TimFix (pre-project)
“Fire Dynamics in Timber Structures – Extending the current design limits for future timber buildings”

TimFix

pre-project

Final Report

August 2022

This document should be referenced as: Schmid J., Brandon, D. Just. A., Werther, N. (eds), Fire Dynamics in Timber Structures – Extending the current design limits for future timber buildings, ETH Zürich, Switzerland, 2022.

This document is the final report of the TimFix pre-project. The project represents a summary of the state of the art including a gap analysis. The gap analysis should allow the wood working industry, affiliated associations and other funding bodies to invest goal-orientated in small-, middle- and large research projects. This report comprises the outcome of several technical WPs. Numerous actors participated in the drafting of this project report including an independent, international external review. Furthermore, a global survey was conducted to evaluate the state of knowledge with respect to timber and fire related topics.

Versions

Version “Month 7”	Document for external review	2021-04-09
Version 0	Document for review by work package leaders	2021-05-20
Final draft	Document to project partners	2021-08-31
Final version	Document for submission	2022-08-31

Project Lead and main document editor: J. Schmid
August 2022

Preface

This publication is the result of work carried out within the pre-project “TimFix” by several research performers, universities and external experts. The research partners conducting this gap analysis were (alphabetical order) Arup, CSTB, ETH Zürich (chair of timber structures), London Imperial Collage, TalTech, Technical University of Munich (chair of timber structures), RISE. International experts from Australia, New Zealand, Finland and France blindly reviewed the document. The project was funded by several funding partners representing member associations of CEI-Bois.

This document was created from all participants of all working groups dealing with the Work Packages (WPs) and can be considered as summary document of the state of the art and state of practice. The information presented in this part of the report was carefully selected by experts from various sources. Sources were among others, engineering knowledge, fire safety science knowledge, standards, recently published research results and building practice. The participants of the working groups, the authors, the editors and the publisher disclaim any liability in connection with the use of this information.

Neither the research partners nor the funding partners nor any person acting on its behalf is responsible for the use of the information contained in this publication.

Table of content

1 Introduction

1.1 General

Currently, the widely available standard design guides for structural fire design of timber structures are predominantly based on standard fire, i.e. a defined time-temperature ratio typically used in fire resistance tests (e.g. EN 1363-1, ISO 843-1, ASTM E119). The availability of tools for non-standard fire design is limited.

Overall aim of TimFix will be to develop guidance to reduce this limitation especially when focusing on complex and/or tall timber buildings where a performance based design (PBD) approach is requested. Doing so, the project will aim for creation of the basis for prescriptive design rules whenever possible.

The pre-project of TimFix aims for the identification of knowledge and research gaps and is relating these to an action plan to overcome the obstacles identified. Furthermore, suggestions for research topics are given. These topics are given in the beginning of the document while the motivation can be found throughout the document text.

Various gap analysis documents are available with respect to the fire design of structural timber (e.g. Gerard et al., 2014; Brandon and Östman, 2016, Winberg et al. 2019, Petterson 2020). In the following, a gap analysis is presented based on knowledge, which has been gathered in the WPs of this pre-project. In contrast to previous gap analysis documents (1) the gaps are related to building categories, distinguished by certain building properties, such as degree of complexity, consequence class, or the building height. As important element of an action plan (2) required steps to address the gaps are suggested. Initially various characteristics and tools are listed with respect to fire dynamics and structural timber design.

The aim of document is the identification of influencing factors that are (a) essentially needed to be considered or (b) potentially needed to be considered for either (1) the prediction of the fire dynamics if structural timber elements are involved or (2) the development of tools to allow for the prediction. For the reason of completion, besides relevant factors, factors believed to be irrelevant are included in the listing to allow future works to re-evaluate taken decisions.

2 Limitations

Several project limitations were encountered which comprise the organisation of an international research project without a common legal framework, budget limitations but furthermore, technical limitations that can be found in the particular sections.

It should be stated that the statements and conclusions in this report may be still under discussion and neither a common understanding within the participants of this pre-project or agreement with the reviewers could be achieved in the limited duration of the drafting.

General challenges were encountered arising from different national perspectives on fire safety. E.g., it is not clear if buildings are required to survive a full design fire (examples of exceptions exist in Denmark and Norway where certain types of buildings are not required to survive an accidental fire event considering standard fire). Furthermore, there is no common understanding if the framework of fire resistance can be applied to combustible building products such as timber structures

Due to the risk of uncontrolled fires, already COST Action FP1404 (www.costfp1404.com) recommended the design of certain buildings to withstand burnout in uncontrolled fires. Furthermore, the United Kingdom (UK) based Structural Timber Association (STA) suggest similar design actions. By trend, it is recommended designing to withstand burnout when the fire brigade cannot reach all (internal and external) areas of the building from the outside, if collapse of a building cannot be ethically accepted or when the sprinkler reliability (if installed) is not sufficient.

Some definitions are used in this document. They are intended as proposals for definitions and a common terminology is suggested. Currently, these terms are not yet well established but the terms are frequently used with various meanings. Consequently, in addition, the motivation for the definition is given. The definitions should be considered as an attempt for a common terminology for the structural fire design of timber buildings.

3 Research project suggestions (project action plan)

Based on this report, the following projects were proposed to perform research on. The projects may comprise or exceed the research items identified in later sections but represent potential projects where well-coordinated activities should be performed.

1. Fire Dynamics: Large compartments with exposed timber (hor. surface fire spread within a compartment) in continuation of Arup compartment tests 2021; including quantification of counter measures (conventional sprinkler, mist sprinkler, surface fire retardant treatment).

2. Fire Dynamics: Survival of lightweight construction (Modular elements not platform building); resilient construction technique needed.

3. Fire Dynamics: Façade fire spread (vertical fire spread);

4. Fire Dynamics: Development of a common guidance (e.g. Eurocode) is not available on Fire dynamics;

5. Fire resistance testing: Variability of fire test results ⍰ better testing needed; focus on fire exposure (focus: gas composition and gas movement); OBS: better test methods may not lead to favourable results;

6. General material properties (mechanical- and thermal-) to allow for wide application (for general fire exposure) including variability to give plus/minus ranges of characteristics and consider them in calculations/simulations; dependency on thermal- and fire exposure including its history;

7. Smart detailing; to avoid smouldering/glowing and allow for the application of the design models; Charring in penetrations (horizontal and vertical);

8. Model for charring phases in non-standard fire situations; protection and encapsulation (model) and also improved materials (1 layer product; improved joints, thicknesses….);

9. Education: especially digitalization, linking tools and digital application and knowledge transfer; ETH Zürich and Lignum will soon start project and are looking for partners.

10. Comparison of standard buildings in various countries to allow for guidance and education; it is further suggested that a board will update these building designs and provide educational material

based for these building types (e.g. school, office, residential) considering building regulations in different countries.

11. Development of a web-based database that is publicly accessible; the database should contain research projects (running and concluded), fire accidents and fire test and experiments as currently implemented.

12. Fire from above: protective function of typical layups (encapsulation, protection from contributing to the compartment fire load) should be studied. Currently, a very limited product number is covered. Especially concrete based floating systems can not be assessed.

4 Factors influencing the fire design of structural timber

4.1 General

This part of the final report was drafted by WP2 under the lead of ETH Zürich (J. Schmid) and has been revised by external experts.

4.2 Introduction

In the following sub-sections, various factors are listed alphabetically and the motivation for their inclusion is given together with the references when available. They are divided in factors that are (i) mainly related to the building material wood and (ii) mainly related to the compartment characteristics. If both relations are applicable, they are listed under (i). As many characteristics may be influenced by several factors, they are listed as sub-points and –if considered important – referenced to other points.

The influence on the fire dynamics is intuitively given using a range from ++ (very high), high, o (not relevant/existing or neutral) to insignificant and -- (very insignificant).

4.3 Factors related to the building material

The following items list factors that are mainly related to the building material. As these factors are partly linked and could be assigned to various groups, they are listed alphabetically to allow for locating the items when studying various topics.

4.3.1 Arrhenius equation

Material related model to describe chemical- and physical changes comprising the change of density, local vaporisation (NOTE: moisture movement cannot covered directly, compare Pecenko et al. 2015), decomposition and heat release. For advanced calculations, the Arrhenius equations can be used (e.g. Mindeguia et al. 2018, Wade et al. 2020). Some proposals for the kinetic factors used are available and describe the activation energy and the frequency (NOTE: different Arrhenius equations exist which may use a significant number of parameters, compare e.g. Di Blasi 1998). Depending on the type and parameters used, a feedback to the heating source still needs to be considered. If available, the models based on this type of equations could be used to describe the combustion behaviour of the material in complex simulation software, e.g. field models (NOTE: This is not really a factor related to the material but more a numerical tool aiming at simulating a thermally activated chemical reaction).

Influence on the fire dynamics (o):

It can be assumed that the use of Arrhenius equations, when used as a model for the reaction of the wood material (component) can provide a quantification about the reaction of structural timber (virgin wet wood, virgin dry wood and the char layer), and, thus, their contribution to the fire dynamics.

4.3.2 Adhesive

Adhesives used in glue lines creating bonds between layers (face gluing) have been used for more than 100 years to create linear, multi-element members. Adhesives are used in finger joints (understood in this document as linear extension) and on lamella's surfaces to create bond lines between lamella surfaces (understood in this document as layup extension). Both types are used to create linear members such as glulam elements used as beams and columns. More recently, plane members (cross laminated timber, CLT; solid timber panels, STP) have been introduced to the market utilizing bonding by adhesives. A large number of adhesive products is available which may be grouped based on their major components (e.g. phenol-resorcinol-formaldehyde or polyurethane adhesive) or whether they are applied as one or two component adhesive. For further information on adhesives, comprehensive literature exists, e.g. Dunky 2003. Different adhesive types are typically provided with varying assembly time (sometimes referred to as "open time"), i.e. the duration until the adhesive starts to cure significantly and any mechanical change (e.g. by the movement of a surface in contact with the adhesive) may risk to influence the bonding behaviour. Using the adhesive (sometimes referred to as glue), a joint between two wood surfaces is created whereby the penetration depth of the adhesive is limited, compare e.g. Sterley 2016. In general, for softwood, a penetration depth of about six wood cells can be assumed. Consequently, the bond line may be described by various zones, which are (1) the wood material, (2) the wood material with adhesive, (3) the actual adhesive joint (glue line) and the corresponding sequence in the second member. The bond line (3) shows thicknesses typically between 0.1 and 0.3 mm (e.g. previous EN 386 (2001) replaced by EN 14080 (2013)) Apparently, the quality of the surface prior to bonding and the pressing technique (especially vacuum vs. hydraulic presses) may have an influence on the bond line integrity and consequently the bonding. All adhesives have to pass various tests temperatures before they can be used in structural timer. These tests focus in general at normal temperature use. Thus, only temperatures considered useful to describe their behaviour under normal use apart from fire design is done. For normal temperature use, the maximum temperature reached in tests are lap shear tests and creep rupture tests according to EN 302-1 and -8, respectively also known as "delamination test", see Kemmsies and Lind 2002. In the tests, between two temperature levels can be chosen from, i.e. 70°C or 90°C). However, limited knowledge is available about the mechanism in the bond line when exposed to high temperatures, understood as range between 100°C and 1200°C. Typically, studies relate to tests with constant temperatures below 300°C, e.g. Frangi et al. 2012, Wiesner et al. 2021. For cross-laminated timber, where in the case of fire, large shares of the bond lines are exhibited to similar temperatures, debonding was observed in fire resistance tests and ad-hoc testing, e.g. Frangi et al. 2009, Crielaard 2015, Bartlet et al. 2015, Su et al. 2018. It was observed that the charring layers (exhibiting temperatures between 20°C and 300°C) or charred layers (exhibiting temperatures exceeding 300°C) may fail when a certain temperature was reached in the bond line. The failure temperature is largely scattered, depending on the measurement technique (incorrectly placed or installed TCs), the actual adhesive product and its chemical mixture may vary between 80°C (non-structural adhesives e.g. PVAC) and temperatures above 300°C (some structural adhesives), see Klippel and Just (2018) and may even exceed 500°C, see Figure 1.

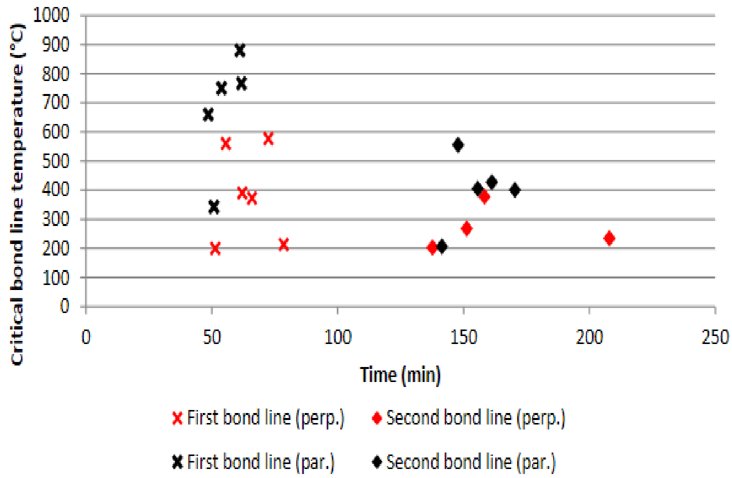


Figure 1: Critical bond line temperature and time of delamination of the first and second layer in PU1specimens and compartment tests (from Brandon et al. 2018); Measurement wires were installed inserted from the back side (perp.) and parallel with the isotherms (par.).

