire loads, or bounding loads. Sometimes fire protection engineers determine the most likely fire loads for many different scenarios and analyze them all. The potential problem with using the most likely fire loads is that relatively minor changes to a building can result in requiring a new analysis and additional fire protection unless the original analysis was sufficiently conservative. The assumed fire loads and design fire scenarios must then be documented. Whenever any feature or use of the building departs from the documented assumptions, the performance-based design may no longer be valid. Selecting appropriate fire loads and design scenarios is therefore extremely critical to the performance-based design process. Understanding the science and being able to determine fire loads is just the beginning. To implement a performance-based design, the applicable code must permit it either by being a performance-based code or by allowing performance-based alternatives to prescriptive code provisions. If such designs are permitted, performance criteria must be agreed upon, plausible designs must be developed, the designs must be tested against the performance criteria, and a final design must be selected. Other considerations include coordinating the design with the other disciplines, developing, and updating the design documentation, and getting the authority having jurisdiction to accept the design. (Jane, 2002)

In selecting design fire scenarios (the design fire load) for a performance-based design, all possible fire scenarios should be considered. Determining all possible fire scenarios requires knowing as much as possible about the building and its contents and occupants. Examples of necessary building information are its construction, layout, and building services. Relevant features include fire resistance ratings, fire cutoffs, and the type and arrangement of building services (electricity, gas, oil, HVAC, communications, etc.). Information about existing or proposed fire protection systems would also be relevant. Obtaining information about the building is usually straightforward. Examples of information needed about building contents are processes, operational characteristics, and combustible loading. Relevant features include hazardous materials used in the processes, process energy input and output, process material flow, and the likelihood of the occupancy to change. In most buildings, the processes and operational characteristics dictate the combustible loading. Determining the likely combustible loading can be very challenging, but it is one of the most important factors in estimating reasonable fire characteristics. Necessary information about occupants includes their number, distribution throughout the building, familiarity with the building, and physical and mental capabilities. This enables a performance-based design to account for and control the effects of fire on people. Many resources are available for identifying possible fire scenarios. Historical data about the facility and about facilities of similar occupancy can be useful. Simple brainstorming about "what if?" an event occurs can also yield useful results. More analytical techniques include event tree analysis, fault tree analysis, failure analysis, and hazard operability studies. Once all possible fire scenarios have been developed, they can be sorted into groups with similar likelihood and outcomes. The next step is then to select a representative fire scenario from each group with risk that exceeds the agreed upon level of acceptable risk. The filtered set of scenarios form the basis of the design fire scenarios to be used in the performance-based design. In selecting the design fire scenarios, the fire protection engineer must be sure that they bound the potential hazards. The most likely fires could be too lenient; likewise, the worst possible case can be too severe. The selected design fire scenarios should reflect the facility's risk from fire as accurately as possible while being appropriately conservative. (Jane, 2002)

Performance design use fire scenario analysis to demonstrate fire safety. In this method a number of reasonable 'worst case' scenarios are analysed. In each scenario the likely growth and spread of fire and smoke is compared with detection and occupant movement, taking into account all the active and passive fire protection features and structural behaviour,to establish whether the performance requirements have been satisfied. An overview of scenario analysis is shown in Figure 6. Within the selected scenarios it is possible to ask a large number of 'what if? questions to find the worst cases and optimize the design.(Buchanan & Anthony ,2017)

Figure 6.Overview of scenario analysis(H. Buchanan & Anthony K. Abu,2017)



4.3.3 Building class and height

Multi-story timber building is fire class P0 with the height more than 28m with more the 8 story if building designed by performance design approach in performance-based design approach the fire load must always be know to know fire scenario. Information is required on the location and combustion characteristics of the fire load. The height of the building affects the fire class of the timber building and thus the fire safety requirements of the building as a whole (for example, the requirements for the class of load-bearing and stiffening structures). The taller the building, the greater the possibility of a fire occurring on an upper floor and people being trapped above the fire floor - a potentially disastrous combination. Tall buildings require a long escape time, and they have slow internal access for fire fighters. It is likely that full encapsulation may be required in order to meet the performance requirements for timber buildings taller than about 8 storeys.(Buchanan, Östman & frangi, 2014).

In multi-story timber building active and passive fire-safety precautio sprinklers and Massive timber cross sectional area will help to reduce the risk of serious damage. In Canada for instance, there is now no material-specific limitation on building heights as long as a building's design meets required objectives in accordance with applicable regulations .Some prescriptive building codes give the opportunity for performance-based selection of structural assemblies. For example, if a code specifies a floor with a fire resistance rating of two hours, the designer has the freedom to select from a wide range of approved floor systems which have sufficient fire resistance.

Dimensioning of load-bearing structures based on assumed fire development. Conditions according to the assumed fire development must be used as the fire stress so that the fire stress is likely to cover the situations in the building in question. The design of load-bearing structures based on the assumed fire development may take into account the slower rise in temperature and the cooling of the load-bearing components when the building is equipped with a suitable automatic extinguishing system.