For the face bonding of load bearing timber members, three requirement standards are existing. These are EN 15425 for one-component PUR adhesives, EN 301 for MUF, MF and PRF adhesives and EN 16254 for EPI adhesives. Within one adhesive group, there are large differences regarding there product formulation and it is therefore very unlikely that it would be possible to generally assume that one adhesive group may maintain the bond line integrity during a fire in general. The change of the mixture (e.g. thermoplastic parts and cured parts) in the adhesive product to improve certain characteristics (e.g. curing times) may counteract the performance of glued products in fire. For simplicity reasons, if non-heat resistant adhesives are used, the charring temperature (300°C) is typically understood as the failure temperature of the bond line. This failure of the integrity of the bond line results in debonding and consequently fall-off of the charring or charred lamella. Currently, a test methodology (Bond line integrity in fire, GLIF) is under development, which allows comparing any engineered wood product made from layers (e.g. CLT) to solid timber. The methodology is intended for panel type members but might be used also for the linear type members (glulam) where no such method is available. The GLIF methodology (unloaded, eventually loaded tests in model- or large scale) under development is linked to a severe design fire used for the PRG 320 method according to ANSI/APA PRG 320:2019 (loaded full scale test). In a previous version of the GLIF test, it was intended to compare the performance of the bond line with a maximum possible mass loss of solid timber where no bond line is observed. This is done for a reference density of 450 kg/m^3 at 12% equilibrium moisture content (spruce wood). As a basis, for a char layer mass of zero, Eq. (5.1) would give the maximum allowed mass loss per square meter:

$$\Delta m_{max} = 0.67\ mm/min \cdot 60\ \mathrm{min} \frac{450\ kg/m^3}{1000} = 18.1\ kg/h \qquad (5.1)$$

It should be noted, that the charring rate typically decreases with time, thus, for fire resistance tests exceeding 60 min, instead of 0.67 mm/min a charring rate of 0.55 to 0.72 mm/min may be applicable, see Figure 2.

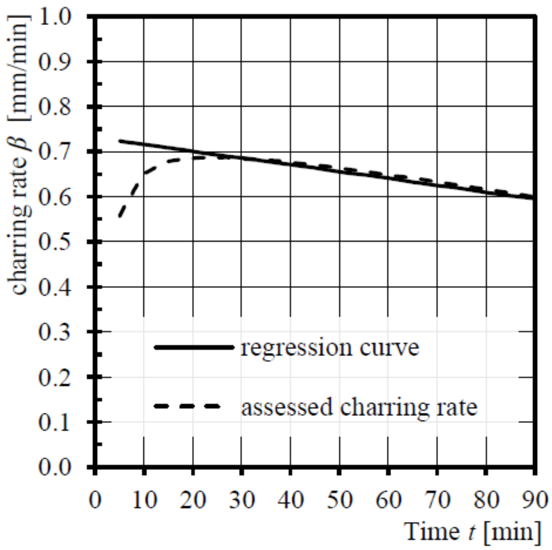


Figure 6: Measurement device (left). Assessed charring rates using the special made meter (right).

(a)

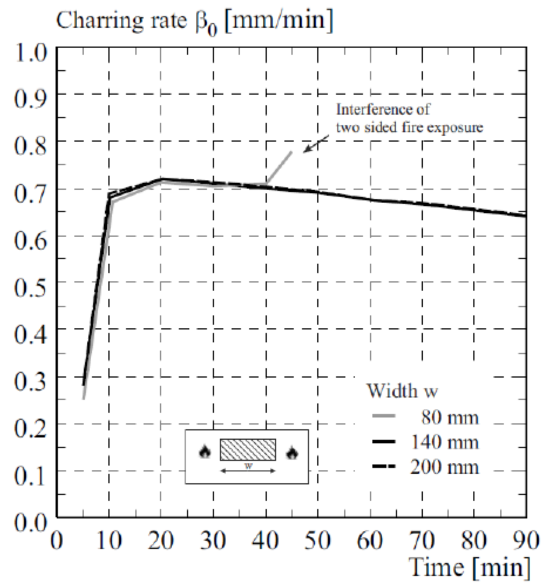


Figure 7: Simulated charring rates (Klippel, 2014).

(b)

Figure 2: (a) Charring rates measured by König and the corresponding simplification as linear trend (regression curve) derived by König (1999) and (b) simulation by Klippel (2014).

The charring depth and its distribution over the exposed area should be verified in the test. Further, it should be noted that the calculation in Eq. (5.1) assumes zero density for the char layer, which is not valid. Typically, the values between 30 kg/m^3 and 90 kg/m^3 are more reasonable. Consequently, the limit is in the order of magnitude of 14.5 kg/(m^2·h). For other wood species than spruce similar values should be derived.

If the mass loss is higher, this indicates that pieces of the char have been released in the test. Consequently, in a fire compartment, the material would be fire exposed to a different environment at the floor (see fire exposure, i.e. thermal exposure and gas environment) exposed on multiple sides. Experiments with lamellae in the same direction show that the failure of charring layers is apparently not linked to differential dilation of lamellae (see Frangi et al.) The following decomposition (i.e. combustion) of the material at this location is currently unknown. Besides face gluing, side gluing exists. Some CLT products are made using side gluing (structural edge bonding). In this process the lamellas of each layer are first glued to each other, so that the side of lamellas are glued the sides of adjacent lamellas (laminations). Side gluing is the bonding of the lamellas short sides in the same layer of CLT. It provides a tight structure while gaps between lamellas may allow fire spread through the CLT. Consequently, non-face gluing may risk non-air tight construction elements, which enables fire spread, smouldering and glowing combustion. Thus, conditions for firefighting and assumptions for burnout calculations may be challenged. Currently, the Austrian timber association is documenting the limited likelihood of overlaying gaps in CLT (see Klippel et al. 2018). The determination of the mass loss appeared to be too complex for testing labs. Reasons may be found in the delayed extinguishment process that lead to unreasonably high mass losses exceeding the theoretical maximum as estimated in Eq. (5.1) but also the undefined fire exposure (thermal exposure comprising of the radiation and gas temperature and the gas composition and its movement, see 4.4.16) in the furnaces.

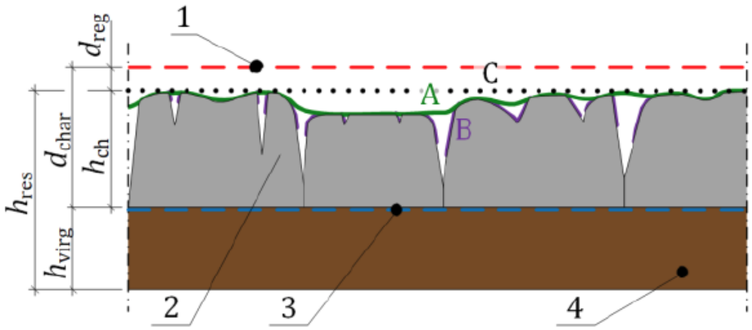
The strength of bonded timber members was analysed by Källander and Lind (2001, 2005).

Influence on the fire dynamics (++):

This characteristic is able to significantly influence the charring behaviour and further the fire dynamics of the compartment fire. Currently, limited test methods are available to predict the adhesive's influence on the product performance and, thus, the compartment fire dynamics (Brandon and Dagenais, 2018; Klippel et al., 2018, Klippel and Schmid et al. 2018, Craft et al. 2018).

4.3.3 Charring behaviour

The charring behaviour, which is responsible for the loss of parts of the cross-section is the most apparent characteristic of structural timber when exposed to fire. Charring depths and charring rates have been documented since the beginning of the development of design rules for structural fire design of timber structures. In general, it is described that charring is the reaction of timber to fire exposure; i.e. due to the applied temperatures in a furnace or compartment, a char layer is formed. For solid timber under the standard fire exposure, this characteristic is considered well researched. In simple engineering models, the charring behaviour is normally considered as a function of time, thus, a charring rate is defined; linearization is applicable depending on the time of interest. In fire tests, the charring depth is assessed using geometrical, temperature measurement based or other methods (see e.g. Schmid, J., Klippel, M., Presl, et al. 2020). The charring behaviour is considered to be depending on the fire exposure, the availability of active or passive fire protection system applied to the member, the species, the initial density, the moisture content. Traditionally, the rate of charring has been used only for the assessment of the structural capacity of timber members describing the reduction of the cross-section. Measureable characteristics describing the charring behaviour are the charring rate (NOTE: the installation of the TCs should be done considering the highly conductive material of the TCs, compare Fahrni et al. 2018), the char layer surface regression (leading to the volume of the char layer) and the char layer density (a measure for the combustion), see Figure 3.



Key:

1	Original (fire) exposed surface (red)	C	Char layer surface (idealized)
2	Char layer	d_{reg}	Char layer regression depth
3	Char line (blue)	d_{char}	Charring depth
4	Virgin wood	h_{ch}	Char layer thickness
A	Envelope curve (green)	h_{res}	Residual (total) section thickness
B	"deep surface sections" (purple)	h_{virg}	Residual virgin section thickness

Figure 3: Measurements and definitions related to the residual virgin cross-section of a previously fire exposed timber member (Schmid et al. 2021).

Influence on the fire dynamics (o):

It appears that there is a strong correlation between charring rate, the structural fuel and the heat release rate (Schmid and Brandon et al. 2016, Schmid et al. 2019) and also between charring rate and mass loss rate (Klippel et al. 2018). Therefore, the rate of charring gives a strong indication of the timber's contribution to the fuel load of the fire, regardless if the fire dynamics of a compartment or in a fire resistance-testing furnace are evaluated, compare Schmid et al. 2018.

4.3.4 Char layer formation

The char layer formation is a significant characteristic of structural timber when exposed to fire. Recently, it became evident that the consideration of the char layer as separate material from timber is needed to answer important questions when it comes to the fire dynamics in compartments where timber is fire exposed (Schmid et al. 2020, Schmid and Frangi 2021). Normally, the char layer material deforms due to drying of wood beneath, volume reduction due to consumption of the char layer by oxidation and the thermally modified materials limited tensile strength. The char layer cracking follows apparently a certain pattern, which might be relevant for the protection ability for the virgin wood section below the char layer. (Winter et al. 2009, Li 2016). Besides the increase of the char layer volume by the progression of the char line, i.e. the charring rate, it appears that mainly in oxygen rich environments, a char layer surface regression can be observed (Schmid et al. 2016 and Schmid et al. 2021). It should be noted, that the definitions in Figure 3 differ slightly from the common definitions (e.g. given in Eurocode 5, CEN 2004) when it comes to the residual cross section, which fails describing the effects observed in connection to compartment fires (char layer surface regression).

Influence on fire dynamics (++):

The decomposition of the char layer may be described by the loss of volume and density (Schmid et al. 2021) which is clearly related to the energy released from this material (Schmid et al. 2020). Consequently, the char layer formation and its behaviour influences the enclosure fire dynamics.

4.3.5 Charring temperature

This characteristic is also known as “critical temperature for charring” In engineering standards, the charring temperature is specified as the isotherm of 300°C or 550°F. Previous studies indicate that for slower heating rates, the charring temperature might be lower. Pecenko and Hozjan (Holzforschung 2021) numerically show that for slow parametrical fires, charring can occur at temperatures lower than 300°C, and that the charring temperature decreases for deeper locations into timber. This kind of results clearly underlines the fact that under particular configurations, using the 300°C isotherm can be non-conservative. Simulating the charring behaviour by a more general way under consideration of the kinetics of the material, the char line is typically defined as the zone where the highest rates of decomposition can be observed. Differences in charring temperatures are apparently linked to the decomposition of one, or more, wood components. For instance, it can be assumed that cellulose decomposition (pyrolysis) is mainly responsible for the combustible volatiles production (and then possibly for flaming combustion) whereas lignin decomposition is mainly responsible for char formation. This point is important to take into account when using a pyrolysis model. While for high exposure levels, the difference of the charring temperature of plus/minus 50 K is considered as very limited and, thus, insignificant, for slow heating curves and the cooling phase of a fire it might be relevant to find a correct definition independent of the reference scenario (currently EN/ISO fire exposure).

According to standardisation, temperature in a low conductive material shall be measured with wires parallel to the isotherm (50 mm). Otherwise temperature measurements risk to be significantly incorrect (lower; thus, often non-conservative) due to the cooling of the tip by the highly condictive material. Often CLT charring and temperature measurements are taken disregarding this limitation and TC channels are drilled from the back side, wires or tube TCs (sheathed TCs) are installed perpendicular to the isotherms. In more recent studies, advanced installation using drilling cores have been developed, compare Figure 4 below.

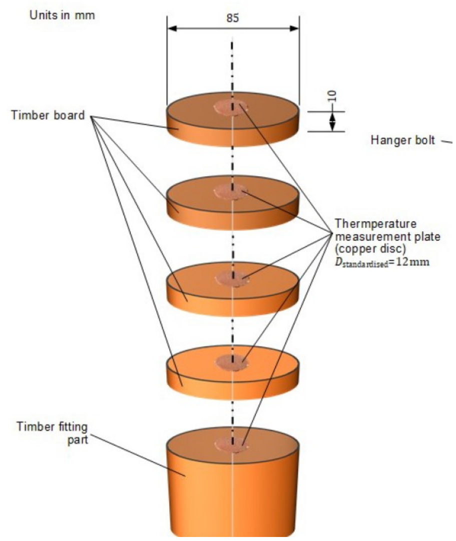


Figure 4: Drilling core to be inserted in a CLT floor slab (copyright by IGNIS – Fire Design Consulting).

Other studies (e.g. Su, Brandon and Dagenais) use a drilling method after the fire test to detect the sudden change of the material density.

Influence on fire dynamics (o):

Although different charring temperatures can be found in literature, the charring temperature of timber is generally the same, independent of wood species (Buchanan, 2017). Only for long heating durations, an influence may be expected. Therefore, no meaningful statement can be made about the impact of varying charring temperatures on the fire dynamics.

4.3.6 Char layer contraction

The char layer contraction (sometimes referred to as "char layer recession", "char layer oxidation" or "char layer surface regression") describes the change of the original surface location and is a measure of the reduction of the total cross-section thickness, i.e. virgin wood and char layer thickness. Traditionally, the char layer is considered as an insulation layer, which protects the virgin wood section. Thus, any thickness reduction of the char layer would counteract this function. This characteristic appears to be a result from the oxidative process consuming the char layer.

Influence on fire dynamics (o):

No meaningful statement can be made.

4.3.7 Char layer oxidation

The term of char layer oxidation is not uniformly defined. Commonly it can be understood as the characterization of an exothermic reaction. Thus, in general, it comprises the smouldering (emission of heat) and glowing (emission of heat and light) combustion but also flaming combustion of the char layer as fuel can be understood as char layer oxidation. The char layer oxidation is a measure of the released heat. It should be noted that smouldering might occur at very low oxygen concentrations, Lange et al. (2020) detected smouldering of a solid timber slab in a furnace where the oxygen concentration was significantly below 10%. All oxidative reactions go along with the mass-loss of the char layer. Exemplarily, the contribution to the fire of the char layer decomposition in a furnace was estimated to between 45 and 90 kW/m^2 based on the remaining mass of the char layer (Schmid et al. 2020, Schmid and Frangi 2021). In a real fire, this may be exceeded depending on the compartment environment (fire exposure) in contact with the (structural) timber and the char layer surface, respectively.

Influence on fire dynamics (++):

The released energy contributes to the heating of the compartment (released heat) and the pyrolysis of the virgin wood (Schmid et al. 2020). In some studies, it is understood as the char layer surface reaction, i.e. the char layer contraction while this study suggests to declare the oxidation in view of the decomposition of the char layer (indicated by its mass loss).

4.3.8 Combustibility

Wood is a combustible material and, therefore, has a potential to contribute to fires as a fuel load. In Europe, standardised test methods exist to determine reaction-to-fire classes which are linked to the combustibility of a final product. Most softwood products would have reaction-to-fire class D (min. thickness and min. density applies). This class indicates that exposed wood surfaces contribute to flashover. After flashover, exposed wood will continue to contribute to the fire until the fire completely (all flaming and smouldering combustion of the timber) stops.

Influence on fire dynamics (+):

The combustibility of the structure may have a significant influence on the fire dynamics in a compartment. With respect to fire resistance testing, the combustibility reduces the external fuel required to follow the defined time-temperature curve (Schmid et al. 2018, Lange et al. 2020). However, considering the terminology of "fire exposure" fire resistance test represent ventilation controlled, fully-developed, post-flashover fires where the compartment shows a very limited oxygen concentration.

4.3.9 Connectors

In timber structures, connectors (also referred to as fasteners) are generally used to connect multiple structural members. In many cases, connectors can be a part of the structural member as well. This is the case for example for nailed laminated timber or timber frame assemblies. Fasteners are often made of steel, which has a significantly higher thermal conductivity than timber, which can influence the fire performance of the structural timber. Steel grades may have different thermal conductivity. In fire design, connectors may be protected individually by plugs made from a low conductive material or by fire boarding or inserted with a surface offset to exploit shading effects (compare e.g. Palma 2017).

Influence on enclosure fire dynamics (+):

Heat penetrating deep into wood members through steel/aluminium fasteners can potentially result in smouldering combustion in well-insulated locations. This may increase the risk for re-growth of a fire that was considered extinguished. See 4.4.22.

4.3.10 Density

While some models for the prediction use the density of the material timber to predict its charring rate, other models omit this characteristics mainly due to the large variation of the density in cross-sections and for simplicity reasons. However, the local density of timber does affect its charring rate, and the extent of this dependency depends on the range of density that is considered (Bartlett et al, 2019). The density has a strong influence of thermal diffusivity of material $\lambda/(\rho \cdot c_p)$, and then can accelerate (low density woods) or delay (high density woods) the start of charring/burning. However, it seems obvious that under high heating rates (as during a fire), unexposed wood starts charring very rapidly, indicating that the "pre-heating" phase is too short for density to have a real influence

Influence on fire dynamics (-):

The heat of combustion (per mass) of timber is approximately constant for most cellulosic materials, such as timber (Beyler et al. 2017). Wood with a higher density therefore can lead to higher combustion energy. However, it is known that wood with higher densities char slower, when exposed to fire. There are no known experimental studies that study the influence of wood density on fire dynamics of compartment fires. However, a parametric modelling study (Brandon 2020) indicated that the impact of varying density on the mass loss rate of timber members exposed to standard fire resistance test conditions is minimal, because the increased combustion energy per volume is to an extend compensated by the slower charring behaviour. Su suggests to set the heat of combustion L to 21.0 MJ/kg.

4.3.11 Extinction

In general, extinction is reached when one of the four elements from the fire-tetrahedron (oxygen, fuel, heat, chain reaction) are removed. Further information is given below in this and the following sections. The combustion process of a burning timber specimen, a burning timber member or a burning timber structure can automatically stop before all combustible material is combusted. The combustion behaviour of structural timber is strongly linked with the creation of the char layer, which is considered as a thermal insulator, is the location of smouldering and glowing combustion and governs the heat supply to the charring front. With respect to extinction, various combustion modes can be addressed: (A) flaming combustion extinction – with the emission of flames, light and heat, (B) glowing combustion extinction – with the emission of light and heat, and (C) smouldering combustion extinction – with the emission of heat. The extinction process can be reached with or without manual intervention. From recently conducted experiments, it appears important to highlight that this is not only a material property but should be seen in the context of the fire exposure. With respect to the actual research activities, it should be highlighted that currently ongoing research addresses multiple or isolated modes of combustion. Often, in the studies only the flaming extinction has been addressed. It is of increased interest as flames might appear near a member's surface (so called surface flaming) re-radiating to the member and influencing the fire exposure of other members. Points, which are strongly related to the extinction of structural timber (compartments):

- Failure in bond line integrity (GLIF, sometimes referred to as debonding or delamination in the fire situation) has occurred for layered wooden material (eg. CLT), exposing virgin wood to heat flux , which led to a second flashover in some cases preventing the self-extinguishment (McGregor 2013, Medina Hevia 2015, Brandon and Östman 2016, Hadden 2017, Su et al. 2018 and Terrei, 2020).

- Encapsulation failure: The fall-off of the fire protection systems, i.e. linings (e.g. gypsum plasterboards) has occurred, exposing (virgin) wood surfaces to a compartment fire, e.g. described by a suddenly increased external heat flux (Brandon 2018b)

- Other phenomenon may lead to sudden exposure of previously unheated (structural) fuel to high compartment temperatures or incident radiant heat flux (Brandon 2018b), e.g. failure of (non-) structural elements protecting other structural elements, furniture fixed to structural elements.

Influence on fire dynamics (+):

Flames at the wood surface impose a high heat flux to the surface. Extinction of flaming combustion therefore, leads to a reduced heat flux onto the wood surface. Extinction of flaming combustion, however, does not indicate that combustion completely stops. Several compartment fire experiments have experienced a regrowth of the fire, after flaming combustion extinguished (Medina Hevia 2015, Su et al 2018, Brandon et al. 2018c).

4.3.12 Extinction of smouldering and glowing combustion

Extinction of all smouldering and glowing combustion indicates that the fire has completely stopped. This appears to be different from extinction of flaming combustion. The extinction of smouldering and glowing combustion can be described as the end of the mass loss of the member indicating the end of exothermic reactions. In that case, no manual extinguishment is needed. No distinct setup is available to test the end of mass loss. Previously, some authors used various techniques to estimate the end of the mass loss at certain exposure conditions, e.g. about 3.5 kW/m^2 in cone calorimeter tests at ambient temperature (Crielaard 2015). Recently, a significant scatter of such tests results were observed, among others on the orientation (vertical or horizontal), see Arnosson 2020, and the gas velocity at its surface. This is in accordance to Schmid et al. 2020. Typically, standard cone-calorimeter tests (CEN 2015, ISO 5660-1) are stopped too early (e.g. after 1200 sec) or do not represent fire exposures in fire compartments. The question is if the classic fire resistance ratings do account for the self-extinction in non-combustible enclosures (Choe et al. 2020). Lacking is the application of knowledge derived from small- and medium scale tests and experiments in larger scale. While cone-calorimeter tests show a specimen size of 0.1 m x 0.1 m and roughly defined fire exposure conditions (gas flow at the surface), FANCI tests (Schmid et al. 2020) provide with 0.25 m x 0.25 m still a limited area.

Influence on fire dynamics (+):

Although the complete extinction of smouldering and glowing combustion completely stops the fire and, therefore does not require any fire service intervention, it can be questioned whether a complete stop of smouldering and glowing combustion can ever be guaranteed under a reasonable time (e.g. 6 h after accessibility of the compartment by specialists). Consequently, it is recognised that firefighting intervention and water application is needed to get to a zero fire. This is not only related to the combustibility of building materials but because objects with a low thermal inertia, or very slow burning objects in the compartment near a protected or exposed combustible element may compromise the ability of adjacent (building) elements to withstand a full fire duration. Furthermore, limited changes of the building design (e.g. refurbishments) during the lifetime of buildings would likely to compromise a building's ability to prevent continued smouldering in all locations. The situations discussed above can be considered reasonably likely and, therefore, a fire in such a building would require a check for smouldering combustion and extinguishment of this combustion by the fire service when required.

4.3.13 Flaming combustion

In the fire design for timber structures, flames are associated with the combustion of gaseous by-products of wood pyrolysis. Flames can set on when an appropriate mixture of gaseous fuel and oxygen is present. For small-scale fires, gases can be auto-ignited at high gas temperatures, or be ignited by an external heat supply, especially hot spots on wood or char surface (Terrei 2019).

Influence on enclosure fire dynamics (++):

The flaming combustion appears to affect the conditions in a compartment more than the smouldering and glowing combustion as it may counteract the accessibility for manual suppression work and influences fast fire spread on surfaces. The difference between compartment heat loss and the flaming combustion contribution is expected to be decisive for the fire development.

4.3.14 Gap sizes

Gaps may exist between components, members or within a component. Engineered timber such as CLT can have gaps between lamellas of the same layers. The size of this gap has an influence on the charring rate (Fornather et al 2001). Typically, it is assumed that a gap of max. 2 mm has insignificant effect on the charring. For CLT products, 6 mm gaps are accepted in the corresponding European product standard. In case of gaps larger than 2 mm, it should be evaluated to what extent (influence area) the charring may affected, e.g. by an increase of the notional charring depth or the consideration of multi-sided heat exposure of the element. Side-gluing of adjacent elements with heat resistant glues may address this issue sufficiently. No study is currently available with respect to the heating effects of the virgin wood beyond the char line. The likelihood of overlapping gaps in multi-layered CLT has been assessed in a recent study and found to be very limited (Klippel and Just, 2018).

Influence on enclosure fire dynamics (+):

Research indicated that an increased gap size in a timber panel leads to increased charring rates in standard fire resistance testing when the gap is exceeding 2 mm width. It can reasonably be assumed that this also leads to increased combustion in enclosure fires and gaps counteract extinguishing of smouldering and glowing combustion.

4.3.15 Glue line integrity failure

This characteristic may be referred to as Bond line integrity failure, (fire induced) debonding or fire (induced) delamination The integrity of bond lines of glued timber products can be compromised in fire conditions. Weakening of the bond line can result in the fall-off of lamellas and layers, which can significantly increase the combustion of the wood, thus the charring rate within the timber element and influence the fire dynamics of enclosure fires (Brandon and Östman 2016, Su et al. 2018). Whether glued products exhibit bond line integrity failure is dependent on the fire exposure conditions as well as the material parameters, such as the thickness of the exposed layer and the adhesive product. The failure modes of the bond lines during a fire are not currently well understood. The impact of important parameters such as the loading need to be documented. Tests methods to identify CLT products that do not show bond line integrity failure have been proposed by Janssens (2017), Brandon and Dagenais (2018), Craft et al (2018).