Table 10. Design criteria when designing essential load-bearing structures is based on assumed fire performance approach (Decree of the Ministry of the Environment of Finland on fire safety of buildings)

Building	**Height**	**Fire resistance of essential load-bearing structures**	**Design fire load density MJ / m**
2-storey, usually	Height up to 9 m	30 minutes without cooling	$Q_{fi,k}$, not less than 600 MJ / m
2-storey, usually	Height over 9 m	60 minutes without cooling	$Q_{fi,k}$, not less than 600 MJ / m
More than 2 storeys	Height up to 28 m	Fire and cooling phase	$Q_{fi,k}$, not less than 600 MJ / m
More than 2 storeys	Height over 28 m	Fire and cooling phase	2.0 * $Q_{fi,k}$, not less than 900 MJ / m
$Q_{fi,k}$ is a statistically or computationally determined characteristic value of the total fire load density (80% fraction)			

4.3.4 Compartment for performance based design

Fire detection and suppression methods have been developed to an extent where it is no longer necessary to simply contain localized fires within combustible compartments long enough for building evacuation or arrival of the firefighters. automatic fire sprinklers . If the number of sprinklers increased then, fire compartment size requirement relaxed.Fire-protective coverings (to prevent fires entering the void), specification of non-combustible insulation specification of cavity barriers (to prevent uncontrolled fire spread through cavities if a fire enters or starts within a cavity) no unfilled voids or cavities permitted if the massive timber provision is applied.

4.3.5 Loadbearing for performance based design

In performance-based fire protection, the designer must assess the potential fire scenarios for a situation and design the fire safety based on the identified risks. FOR EXAMPLE if wall is exposed to fire both side, load carry capacity (R-VALUE) of wall would be reduced unless utilization ratio is reduced, and fire rating requirement relaxed if many approved water curtain sprinklers is added to wall space and loadbearing structure cross-section size is increased .If the amount of sprinklers increased the fire duration tended to be extended beyond specified time of resistance in prescriptive measurement . All the floors and loadbearing elements of mass timber buildings exceeding 8 storeys must have a fire-resistance rating of not less than 2 hours to comply with the objectives and functional requirement of Finnish national building code.

5 Discussion

What are the advantages and disadvantages of different fire design methods? Timo Jokinen, (Senior Fire Safety Specialist, at Kauriala Oy) explained their advantages and disadvantages of performance design approach and perspective design approach in the table 11.

Table 11 Advantages and disadvantages of performance design approach and perspective design approach (T.Jokinen, personal communication, 2022)

Advantage of Prescriptive based design approach	Disadvantages of Prescriptive based design approach
The design process itself is relatively cheap, easy, and quick. Risks of delays in building permit and authority approval are relatively low. Direct analysis and nterpretation of the requirement.	Can limit architecture greatly. Can in some cases increase building costs greatly without increasing overall fire safety. Inflexible in general e.g., limit height of timber building to 8story or 28m and compartment size fixed. Specific recommendations which sometimes are not clear.
Advantages Performance based design method	Disadvantages Performance-based method
Can greatly open up possibilities in the architecture. Can in some cases decrease building costs greatly without decreasing overall fire safety. Very flexible in general e.g no high limit and no specific materiall for fire resistance in timber building. Architectural freedom . Cost-efficient fire equipment collaboration with the entire design perspective code. Savings in maintenance costs	Design process itself is usually much more demanding, and will require more time and specialized experts, and thus it is often more expensive to perform. Risks of delays in building permit and authority approval are much greater, and often an additional step of 3 party inspection is required. Also, variance between authorities has a greater impact (what may be accepted in city, may require additional studies in another city). Availability of ready-made design methods and standards are limited. Own expertise (and even scientific research) is often required to develop sufficient methods and design tools

Is there a way to combine different methods (prescriptive vs. performance based)? use in the same multi-story timber building design?

According to Jane I. lataille , Fire Protection Engineer, future prescriptive fire protection codes and codes for all the other engineering disciplines will continue to merge prescriptive and performance-based design elements until the differences between the two types of design are imperceptible. According to Timo Jokinen, (Senior Fire Safety Specialist, at Kauriala Oy) explanation the performance-based fire design is always a combination of prescriptive design and performance-based design. Performance-based design is usually focused on one, or at most a few, aspects of the buildings fire safety (e.g. structural fire resistance, evacuation safety, smoke exhaust systems. etc.) and the rest of the fire safety design is done using prescriptive rules. If the whole design would be done using performance-based approach you would have to check every aspect of the fire safety requirements separately for the building in question, which is not necessary or practically even possible (for example, how would you design your own escape route signs using performance-based approach, and why would you do that if it is not necessary?). Thus, if a building doesn't fulfill some prescriptive requirement, only that requirement, and aspects directly related to that requirement, can be designed using performance-based method, and all unrelated requirements can be designed using prescriptive rules. In terms of can the same building have areas designed with performance-based rules and other areas designed with prescriptive rules, the answer is yes. But if the performance based-design aspect can have effects on the prescriptive areas of the building, you must extend the performance-based studies to those areas as well to ensure the fire safety of the building will work as a whole. For example, you cannot focus your evacuation simulations strictly to a localized part of the building even if the surrounding areas would fulfill the prescriptive egress requirements; you have to extend the simulations to surrounding areas to account the people flow in and out the different parts of the building.