Influence on enclosure fire dynamics (++)

Due to sudden exposure of (uncharred) timber surfaces to high heat fluxes (or radiation temperature), the heating rate of timber suddenly increases, which leads to an increased mass loss and potential high heat release (Brandon 2018b). Experimental studies have indicated that the effects can significantly impact the dynamics of enclosure fires (McGregor 2013, Medina Hevia 2015, Hadden et al. 2017, Su et al. 2018). In one test by Su et al. 2018 and one test by Brandon et al. 2018 the increase of temperature and heat release /mass loss was temporary and the fire showed a decaying trend, despite the occurrence of bond line integrity failure at a later stage of the compartment fire while in another test by Su et al. 2018 with a different fire severity, a second flashover and no self-extinguishment were observed.

4.3.16 Grain direction

Limited knowledge is available about the charring behaviour along the fibre direction, as it has been considered limitedly applicable in practice. Similarities at ambient behaviour (increased moisture transport) lead to the conclusion that the typically increased charring rates along the fibres is caused by the increased diffusivity of the material. The thermal conductivity parallel to the grain is about twice that perpendicular to the grain. Volatiles generated just below the surface of the unaffected wood can escape more easily along the grain than at right angles towards the surface. Both are important for the ignition/burning of the wood, compare Roberts (1971). For glued assemblies, it is not known if the grain direction may affect the fall-off of layers of layered products such as CLT. Indicative studies showed that there is no such influence (Frangi et al.) but further researchers are currently investigating this issue.

Influence on enclosure fire dynamics (+/-):

Dependent on the construction type, the increased charring along a grain direction might be of concern. When the fire gets through a CLT joint plane, charring along fibre direction may be a very important factor. This can occur for several reasons (poor precision when machining assembly plane, large displacement of timber structures during fire opening assembly plane, etc.). Surface flame spread may be influenced by the outer grain direction.

4.3.17 Gypsum board fall-off

Fire protection systems of gypsum boards can be used to protect structural timber and to ensure a level of fire resistance. Gypsum boards can also be used to avoid or limit the contribution of a timber structure to the fire load (Brandon and Östman 2016). Predictions of the fall-off of gypsum boards in fire resistance tests is generally done using empirical fall-off times (Östman et al. 2010). For parametric and natural fire exposure, a failure criterion considering the temperature on the unexposed side of gypsum boards was proposed by Brandon (2018).

Influence on enclosure fire dynamics (++):

Due to the sudden exposure of previously unexposed but eventually pre-heated timber surfaces to high temperatures (gas and radiation temperature and convection), the heating rate of timber suddenly increases, which leads to ignition with an increased mass loss and potential high heat release (Brandon 2018b). The effect of the fall-off of gypsum boards on enclosure fire dynamics was first observed in experiments by Hakkarainen (2002), where a single layer of type A gypsum boards failed in protected plane timber elements already after about 13 minutes (ventilation controlled fire). The test series carried out for NFPA in 2018 (Su et al.) showed that different configurations of gypsum boards protection installed on the same compartment lead to a different behaviour during fire (heat release, temperature, charring, duration of fire). See particularly the difference between the test 1-5 and the test 1-6. We propose them to be less conclusive here. The fire dynamics showed a resemblance with those of a similar compartment with all mass timber surfaces were initially exposed, which was presented in the same publication. It should be noted that the performance of passive protections (time of protection, time of fall-off) is also dependant on the severity of the fire within a compartment (Jones, 2001).

4.3.18 Ignition temperature

Ignition temperature is a threshold temperature above which wood is most likely to burn with flaming combustion. A commonly used value is 350°C although literature and some standards and building regulations suggests to rather use values of incident heat flux (e.g. 12 kW/m^2) at ambient gas temperature. The temperature limit seems to be difficult to link with physical phenomena (Babrauskas, 2002) and a significant scatter has been observed (see e.g. Bartlet et al. 2018). In some publications (e.g. White & Dietenberger, 2001) ignition is not only linked to flaming combustion but also to smouldering and glowing combustion. Typically, the ignition temperature has been studied at ambient temperatures with radiation emitting test setups with and without pilot ignition source. Consequently, testing conditions limit the relevance for higher gas temperature environments. However, for untreated timber products, the time of ignition in a compartment fire compared to the flashover temperature is short in the view of the entire fire duration, see e.g. Studhalter (2013). However, Studhalter based his studies on the ISO-compartment with very limited dimensions (< 10m^2 room). The ignition temperature should not be mixed up with an extinction criterion.

Influence on enclosure fire dynamics (+):

Recent work shows a very large range of surface temperature at ignition, which questions the relevance of the concept of "ignition temperature" (Terrei, 2019). As the ignition criteria are expected to significantly influence the flame spread, the influence on the fire dynamics is apparent.

4.3.19 Mass loss

The mass loss is a measure to locate (chemical) reaction associated with exothermic reactions within a fire exposed sample or specimen. For example, it is used to verify the self-extinguishment. Consequently, the mass loss (rate) can be used to assess the extinguishment. In standard fire resistance furnaces, it is recently proposed to be used to verify that CLT performs as solid timber without the influence of the bond line integrity and without considering the loading (see Klippel et al. 2018). However, in general, it is not a reliable measure for other properties such as the charring rate. Recent research highlighted that mass loss of the structural timber might be related to either material conversion or material loss (see e.g. Schmid and Richter et al. 2021). Thus, traditional mass-loss measurements in compartment fires fail to cover the accurate description of the fire dynamics (the measured loss of one unit mass may describe the combustion of one mass equivalent timber or the conversion of about two mass units to one mass unit char layer which exhibits about half of the density but increased heat content). Thus, no appropriate measurement tools are currently available to estimate the meaning of recorded mass loss for the fire dynamics.

Influence on enclosure fire dynamics (++/o):

The mass loss describes either the release of combustible material from the timber structure or its conversion to char. As it is the measure of other factors describing the combustion of the material it can be classified as "++" or "o". Consequently, the mass loss is a major measure for the structural timber contribution to the fire dynamics in fire.

4.3.20 Modification with fire retardant treatments

Wood modification of the surface (wood surface treatment), the depths closer to the surface and of the complete section are available. Some studies show that the ability to create combustible volatiles can significantly be changed by the application of wood modification. However, available reports indicating a reducing effect on the charring rate (and thus, contributing to the improvement of the loadbearing capacity) are limited unless a reactive fire protective system is applied (compare Nussbaum 1988). It should be highlighted that the measurements were done in cone-calorimeter tests and not compartment tests where other effects (delay of surface flame spread, delay of flash-over) may be expected. In fire resistance testing, no such effect is expected as burners would compensate for the eventually reduced limited combustibility of a product due to its treatment. It is unclear if non-extruding treatments (surface treatment or impregnation) is able to change the structural fuel load available for the combustion in a compartment: while some treatments create water when heated, other treatments are said to break the chain reaction needed for the sustained combustion. However, the only material that is known to break the chain reaction is Halon, which is forbidden since the year 1994. Recently, a method which has been improved is the (in-situ) silicification of wood material (Merk 2016). However, it is not clear if only the charring rates are changed or the heat of combustion. With respect to flame spread, the durability of fire retardant treatments is not required in many countries but test methods exist (Windandy 1998, Östman et al. 2016).

Influence on enclosure fire dynamics (++):

If there are less combustible volatiles, the fire is likely shorter or cooler or might not develop at all. Therefore, (dependent on the compartment, fuel etc.) it is very likely to has an influence on the structural loadbearing capacity as well.

4.3.21 Moisture content

Typically, the moisture content (MC) of structural elements made from timber vary depending on the indoor climate. Typically, in heated indoor environments small members may exhibit moisture contents below 8% while mass timber can be assumed to exhibit a moisture content around 10% indoor. Werther (2016) investigated the influence of varying moisture content on the charring behaviour for various fire exposures and could quantify the reduction of charring with increased MC. The results of the fire tests with different initial moisture contents (0M-%, 6M-%, 12M-%, 18M-%) showed that an increase in moisture content of about 1 M-% led to a decrease in the charring rate of 1 %. After 120 min of standard fire exposure, a difference in the charring depth of 20mm was observed between the kiln-dried test specimen (0 M-%) and the test specimen with a wood moisture content of 18 M-%. This findings can be confirmed by other authors (Mikkola 1990, Huntierova 1995 and Schaffer 1967).

However the investigation revealed that for practical applications with a moisture content between 8 M-% and 12 M-%, the moisture influence on charring can be neglected compared to the influence of the potential fire scenario.

Influence on enclosure fire dynamics (-):

Wet wood is more difficult to ignite than dry wood, as it requires more energy to heat up to temperatures exceeding 100°C. Thus, heating and the charring rate is reduced. There is however, as far as known by the authors, no experimental study that studies the influence of moisture concentration on enclosure fire dynamics.

4.3.22 Lamellae dimension (layer thickness) of CLT

Engineered timber is generally made of wood-based elements or lamellas. The lamellas thicknesses can vary (in product standards starting from 6 mm, in fire design standards starting from 25 mm; typically up to max. 45 mm). As a rule of thumb, higher (visual) grades are available in less thick layers. It is known that the thickness of lamellas has an influence of the fire performance of some mass timber materials, such as CLT (Klippel et a. 2018) and potentially glued laminated timber (Andersson and Ek 2017). For example, it is considered more severe for the adhesive and the timber to test a 7-ply CLT with 20 mm thick lamellas than a 5-ply CLT with 35 mm thick lamellas (Craft et al, 2018).

4.3.23 Lay-up of CLT

CLT comprises of layers that are glued in a cross-wise fashion, but sometimes consists out of two layers that are parallel glued. The thickness, the number of layers can be varied, resulting in a large amount of possible CLT products with different lay-ups. Compare Bartlett et al. 2021.

Influence on enclosure fire dynamics (++):

The bond line integrity failure is not only dependent on the adhesive used, but also on the lay-up of the CLT.

4.3.24 Pyrolysis temperature

The temperature at which pyrolysis of wood starts is reported to be approximately 200°C to 250°C (conservative values). This value is depending on the exposure conditions (duration, thermal exposure and gas composition) and also the wood components (lignin, cellulose, hemicellulose), see e.g. Drystale (2011). The temperature is currently implicitly tested by the encapsulation fire resistance test (CEN 2004); compare also Chorlton (2020). It should be noted that, in this standard test, further the fixing methods (in Eurocode 5 terminology: fixations) have a significant influence on the encapsulation criteria. At temperatures that reach this range, wood is able to contribute to the fuel load of a potential fire. Rules in Eurocode 5 (CEN 2004) seem to be in contradiction to this limit, however, for the structural fire design for post-flashover compartment fires with the exception of smouldering fires, the use of 300°C as the limit can appears to be appropriate.

4.3.25 Smoke creation

Combustion creates reaction products, among others combustible volatiles, flame, heat and further more soot and smoke. It appears useful to distinguish between the “dense” gas products (comparable to exhaust gases) and the smoke where further air dilutes the “dense” gas products and describes the volume depending on the distance from the fire (flame), e.g. the height of the plume. Typically, for the design of smoke extraction systems (natural or mechanical) and for the evacuation route design, the contribution by the interior is considered but the structural fuel is left unconsidered. Schmid et al. proposed the following description of the gas creation by charring timber using the stoichiometric burning ratio, the charring rate and the description of the combustions behaviour:

$$V_{gas,cold} = \rho_{dry}/r \cdot \beta_{st} \cdot \alpha_{ch} \tag{5.2}$$

where

$V_{gas,cold}$ gas volume at 20°C created per square meter, in m^3/m^2;

β_{st} is the time dependent charring rate; in mm/min;

r	is the stoichiometric burning ratio, 5.14;
α_{ch}	is the energy release factor considering the combustion behaviour of structural timber, for the fully-developed burning phase in ventilation controlled fires, a factor of 0.4 may be assumed.

Influence on enclosure fire dynamics (++/o):

A significant influence of combustible surfaces (e.g. ceiling soffit) on the smoke production can be stated. This is due to the (incomplete) combustion of the structural timber. An increase of the extraction capacity exceeding 50% may be expected based on stochastic combustion models. The estimation can furthermore be used to predict the contribution to the gas mixture and the gas flow inside out from the compartment. It is expected that this behaviour will be implemented in CFD models to realistically model the fire exposure of timber members.

4.3.26 Smouldering combustion

Smouldering combustion is a combustion reaction between degradation products of solid wood (mainly char) and gaseous oxygen associated with the non-existence of the emission of light. Various literature sources are available, among others the SFPE handbook (2016). The porous structure of char allows oxygen to diffuse through it and react with it. This can occur only if enough oxygen can diffuse through the char layer. For this reason, it occurs in a thin layer at the char surface. It rarely occurs together with flaming combustion, the latter preventing oxygen to reach solid surface, see Boonmee 2005. Furthermore, smouldering combustion may imply a risk for re-ignition of the fire when it has been considered extinguished or if the fire was able to reach construction cavities (gaps, joints, connections, voids). The latter lead to (deadly) fire incidents earlier (not necessarily related to timber structures), e.g. when toxic gases from smouldering fire in insulation spread to adjacent residential units (Germany: combustion of paper insulation layer between houses). Eventually, timber frame construction may be more sensitive to smouldering combustion which appeared also when prefabricated wood modules with (improper) or no cavity insulation was designed, Östman et al. 2014. It should be noted that in several cases the fire spread was observed downwards (Luleå 2013, Salzburg 2010) from the fire origin, which is often believed impossible by designers and, consequently, not further considered in the design. Test standards which may be relevant to describe a product or material's ability for smouldering combustion are:

- DIN 4102-15 and -16 "Brandschachttests" (Germany);
- CAN/ULC-S129-15 – Basket method (Canada);
- BS 5803-4 1985 (UK) Thermal insulation for use in pitched roof spaces in dwellings - Methods for determining flammability and resistance to smouldering;
- NT FIRE 035 (Scandinavia);
- ASTM C739-03 (USA);
- 16 CFR 1209.7 (USA);
- Ad-hoc experimental setups in research projects.

Figure 5: Initial phase of the European smouldering test EN 16733 [Photo: TUM].

Currently, a new European test standard, EN 16733, is addressing this behaviour. At the moment, this standard is barely referenced in building regulations and CSTB stated that this standard is not appropriate to describe/test smouldering at the structural level (expressed at the French level). It should be noted that timber in its original form is not prone to smoulder fire but some related products (wood fibre insulation and the char layer).

In various research projects, where compartment tests were performed, it was shown that for the limited areas tested (up to about 50 m^2), fire services have no problem to account the extinguishment of smouldering combustion in timber structures. However, it is appeared that the firefighting technique may be adapted as additional time and cleaning of the elements from the char layer may be needed [Kempna et al. 2018, Engel et al. 2020].

Influence on enclosure fire dynamics (+):

Smouldering (as glowing) combustion may counteract the self-extinguishment and burnout behaviour of compartments with structural timber. Components which surfaces undergo smouldering or glowing combustion should be accessible for extinguishment work, see 4.4.22.

4.3.27 Surface flaming

Surface flaming is considered as the flaming combustion (see Subsection 13) originating from vertically or horizontally orientated combustible surfaces, i.e. structural timber. Flames emit energy from the combustion of the emitted combustible volatiles. Consequently, this behaviour is considered related to the received heat flux to the surface of the combustion material and net rate of the heat transfer and, furthermore, the oxygen concentration in the compartment (location) and may only be predicted in the context of a tool to predict the compartment oxygen concentration (e.g. multi-zone or field models). In the decay phase, all members regardless their combustibility have stored energy (heat) and will re-emit the heat to the compartment and, thus, delay the cooling of the compartment. However, surface flaming will counteract the cooling further and may feed radiation energy to the element of (a) its origin and (b) adjacent members. Consequently, a design tool may need to consider this effect.

Influence on enclosure fire dynamics (++):

Surface flaming is considered relevant for narrow compartments but also for the extended duration of the fire when cooling of the compartment (e.g. by ventilation openings) cannot overpower the feeding of the compartment temperature by (surface) flaming.

4.3.28 Species

There is limited experience with comparative fire testing of different wood species. The range of charring rates have been investigated in some studies, summarized e.g. by Leikanger 2011. Hugi et al. (2007) have performed several tests on small specimens with different wood species. They did not find a direct correlation between charring rate and density (range 350 – 750 kg/m^3); in that case, species, or more particularly the oxygen permeability presented a better correlation with charring rates.

Influence on enclosure fire dynamics (-):

Thermo-gravimetric analysis (TGA) of different wood species shows that there can be differences of thermal decomposition at elevated temperatures. In nitrogen (oxygen deprived) conditions the remaining mass fraction after pyrolysis can differ for different wood species (Brandon 2020). Further investigations on the impact of species on charring rate and mass loss rate need to be performed.

4.3.29 Strength and stiffness reduction (change of mechanical properties)

Strength and stiffness reduction due to heating have been directly investigated for constant temperatures (“oven tests”) where further effects such as creep and mass transfer do not appear as when investigating larger sections under transient conditions (“furnace tests”). As no separate, simplified models for strength and stiffness and creep and mass transfer exist, the reductions are described typically as effective reduction properties (compare e.g. Schmid et al. 2012). Typically, the effective material properties are considered valid only for standard fire as they were derived by means of backwards calculations (compare König et al. 1997 and König et al. 2000). However, the tested comprised furnace tests in standard fires and parametric fires are initially unprotected and protected situations. It should be highlighted that the mechanical properties have been used to derive the mechanical response of timber members protected by gypsum plasterboards, consequently, the surfaces were not exposed to standard fire. The reduction of the mechanical properties is done in practice by means of the effective cross-section method (ECSM) where a zero-strength layer (ZSL) accounts for the losses of strength and stiffness.

Influence on enclosure fire dynamics (-):

There is no influence of the strength- and stiffness reduction on the fire dynamics but reversely. However, the change of (mechanical) material properties is currently under discussion.

4.4 Factors (mainly) related to the compartment design and building structure

4.4.1 Active fire protection system

Active fire protection systems such as sprinklers, aim to actively extinguish the fire. Currently, it is not clear how the fire protection systems can be addressed in the design of timber compartments as basic research has mostly been done for non-combustible structures (e.g. applicability of the reduction of the fire load by a general factor of 0.61 in EN 1991-1-2), how spray sprinkler may change the overall risk assessment and how various arrangements (e.g. set-off distance between sprinkler heads and surfaces and soffit, increased density near facades) may affect the compartment design.

Influence on enclosure fire dynamics (++):

The presence of active fire protection systems significantly reduces the risk of fire development and fire spread. However, it is important to note that the reliability of these systems is not 100%. Reported national statistics of sprinkler reliability lie generally around 90%

4.4.2 Balcony design

Building regulations may consider the balconies as optional evacuation routes, temporary assembly point. Balconies may act as shield to detach façade flaming's from the upper parts of the facades. If designed from combustible materials, increased vertical fire spread may be enabled. Some qualitative design rules are available in guidance books (e.g. Lignum documentation 2015 and 2019) while simulation may be considered not reliable yet.

Influence on the fire dynamics (+):

The negative effects of external flaming may be reduced or increased by the balcony design.

4.4.3 Burnout (definition)

Burnout – or a likely burnout – may be required by some regulators. It is suggested that this characteristic describes the 90% consumption of the movable fuel and the decay of the compartment fire to an average (average over height) fire temperature of 200°C (NOTE: this value describes the thermal exposure comprising of contributions by the radiation and the gas temperature). For these conditions, a likely burnout can be stated but depending on the actual boundary conditions (gas movement, slow burning or inert items of the interior, conductive installation). It should be observed that smouldering and glowing combustion may still continue and will need to be extinguished manually and corresponding measures should be foreseen in the fire strategy (compare section 3.4 below and Mindeguia et al, 2020). A construction or a product made from layers that fail (i.e. passive protection or timber layers) during the decay may result in a change of the enclosure conditions or the fuel characteristics and may result in a regrow of the fire, eventually a further flashover and risk for cycling. A pre-condition for enabling successfully executed manual fire-extinguishment of combustible components is that the corresponding glowing, burning or smouldering surfaces or parts of the construction can be reached by water and (visually) detected, see below. Burnout of a structure should not be misunderstood as burn down (entire consumption of the structure implying collapse).

4.4.4 Burnout, design for burnout

This design objective should not be mixed up with burn down, i.e. the combustion of the movable fuel and combustible structure. Design for burnout is understood as the design for likely auto-extinguishment, which comprises the total consumption of movable and the activated structural fire load as part of the structural timber in a fire compartment. As the structural fire load is a variable, i.e. depending on the member's fire exposure in the compartment, the structural fire load is neither a constant value nor solely material dependent but a matter of the compartment design. Currently, no common terminology exists (compare 4.4.3). Burnout may be described using the term "likely self-extinguishment" of a compartment or structural timber members and combustible component. However, the term self-extinguishment is complex when smouldering and glowing combustion should be reduced to a minimum or to zero (compare 4.3.12). The product choice may be considered as necessary basis for the burnout design but the overall parameter is the compartment design with its ventilation and the sum, (relative) location and orientation of the combustible surfaces. Thus, in general, it is recommended to design for burnout as it supports the manual suppression activities significantly by product choice and product protection (e.g. encapsulation) and by the compartment design.

Influence on the fire dynamics (+/-):

The burnout is the end of a compartment fire because of the compartment fire dynamics. The terminology of burnout should be defined to create a common understanding. For building design, burnout should be discussed with the ability of the fire brigades to undertake the manual suppression (at a certain limit) and the likelihood for burnout. It appears to be unreasonable for any structure to give a guarantee for likely burnout (compare Choe L et al 2020), apparently the risk for smouldering combustion remains for items of the movable fuel and particular areas of the structural timber (e.g. details, narrow elements, voids).

4.4.5 Burning rate

In many studies, the combustion of a material is described by a burning rate, e.g. in g/s. The burning rate of a representative of the interior/movable fire load should not be mixed up with the non-defined burning rate of the structural fire load. Furthermore, sometimes burning rates are incorrectly understood as charring rate while the majority of researchers understand burning rate as a measure of the heat release.

Influence on the fire dynamics (++/o):

The burning rate may be translated to the HRR when the mass change and the material's heat content of all materials involved in the fire is known. According to the SFPE handbook, the HRR of a structural timber component (comprising of virgin wood and char) can be described by:

$$HRR = \Delta H_{ww} \cdot \dot{m}_{ww} + \Delta H_{ch} \cdot \dot{m}_{ch} \tag{5.3}$$

where

HRR	is the heat release rate per square meter, in kW;
ΔH_i	is the heat content of the material i; MJ/kg;
$\dot{m}_i$	is the mass loss rate (MLR) of the material i; kg/s;
ww	is the index for wet wood;
ch	is the index for the char layer material;

NOTE 1: for wet wood at 10%, a heat content of 15.5 MJ/kg can be assumed, for the (dry) char layer material, a heat content of 31 MJ/kg can be assumed (compare CEN 2002, Schmid 2021).

NOTE 2: For the application of Eq. (5.3), the conversion of wet wood to the char layer needs to be considered.

4.4.6 Compartment size

The appearance of localised fires, which change their location within the compartment is called "travelling fires" (TF). The appearance of TF is currently under discussion when structural timber surfaces are left exposed. In general, for TF various tools are available, e.g. iTFM developed at Imperial Collage, fTFM developed by CERIB, Imperial Collage and Arup and eTFM by University of Edinburgh. Exposed combustible surfaces may lead to the appearance of severe fires depending on the compartment size. For very small compartments (<10 m^2), the effect is limited (compare Studhalter 2013) but for larger compartments the presence of exposed combustible surfaces at the soffit may induce the appearance of other types that post-flashover fires, i.e. travelling fires. Research on travelling fire has been progressing while few design tools are available (Rackauskaite 2015, Dai 2020, Heidari 2020). A devastating fire at the chemistry lab in Nottingham (year 2014) or the motorcycle museum in Austria (year 2021) for which significant combustible surfaces were exposed did not show the presence of a travelling fire. Further research is currently being conducted on that topic. Fire tests at CERIB 2021 showed fire growth rates exceeding "ultra fast" in an about 400 m^2 compartment with exposed CLT ceiling (see online reference in expectation of a journal publication LINK).

Influence on the fire dynamics (++):

The compartment size affects the fire dynamics and the fire growth. Traditionally, the time to flashover has been investigated for limited -small compartment sizes(<100m^2). Every recent indicative experimental results for larger spaces show that fire travels in the compartment (Hidalgo 2019,Heidari et al. 2020,Nadjai 2020), while the combustible surfaces (soffit) are able to influence the spread significantly (Nothard et al. 2020).

4.4.7 Connections

Regardless the loading, connections are considered as joints when a connector is used. Consequently, the connector may influence the heating of the connection section. See #39 #40 #27.

Influence on the fire dynamics (+):

If metallic or other high density or highly conductive material connectors are used, they may lead heat to adjacent elements or cavities where (re-)ignition of combustible building components may occur. General design rules for detailing may help to identify these areas and avoid corresponding risks.

4.4.8 Joints

Fire can spread through joints between members with a compartment separating function. Compartment tests that involved fire spreading through joints were reported by McGregor (2015) and Su et al. (2018).

Influence on the fire dynamics (++):

Joints bear the risk for (unrecognised) fire spread. Detailing has to be designed to prevent fire spread. Education of the designers and practitioners and the quality management (by others than the contractor) at the building site appears to be required

4.4.9 Cavities

Cavities (voids) may represent risk for non-recognisable fire spread within construction. See also Subsections 23, 35.

Influence on the fire dynamics (+/o):

Cavities have no influence as long as the joints to these cavities are designed properly so that fire does not enter the cavity and spread unseen or undetectable.

4.4.10 Compartmentation

The limitation of the volume, which is involved in a potential fire, is called compartmentation. Compartmentation is provided by appropriate design of wall and floor construction, connection and joint details, service penetrations and doors. Depending on the occupancy and the building height, limits of the compartments (e.g. floor area) are given in building regulations. Typically, floor limitations consider areas on the same floor as one compartment but also deviating approaches with multi-level fire compartments are available (e.g. office occupancy in UK). Increased allowed floor area may relate to increased exposed structural timber. For multi-story compartments, the external flaming would be superimposed from various compartment floors. Consequently, the external flaming would be increased.

Influence on the fire dynamics (++):

There is an impact in single storey compartments on fire dynamics (transition to travelling fires), that transition may change if the structure is combustible also; multi storey fires will further influence the fire dynamics; all of this will impact analysis methods needed to evaluate the risk of fire spread to other buildings from the compartment on fire.