Multi-story timber buildings don't really differ all that much from the rest of the buildings in this regard. But for example, if you are doing some performance-based design on the bottom floors of the building, it's quite natural to assume that those will have some effect to the upper floors as well, and you must study the building as a whole.

Within a building applies to the design and construction of stairways. A combination of solutions could involve a DTS Solution to address the dimensions of the treads and risers and a Performance Solution to address slip resistance of the tread.(NCC, n.d.)

Performance Solution example In a school, a combination solution might use Performance Solutions for issues to do with fire safety, while DTS Solutions could be used for sanitary facilities and energy efficiency.(NCC, n.d.)

How could we mitigate some problems of performance-based approach?

The biggest problem is the lack of familiarity and education regarding performance-based design on building authority side.

Building authority needs to accept the designs and there are rather few knowledgeable persons in Finland.

What should be done so the methods could be applied in Finland?

Satu Holopainen (Chief Fire Safety Expert at KK-Palokonsultti Oy) explained that Finnish legislation accept performance-based design and it has become more common in recent times. It would be good to have more people familiar with it working at building authorities. It would also be welcome to have more students educated with performance-based design, because as it is they mostly must learn it when they become employed. There have been attempts to create guidelines for performance-based design, but there are various methods that can be used to get the same result. Interpretive models could be favorable.

Timo Jokinen, (Senior Fire Safety Specialist, at Kauriala Oy) pointed out additionally that prescriptive design standards are continuously being improved and updated, but they still cannot always be applied to everything. Current fire codes in Finland allow the use of performance-based design adequately. Perhaps limiting factors for the wider adoption are the high level of expertise required from the fire safety designers (which limits the capable designers to a handful of companies and experts) and the lack of knowledge from potential customers and designers in other fields (architects, civil engineers, etc.) about the possibilities of performance-based design (so they would know when to ask about performance based-design when they encounter a suitable building. Multiple acts in multiple fields are needed in order to increase the Finnish large-scale wood construction. Inspiring examples, development in education, technologies, and research, as well as political support, are needed. Many new fire protection hardware and software tools should be developed so that using of these tools will accelerate the knowledge of fire design using both fire design approach in sophisticated way

Why on earth we need performance-based design approach if prescriptive based design is giving full safety?

Sometime designing multi-story timber building beyond scope of prescriptive prescription and Prescriptive design is important as far as, the advantages overwhelming the disadvantages.

6 Results

Significant findings in thesis is that gathered information that contributed to answer of research question shows that prescriptive and performance based fire design approach go parallel to each other. Prescriptive is old traditional way of designing that restrict use of wood in multi-story timber building to limited height with or without sprinkler but performance-based fire design approach can be utilized in any height of timber building by attaining the same fire safety level with prescriptive design. The nature of prescriptive way of design does not allowing innovation and not rational way of designing that incorporate wish and specification of both designer and client. Since performance-based fire design approach is newly discovered way of designing it has few available literature and prescriptive way of design has easily followable available information. In many ways prescriptive way of design perceived as more save way of designing as its rigid rule and regulations tending to care more safety than economy, but as seen in thesis, even though recently discovered and unfamiliar among many designing societies, performance-based fire design approach promotes same level of fire safety with better economic design by using innovated wood design. For example, by reducing amount of expensive timber material for wall while using in same wall massive timber which has ability to carry load by charring its layers until every occupant escape before building collapses. Performance based fire design prerequisite the competency level of the designer to apply this design. Since many of timber construction materials are being used in multi-story timber buildings are still under discovery and old traditional way of designing is unfamiliar with this building material , it better to use new way of design which focus on how material perform than what material actually it is .

7 Conclusion

Most countries rely on prescriptive building codes, some of which restricts the use of timber in multi-story timber building as timber is combustible materials. Many countries are moving towards performance-based building codes which state objectives and performance requirements and allow any form of construction that meets those requirements. It is very clear how and when to use these two fire safety concepts to make building as fire safe as possible. In multi-story timber building timber can be used in build of 3-8 story by using prescriptive based fire safety approach and more than 8-story story can be designed by performance design approach. Seeing the advantages and disadvantages of both fire design approaches it better to combine (at least it is recommended to use both design Methods combined) as one method compensate the limitations of other. Education in wooden design and construction is still very limited across Europe (Tupenaite, & Geipele, 2021.).So opening educational centers that facilitate wood research academy that in turn will give good social awareness about how to design safely multi-timber building to meet fire performance requirement in order to achieve the Compliance Solution by a combination of both a Performance Solution (alternative designs solutions) and Deemed-to-Satisfy Solution (prescriptive design solutions).

It is good to mention that in the same building design in some areas like loadbearing assembly where priority is given to safety, we apply here prescriptive design approach, which is restrictive rule to follow and, in some area, where Safety could be guaranteed by additional facilities like sprinkler, then performance design applied

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