4.4.11 Decay (definition)

This characteristic of a fire development can be considered as the decrease of the external and internal flaming, the compartment temperature or heat release rate (HRR) after a previous peak or steady state burning phase. The decay phase, which may be the longest stage of a fire event, is characterized with a significant decrease in available fuel or available oxygen if no ventilation is provided. For structural timber, this consideration is challenging as the structural fuel is activated as a function of the thermal exposure of the timber structure. Thus, for compartments with significant surfaces of structural timber, in the phase after the consumption of the movable fuel, the timber structure may further contribute to the fire. Consequently, for compartments with the exposed structural timber, it is suggested to assess the appearance or non-appearance of a in the phase after the consumption of the majority of the movable fire load. Thus, the HRR should be compared in the beginning of the structural decay phase (e.g. when 70% of the movable fire load is consumed as suggested in 1991-1-2, CEN 2002) and thereafter. Thus, for simplicity reasons, it is suggested that the appearance of a decay phase can be stated when the HRR (e.g. described per floor area, in m^2) reduces to a certain degree or absolute value within a certain time. Based on a large number of compartment experiments (e.g. Medina 2015, Brandon et al. 2021), an estimate is the reduction of the HRR of at least one quarter within a maximum of 60 minutes after the point in time when 70% of the movable fuel has been consumed. It should be observed that after the decay, for some products and components, re-growth of the fire may occur. Thus, the appearance of a decay shall not be misunderstood as burnout.

4.4.12 Design fire

Prior to a structural fire design, the decisive design fire scenario is to be established. In the traditional fire resistance framework, this is done by pre-defining the standard fire as a comparative measure regardless the building material. For more complex design cases, project or compartment specific fires are evaluated and consequently used as design fire. Currently, no international standard is available. The DIN 18009-1 gives guidance about the process but structural timber and the influence on the fire dynamics is not considered.

Influence on the fire dynamics (++):

Currently, there is no agreement if localized fires (pool fires), travelling fires or fully developed fires should be considered as design scenario. From previous fire accidents (Chemistry building in Nottingham, UK, Motorcycle museum in Tyrol, Austria, School gym hall in Fukoyama, Japan (Kagiya et al 2002)) did not show an appearance of travelling fires. Research experiments are currently undergoing in France (CERIB 2021) to study the development of travelling fires in large compartments with the presence of combustible structural elements. This is indicatively also shown in first experiments of larger spaces (CERIB 2021). Current practice is the definition of fire design volumes, which might be smaller than fire compartments to estimate a credible worst case scenario, however, no agreement is available yet. Both travelling fire and traditional methods are important and should be considered in the modern designs as shown in Law 2010, Rackauskaite 2018).

4.4.13 Draft

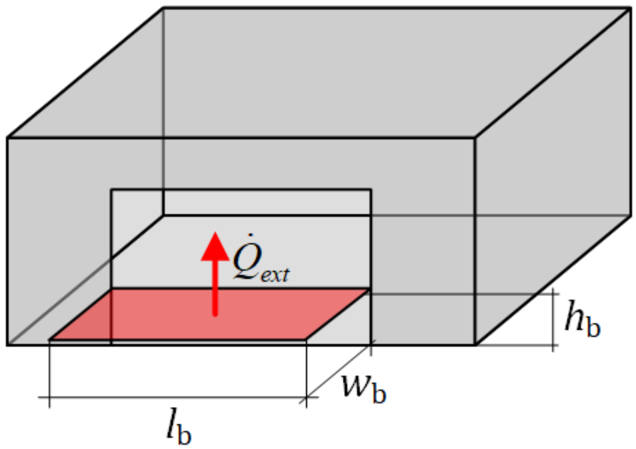
Draft is the movement of gas due to (natural) pressure difference. Consequently, it may influence the heat transfer to surfaces, the movement of hot gases and the fire spread. Atrium designs may increase the draft situations in adjacent/concerned fire compartments.

Influence on enclosure fire dynamics (+):

Draft may interfere with the self-extinguishment when superimposed with the accidental loading case fire. The effect on self-extinguishment has been observed by Crielaard et al. 2019 and quantified with respect to the expected change of the charring rates by Schmid et al. 2019. Conclusions may also be utilized for superimposition of externally implied gas velocities (wind) and fire events.

4.4.14 External flaming

Due to the contribution of structural timber to the total fire load, for ventilation-controlled fires, in the steady state phase, the combustible volatiles created by the pyrolysis of fire exposed structural timber, cant burn inside due to the lack of oxygen but burn outside the compartment. It should be considered that a fuel controlled fire in a non-combustible (NC) compartment may become a ventilation-controlled fire when – in the same compartment - structural timber surfaces would be exposed and consequently involved in the fire dynamics. Multiple observations are available in literature (e.g. Hakkarainen, 2002, Bartlett at al. 2019) where the heat fluxes opposite the compartment and the heat fluxes from the plumes onto the façade were greater with the presence of combustible surfaces within the compartment. Quantification shows that in some cases only 30% of the structural fire load by the timber surfaces (CLT) combust within the compartment (Brandon 2018a). Recently, a novel technique was proposed to estimate the combustion characteristics of the structural timber (Schmid et al. 2020c) which might be utilized by the model of Lee [2012] introducing a virtual burner attached to the compartment openings, compare Figure 3. Using the compartment’s combustion capacity (i.e. combustion capacity by the air inflow), the exterior heat release rate can be determined.



Key:

$\dot{Q}$	Exterior heat release rate;
h_b	Heigt of the neutral plane;
l_b	Length of the virtual burner;
w_b	Width of the virtual burner.

Figure 6: Application of a virtual burner (concept by Lee 2012).

A simplified model is currently under development by the team of Torero J. and the University of Queensland based on experiments using small-scale CLT compartments of ca. 0.5m x 0.5m x 0.3m (Gorska 2020).

Influence on enclosure fire dynamics (++/o):

There is a significant influence of the fire dynamics on the external flaming. Reversely, no meaningful statement can be made.

4.4.15 Extinction (definition)

It appears that extinction is understood as zero combustion after a fire event not only focusing on the timber structure. This understanding appears to be observed for most fire fighters, building authorities and laypersons. In the past, it was observed that in fire experiments with realistic movable fuel load, some parts may sustain smouldering over a long time although the compartment temperature are close to ambient (Choe et al. 2020). Consequently, it should be highlighted that regardless the building material, zero fire/heat generation can only be achieved in a reasonable time if there is (firefighting) water applied in the right amount and location. Currently, limitations for the terms may be assumed in line with Eurocode where fires in compartments up to about 500 m^2 floor area and 4 m height can be predicted, compare also SFEP handbook.

4.4.16 Fire exposure

Exceeding the thermal exposure, combustible material's behaviour in the fire situation appears to be influenced by the gas characteristics (Schmid et al. 2018). It appears useful for the description of the compartment fire dynamics and the combustion behaviour of the char layer material to describe not only the thermal exposure but also the environment in the compartment understood as oxygen concentration and the movement of the gas and its turbulence (Schmid and Frangi 2021). The fire exposure appears to affect the combustion of the char layer and, consequently, the heating of the compartment and the uncharred timber section, respectively. Large differences in charring rates in furnaces may be due to the different fire exposures despite the fact that the temperature control is done similarly. Thus, it is advised to investigate the oxygen concentration and the gas movement (velocity and standard distribution) in future fire resistance tests.

Influence on the fire dynamics (++):

Currently, a limited common understanding is available attributing the description of the fire exposure on the fire dynamics.

4.4.17 Firefighting

Firefighting is an important element of the safety chain available (operative measure). The increased exterior flaming for structural fuel is a concern for mass timber projects. Firefighting guidance is available in various countries. For UK, this is available under UKFRS.com. Concerns of fire fighters are spread currently also on social media, e.g. LinkedIn. Some guidance for the fire fighters has been derived, e.g. Smolka et al. (2018). Currently, there is no common understanding if a structure shall withstand a fire event without intervention of the fire brigade. Some concerns were raised by German firefighting representatives that fire fighters cannot share the responsibility for the structural survival of a building. Consequently, design for likely burnout should be discussed dependent on the building class.

Influence on enclosure fire dynamics (+/o):

There is an influence of the fire dynamics on the firefighting approach. Reversely, no meaningful statement can be made. Firefighting techniques may be challenged in timber buildings due to the hidden charring and smouldering and glowing combustion, see 4.4.22.

4.4.18 Fire load

The total fire load is defined by the sum of the structural fuel load and the movable fuel load. Currently, no tool is available to consider the limited scatter of the structural fuel load. Designers have further the possibility to control how much of the structural timber is allowed to become involved in the fire dynamics by choosing e.g. the level of encapsulation of certain shares of the total surface area.

Influence on the fire dynamics (++):

The relative arrangement of the structural elements, which remain unprotected are relevant for the structural fire design. Although all enclosure surfaces will have an increased temperature in the fire event, the combustion of a structural timber may result in the exceedance of the effect to other elements by radiation of surface-near combustion or flaming combustion. Fire load has an important impact on the allowable ratio of exposed timber surfaces and their orientation when designing for burnout.

4.4.19 Flame extension

The external flaming may be significantly increased when initially unprotected, exposed structural timber is present in the compartment. Currently, no flame extension model is available as the Eurocode approach is considered not to reflect properly the contribution by structural timber. Based on a method developed by ARUP for non-combustible compartments, it fails to describe the physics in this case. The flame extension prediction may be required by the authorities of fire services to check the feasibility of extinguishment measures. In particular, in some countries safety objectives (e.g. fire compartment plus 2 stories height) are considered acceptable. The current draft of Eurocode 5 (CEN 2021) gives a suggestion how the external flaming can be calculated as Eurocode 1 suggests an improper calculation (disregarding the amount of fuel).

Influence on the fire dynamics (++):

The flame extension is heavily influenced by the fire dynamics, especially when timber surfaces are exposed (for ventilation controlled fires). External flame extension is a potential risk for vertical, exterior fire spread to other parts of the building and furthermore, to adjacent buildings.

4.4.20 Gas characteristics

The distribution of the gas characteristics (concentration of oxygen, velocity and degree of turbulence at the specimen's surface) is of significant influence for compartment's behaviour in general and for combustible materials, see fire exposure.

4.4.21 Heat release rate (HRR)

The HRR describes the combustion of the available fuel. A total heat release appears in the context of a compartment fire and may occur inside the compartment or, additionally, exterior. Undertaking the experiments with structural timber it appeared challenging to measure the share of the external and internal heat release, which describe together the total heat release, compare Schmid et al. 2018 and Bartlett et al. 2020. Apparently, the MLR is not a proper measure for the HRR when several materials are involved in the fire (e.g. timber and the char layer material), compare 4.4.5. Thus, improved robust techniques are needed for further model development. HRR of structural timber is typically studied in cone-calorimeter tests at ambient conditions (normal temperature, oxygen rich environment) which is in contrast to typical compartment fire environments. Schmid et al. (2019) described the HRR of structural timber as a function of the charring rate and the combustion behaviour (understood as the share of the energy that is released vs. stored in the char layer); a corresponding equation is currently implemented in the draft for the revision of Eurocode:

$$HRR = 120 \cdot \beta_{st} \cdot \alpha_{st} \tag{5.4}$$

where

HRR	is the heat release rate, in kW;
β_{st}	Is the variable charring rate, in mm/min;
α_{st}	Is the factor to consider the (partly) released energy from the char layer and the (temporary) energy storage.

NOTE 1: the charring rate is typically considered as function of the thermal exposure but physically, furthermore, the consideration of the heat generation in the char layer should be done.

NOTE 2: the factor α_{st} was observed during compartment experiments by Hakkarainen 2000 (about 0.5), quantified by Brandon 2018 for compartment experiments (about 0.4 for the steady-state burning phase in ventilation controlled fires) and is further described by Schmid et al. 2021. The factor may exceed 1.0 when the char layer is combusted but the charring rate is low (e.g. in the decay phase when the char layer is activated by air movement).

4.4.22 Potential for manual extinguishment (definition)

By trend, firefighting of items or structural components can be done effectively in the decay phase. If the firefighting is successful, the combustion can be extinguished. For enabling fire extinguishment of structural timber by manual means (firefighting), the accessibility of the corresponding char layer (surface) should be analysed. Consequently, charring of components may be grouped in the following:

(i) Accessible charring: this comprises initially exposed (visible) combustible surfaces or initially protected surfaces after failure of the fire protection. Ideally, only one-dimensional charring appears. These areas can be directly reached by an extinguishment detergent.

(ii) Indirectly accessible surfaces: this comprises charring behind the fire protection systems, where during some phases of the fire charring may occurred (i.e. after the encapsulation ability has failed). These surfaces comprise initially protected members where single or multiple layers of fire protection have been applied on. These surfaces may smoulder and heat generation may further attack the fire protection system until its fall-off. Consequently, these surfaces may contribute to re-growth of fire when oxygen rich air reaches the smouldering char layer. Thus, these areas need to be checked during the extinguishment work and their extinguishment verified.

(iii) Indirectly accessible encapsulated surfaces: this comprises the charring behind the encapsulation, where for the duration of fire resistance verification no charring should occur. For significantly deviating fires or due to construction faults, charring may be expected at these surfaces. Consequently, various fire developments should be checked to increase the likelihood of successful encapsulation.

(iv) Not accessible surfaces (e.g. appearing in connection with steel works): This comprises surfaces adjacent to voids (within components or in gaps) or in contact with the other components (e.g. steel works supports), where the charring has started during the fire. Undetected fire spread may occur, also detected fire spread that was impossible to extinguish was reported (Östman et al. 2014, Östman 2017, Just et al. 2017). As a rule of thumb, encapsulation conditions should be aimed for. Recently, steel-timber construction (timber slabs on steel frame) became a popular building technique, especially in UK. between different components (e.g. floors and walls) and materials (e.g. steel and timber) the exceedance of 250°C (start of pyrolysis) should be prevented by proper detailing (e.g. see Lignum 2019, CEN 2021) as the increase above the pyrolysis temperature may create a charring layer, which would be able to smoulder after the fire in the compartment has been extinguished.

4.4.23 Horizontal fire spread

Can be understood as (a) the spread of fire in the growth phase towards the involvement of the entire compartment (floor surface) or (b) the extension of the compartment fire to adjacent compartments. The latter, (b), may be addressed by proper design of compartmentation by fire resistance rated components or fireproof walls ("fire wall" with mechanical impact test according to DIN 4102-3) including an improved criterion M (mechanical resistance exceeding the standard classification according to EN 13501-2). The criterion M describes the resistance to a defined dynamic impact after fire resistance testing.

Influence on the fire dynamics (++):

See 4.4.10.

4.4.24 Robustness

Robustness is considered as a structural characteristic of a system to provide resistance against collapse or limited damage after failure of one element. In FSE, the robustness terminology should be translated to the building system in the fire situation, where failure of particular elements of the FSE elements should be evaluated to assess the robustness in fire. Limited information about relevant procedures are currently available compare Schmid et al.

2020b. In general, for timber buildings, the robustness may be considered as a redundant measures compensating the increased combustibility. This may be the surface treatment, sprinkler system, the redundancy of its elements (piping, pumps, water tanks), improvement of automatic fire detection (e.g. multi-channels), of suppression (zone division) or escape routes or other measures.

Influence on the fire dynamics (++/o):

The robustness and a corresponding analysis may be part of structural fire design of structural timber buildings.

4.4.25 Sprinkler system; installation and availability of sprinkler systems

Various sprinkler systems exist with respect to the water supply, in house tanks or (supported by) the public fresh water system, reaction time (dry or wet pipe), activation temperature, reliance (redundant water feeding, pumps and piping) and installation (detached or not). In design, the reduced likelihood for a flashover event is considered, in existing guidance, a reduction of the movable fire load fractile value is suggested. Currently, no proof is available that this factor should be applied also on the structural fire load.

Influence on the fire dynamics (++):

Active suppression systems have significant influence on the fire development, regardless the structural building material. In any case, the structural survival has to be verified for the failed sprinkler systems. Currently, the likelihood of failure of such systems is not clear; consequently, the corresponding reduction of the fuel load is not commonly accepted (e.g. in Eurocode).

4.4.26 Surface area (exposed-)

When structural timber is exposed in a compartment on its surface (initially unprotected surface or when the fire protection fails during the fire exposure i.e. partially protected), the member design is influenced by the fire dynamics of the compartment. However, when the standard fire is agreed upon, the fire dynamics in an enclosure is not considered further as the fire resistance classification does not take into account the amount of exposed surfaces in a compartment. Typically, for low fire resistance requirements (e.g. R30) other requirements, e.g. serviceability, may be decisive. For the prediction of the fire dynamics or the compartment temperature development, respectively, the surface area and its involvement in the fire is decisive. Some codes are currently under development limiting the amount of exposed timber. Some models consider a fuel excess ratio (GER, see Wade et al. 2018), typically a factor of GER=1.3 was found reasonable for typical experiments. Brandon (Brandon 2018) calibrated the factor to a comprehensive compartment series to of GER=1.7, indicating that only 30% of the created char layer would combust inside the compartment in the fully developed fire phase.

Influence on enclosure fire dynamics (++):

Regardless the fire resistance of the member, exposed surfaces get involved in the fire dynamics. While limited exposed surface areas (e.g. provided by linear elements such as beams or columns) are typically neglected, this approach is not correct for large amounts of exposed surfaces regardless if it is linear or plane members. The ratio of exposed timber surfaces as well as their orientation can strongly impact the fire dynamics in a compartment. These parameters need to be considered together with the external fuel load and the ventilation scenario that are applicable. Re-radiation between exposed surfaces also needs to be considered. In a recent research program conducted at RISE, it was demonstrated that the presence of exposed timber corners (between two walls) can prevent achieving a continuous decay phase. Plane members are currently often foreseen in design and may represent a significant (structural) fire load not explicitly included in the design, e.g. Eurocode 1 [CEN 2002]. A proposal for the modification of design equations has been provided [Schmid et al. 2019]. Elements, which may contribute significantly to the fire dynamics are not always just CLT that is exposed. It can be large areas of glulam, dowel laminated timber, nail laminated timber, LVL etc.

4.4.27 Ventilation openings

Ventilation openings have a considerable influence on the fire development regardless the combustibility of the structure. Consequently, this is also valid for structural timber compartments. Two compartments with the same distribution of exposed timber surfaces and the same external load can lead to substantially different results (i.e., occurrence of second flashover, failure of the structural member) when the ventilation openings are different (Su et al, 2018 ; Mindeguia et al, 2020). Current design rules use a heat release factor of the thermally modified structural timber (i.e. the char layer) implemented in the current draft of the fire part of Eurocode 5, α_{st} . It is believed that there is a systematic appearance of this relative share of the released heat in comparison to the pyrolysis front, e.g. Brandon 2018 observed a consistent share of about 0.3 for various openings and compartment geometries. Consequently, it is expected for typically available compartments (openings, areas, exposed surfaces) a pattern for the fire dynamics/the behaviour in the fire situation exists. Statistical analysis by Brandon 2021 (Annex) may help to limit the required analysis.

Influence on the fire dynamics (++):

A significant influence on the available design boundaries on the fire dynamics can be stated. It is expected that a set of input values can be derived for the compartment combustion behaviour α_{st} depending on the ventilation openings and the share of exposed timber surfaces.

4.4.28 Thermal exposure

Considered as the thermal boundary but an effect of radiation and convection by superimposing both impacts on the surface of a solid in a compartment fire. Surface flaming (if available) may add to the thermal exposure of the component. Thus, besides the radiation, the gas temperature has to be considered to describe the thermal exposure. The combination should be done utilizing the mixed (or natural) thermal boundary condition. The convection coefficient is depending on the gas characteristics and the orientation of the surfaces under consideration. See e.g. Wickström 2016, Schmid et al. 2018.

Influence on the fire dynamics (+):

The coefficient of heat exchange (convection especially) will have a significant influence on the heat diffusion to the virgin wood.

4.4.29 Travelling fires

Travelling fires (TF) are the appearance of fires in typically large compartments (and floor areas) where a non-uniform development and temperatures will occur, see e.g. Hidaldgo et al. 2019, Rackauskaite et al 2020, Heidari et al 2020, Nadjai et al. 2020 . The travelling fires approaches are seen often as required verification for large space fire design in some countries, e.g. UK. For structural timber compartments, commonly accepted approaches are missing and first research results are currently discussed (Nothard et al. 2020). Limited travelling fire tests in large timber of compartments are available, see Richter et al. 2020. Travelling fire with higher spread rates are more likely to appear when the soffit is combustible. In the case of travelling fire and a timber ceiling, the flame extension under the ceiling is more likely, a model for the travelling fire with the flame extension under the ceiling is recently develop by Heidari et al. 2020. Based on accidents and experiments, currently, the appearance of travelling fires in compartments with significant shares of exposed timber surfaces is questionable.

Influence on the fire dynamics (++/o):

Travelling fires are fuel-controlled fires, which have significant access to oxygen. Consequently, the appearance of travelling fire may consume a significantly increased share of the timber structure and the char layer material correspondingly.

4.4.30 Vertical fire spread

The vertical fire spread through the construction may be as the horizontal fire spread, while vertical fire spread at surfaces may be more severe in vertical than in horizontal direction.

4.4.31 Water Damage

Very little information is currently available on the re-use and renovation work needed after a fire. In an indicative study (compartment size < 2 m^2), Matzinger et al. (2020) found techniques to measure the smoke damage and proposed renovation measures. A Swedish study showed that the re-use of compartment volumes (modular structure) was possible (report not publicly available). Data requested by industry and designers includes information about the water damage by sprinkler, accidental activation, associated damage by sprinkler and manual suppression systems, and increased damage risk assessment for dry vs. wet pipe installation, local and global damage.

4.4.32 Wind

The effects of wind on the fire ventilation of tall buildings has been researched for non-combustible structures. Chow 2017. Some information about the effect on compartment tests is available (Brandon and Andersson 2018). As the decomposition of the char layer material seems to be depending on the gas flow characteristics at its surface, wind effects may counteract burnout. Eventually applied procedures by the fire services using fans may be evaluated for the applicability in structural timber compartments.

Influence on the fire dynamics (+):

The effect of superimposed gas flow has not been estimated yet.

5 Available fire design tools for structural timber

5.1 General

Currently, the widely available standard design codes and guides for structural fire design of timber structures are based mainly on charring rates under a standard fire exposure i.e. the normalized EN/ISO standard-time temperature curve, e.g. according to CEN 2012, ISO 1999 or ASTM. The availability of design tools for non-standard fire exposures is limited.

The aim of this section is the identification and evaluation of current approaches and tools available for mass timber design in fire. The purpose of the design tools is to predict the thermal impact on structural elements in enclosures, the thermal and mechanical response of mass timber elements and facilitate design recommendations based on application of these approaches. In this report, only those methods that have been significantly studied in literature and that are well documented and applied in industry and standards and experimental case studies are discussed. The documentation aims of developing an understanding of current techniques available for facilitating fire-safe design of mass timber construction. Potential shortcomings and developments for future approaches will be addressed in later parts of this document.

5.2 Available approaches and tools

In the following subsections, various approaches and tools are listed in approximate order of complexity of the calculations and the motivation for their inclusion is given together with references. Approaches can be distinguished for the estimation between approaches to estimate the compartment temperature, the charring behaviour of timber members in the compartment and the reaction of the member with respect to its load-bearing resistance.

Currently, to estimate accurately a compartment fire in which timber is exposed, a simulation model usually bases on an iterative approach requiring to simulate multiple compartment fires over their full duration; alternatively, an explicit FE-analysis with small time steps allows to omit iteration by including the heat release of the timber (i.e. its “reaction”) of the last time increment (i.e. its heat release) in the subsequent increment (i.e. as “additional fire load“). The reason for this is the fact that the total and in particular the structural HRR is influenced by the area of exposed timber and the mass of fuel consumed (kg of timber). Typically, calculations start with an assumed fuel on the floor, i.e. the movable fuel, but the compartment HRR is then influenced by the timber, as it is consumed. The fuel available is linked to the duration of the fire and the duration of the fire is linked to how much timber fuel is consumed. Consequently, a significant feedback loop needs to be addressed. This procedure can be challenging when modelling compartment fires with exposed timber and is a typical error in provided fire designs.

5.3 Main structural design approaches

As shown in Figure 5, three major steps of verification can be observed and described with sub-elements in current approaches to predict the structural response of (mass) timber:

(i) a design fire (prediction of the time-temperature curve),

(ii) charring rates (prediction of the charring depth, i.e. the residual cross-section),

(iii) and structural calculations (prediction of the mechanical response of a section).

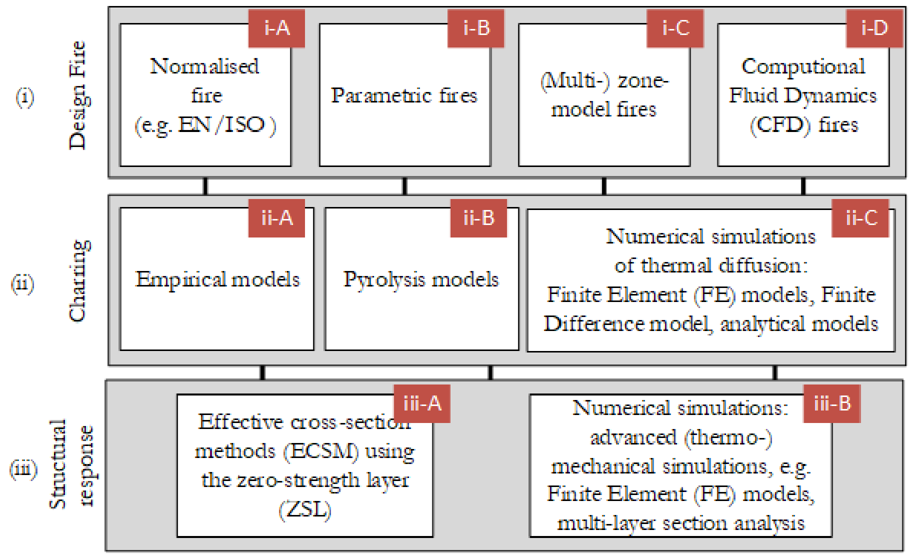


Figure 7: Methods and approaches for mass timber design, and how they can be coupled to predict structural behavior. The elements are described below.

Normalized fires are considered as a comparative measure. However, furnace tests fail in general to simulate fuel-controlled fires and the decay phase. Physically-based fires define/calculate/simulate the compartment temperature as a function of the movable *and* the structural fuel load (in case of exposed timber surfaces). It should be noted that the approach of parametric fires introduced in the first generation of Eurocodes, i.e. EN 1991-1-2 (CEN 2002) and EN 1995-1-2 (CEN 2004), does not consider any structural fire load. Only a modification as proposed by Brandon (2018) would allow for the consideration of the fuel provided by linear and/or mass timber members. For compartments with structural timber, these fire predictions rely on the prediction of the timber charring rates and, consequently, the residual cross-section. The latter, i.e. charring rates, charring depths and the residual cross section, may be predicted using empirical models, pyrolysis models or within FE models.

Zone models and CFD models give physically based fire curves, as some simplified models, e.g. the parametric fire models. The latter, "parametric fires" may be sub-divided further to "modified parametric fires" and "iterative parametric fires".

FE modelling is not a direct method to determine the charring and/or structural response. FE is a numerical tool, but not a physical description of a given phenomenon or behaviour, but a powerful solver. FEM may be used for charring determination by means of thermal simulations, deriving the position of the 300°C (or any other temperature) isotherm. This kind of simulation is also possible by other means than FE: finite difference method, analytical models, use of experimental measurements of temperature. However, FE model can also be used to simulate pyrolysis (see comprehensive literature, e.g. Mindeguia et al. 2018).

The above-mentioned statement with respect to FEM and thermal modelling is also valid for the simulation of the structural response: beside the ECSM method, every calculation tool could be used, i.e. not only an FE model. For instance, an analytical composite multi-layer mechanical model can be used for CLT (e.g. Mindeguia et al. 2020).It should be highlighted that the visualization shown in Figure 7 implies some limitations, e.g. when using temperature-dependent properties in FEM, no explicit charring definition (temperature) is necessary. Correspondingly, pyrolysis models use implemented material models to predict the reaction rate(s) within the solid. For FEM, char properties must be included in the thermal calculation. In a subsequent step, the residual cross-section can be analysed with respect to the load-bearing capacity. Here, the temperature profile within the section is determined and eventually referred to as an effective cross-section (ECS) assuming timber material properties as at ambient temperatures.

FEM often implement so-called effective material properties (see e.g. Schmid et al. 2012), which account for effects that are not explicitly modelled in the FEM. An example is the movement of the moisture inside the timber structure during a fire, which affects the thermal and mechanical behaviour, e.g. Dinwoodie 1975. More recently, a prediction of the moisture transfer has been presented in complex FEM (Pecenko et al. 2021).

One of the challenges when modelling fire dynamics in a timber structure is to account for the coupled nature of the relevant phenomenon. Notably, the compartment dynamics and the compartment fire time-temperature development can become highly dependent on the timber response to thermal fluxes when exposed. Further, it should be noted that timber structures can still produce combustible volatiles after the extinction of the primary fuel source (movable fuel load). Therefore, it might be of crucial importance for some buildings (e.g. depending on the complexity or the consequence class) to be able to predict the fire dynamics of the timber. This point requires a coupling between the fire curve and the material's reaction to fire. This can be done by a direct (two-way) coupling of the timber pyrolysis (comprising the charring behaviour) and the reaction of the compartment temperature or by an iterative approach.

In general, depending on the methods indicated in Figure 7, the fire load and the thermo-mechanical response of the timber is addressed, neglected or implicitly considered. Furthermore, some methods can predict the contribution of the fire dynamics directly or by using an iterative approach. For the prediction of the fire dynamics in compartment fires with structural timber, it may be needed to consider smouldering and glowing combustion. The latter seems to be of great importance when the decay phase is investigated. The decay phase and its duration may have a severe impact on the ability for burnout and the structural design of certain types of buildings (e.g. high-rise structures). The smouldering and glowing combustion may be critical for the operation of fire brigade, the recovery and repair of timber structures and the impact on property protection and business continuity. Consequently, when assessing the methods listed in the following, according to the above-mentioned grouping in Figure 7, this aspect is addressed for all tools. Thereby, different elements under the same group are referred to with capital letters A to D; eventually available sub-elements are further indicated with numbers 1 to 5.

i-A1: Normative fires: EN/ISO standard fire

A standard fire has been defined by a default time-temperature curve in the beginning of the 20th century. This time-temperature curve is today implemented in various standards, e.g. ISO 834 (ISO 1999) or EN 1363-1 (CEN 2012). The thermal loading in the standard is described as a standard time dependent temperature curve for cellulosic compartment fires (compartments with cellulosic fuel sources such as wood cribs). In addition, a slight overpressure (20 Pa; at the exposed surface for floor specimens) is defined. This is a standard fire curve that is simple to use and integrate into other methods and is widely used in many countries for both research and industrial applications. Consequently, a large number of test results is available for this type of exposure. Among others, the charring rates of spruce are well established for standard fire exposure. The EN/ISO fire may be compared to a ventilation controlled post-flashover fire (Schmid et al. 2018). For fire resistance testing of solid timber panels, the fuel provided by the furnace burners amounts to 50% compared to testing concrete panels. Partly, the burner fuel is topped up by the tested specimen (between about 45 kW/m2 and 90 kW/m2 depending on the fire exposure in the furnace), At the same time, less energy is needed due to the reduced thermal inertia of timber compared to concrete.

However, the methodology of a prescribed fire does not consider the design of the compartment, the timber members, and others. Furthermore, the decay phase of compartment fires is not included. Damage of the timber structure (e.g. by smouldering combustion) can occur in the magnitude of hours after the end of the fire, as seen in the experiments of Wiesner et al. 2020, where one CLT ceiling panel failed 29 hours after the onset of heating, which can be attributed to timbers low diffusivity and large temperature sensitivity.

To predict the structural thermal response of mass timber based on a design fire curve, the predicted time-temperature relationship has to be integrated in a temperature-dependant model as a further step. Prescribed linearly increasing charring rates are commonly used for this purpose, often corresponding to the standard fire exposure and being based on fitted test data, see (ii).

i-A2: Normative fires: other fires

Beside the EN/ISO standard fire corresponding to a cellulosic fire exposure, other fires exist which undercut or exceed the EN/ISO fire, see (example for tunnel fires).

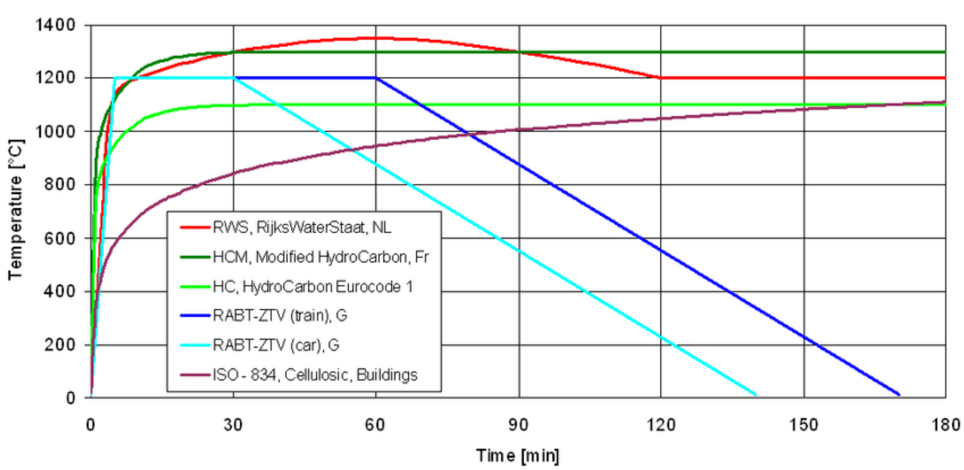


Figure 8: Various normative fire curves (from Promat.com).

i-B1: Parametric fire model

The concept of the parametric fires presented in Eurocode (CEN 2002) is based on the modification of the standard fire exposure. Depending on the fuel (mainly responsible for the duration), and the openings and the compartment thermal inertia (mainly responsible for the peak temperature), the run of the EN/ISO time-temperature curve is distorted, compare Wickström (2016). The validity of the modification is based on the observations of the typical shape of the temperature developments. This assumption was made from measurements of non-combustible structures where similar shapes were observed and the duration of the fully developed fire was about 20 min (later implemented in Eurocode (CEN 2002) in various models). As stated previously, in its original form, no structural fuel load is considered. Schmid et al. (2019) have provided modifications of the fuel load calculation to account for structural fuel provided by exposed timber. Typically, the maximum fuel load density (floor related) is exceeded for structural timber compartments. Modification of the calculation process to account for the combustible surfaces by structural timber surfaces has been proposed by Brandon (2018) and Barber et al. (2020).

i-B2: Natural fire model

The concept of the parametric fires is presented in the German national Annex of Eurocode CEN (2010). Based on zone-model simulations, empirical relationships were developed as found for the parametric fire model, i.e. modification of the duration and peak temperature. Recently, the model was tested for combustible ceilings (McNamee et al. 2020).

i-B3: Travelling fires

There are also a range of design travelling fires, e.g. by TFM/ITFM/FTFM (Heidari et al. 2020). Typically, the flame front and the end of the flaming zone are modelled and compared.

i-C: Zone-models

Zone models divide one or more compartments into homogeneous zones with energy conservation and transfer equations between them. Zone models can determine the thermal response of mass timber compartments, considering the contribution of exposed mass timber. Zone models considering explicitly the contribution of structural timber surfaces range from single-zone (SP-TimFire, see Brandon 2016) to multi-zone (B-RISK, Wade et al. 2018). Compared to CFD models, zone model simulations can be comparatively quicker and simpler, providing ease of use and design. However, complex designs and geometries (e.g. non-rectangular compartments) are challenging to model using this approach and may require additional considerations and sub-models of complex phenomena such as debonding of timber layers (failure of the bond line integrity) and erosion of the char layer (Wade et al, 2018). It should be highlighted that the combustion characteristics of failed layers implemented in B-Risk, however, are not yet researched. The coupling between the fire development and the contribution of structural timber in these models assumes a uniformly distributed timber contribution inside the compartment volume. Due to this simplification, it is challenging to predict the fire load with more complex timber surfaces or to predict transient phases such as extinction. Schmid et al. (2021) proposed a method as add-on to typically used zone-models, eg. CFAST or OZone (Cadorin et al. 2001), which can be used to further develop the exterior combustion (similar to the fuel excess factor GER or alpha_2 proposed by Brandon 2018).

Method applicability for other materials:

Zone models are routinely used in the design practice for non-combustible structures (e.g. concrete, masonry or steel), where the fire dynamics can be decoupled from the impact on the structure. In general, the presence of the structural material has only limited impact on the fire dynamics due to its impact on the relevant thermal properties of the linings in contact with the fire environment (thermal absorption). Although some of zone models have been applied for pre-flashover fire prediction, e.g. OZone (Cadorin et al. 2001), they are more applicable to post-flashover fire models. The models are typically sensitivity to assumptions regarding time to glass breakage, potentially resulting in under-estimating ventilation conditions decisive for the prediction.

i-D: Computational fluid dynamics models (CFD)

Tailored CFD fire modelling tools such as FDS (Fire Dynamics Simulator, McGrattan et al. 2013) or FireFoam (Greenshields 2018) could be used in general to predict the gas phase behaviour close to mass timber elements. CFD can be coupled to pyrolysis models (packages such as FDS have integrated 1D and 3D solid heat transfer and pyrolysis models) to determine the timber charring response. However, the very popular simulator FDS (NIST), is not able to properly consider the pyrolysis of structural timber correctly. Furthermore, the structural response cannot be predicted correctly. CFD models are typically used to simulate pool fires and pre-flashover fires while they are less reliable for post-flashover fires. Consequently, they cannot be used to predict the fire developments in timber compartments. Also for non-combustible (NC) compartments, an extraordinary high scatter has been observed indicating the sensitivity of the models to minor input variations (compare Rein et al. 2009).

Method applicability for other materials:

Like zone models, CFD is routinely used in the design practice for non-combustible structures and the structure mainly has an impact on thermal linings' properties. For the estimation of means of escape or smoke control and outside structural fire design, CFD models are routinely used. However, typically post-flashover fire scenarios are not generally modelled in CFD models due to multiple reasons (validation, time consuming simulation).

ii-A1: Empirical models for charring under EN/ISO fire

With the revision of Eurocode 5 (CEN 2021), the standard proposes tabulated design charring rates for different timber species. Using the European Charring Model, factors are used to consider further effects caused by e.g. gaps, grain direction or metal connectors increasing the charring rates. Using the effective cross-section method, the structural resistance of load-bearing elements can be predicted (e.g. the structural loading of timber beams and pillars are given as numerous worked examples by Porteous and Kermani (2013)). For separating walls, the separating function method is given to design for compartmentation under standard fire exposure. The separating function method assumes a summative function (each protective layer exhibits an individual protective time and the last layer exhibits an insulation time).

ii-A2: Empirical models for charring under general design fires

The cumulative charring model has been implemented for the description of the charring depth development. The model was developed by Werther (2016) and is based on a large study of spruce timber components exposed to parametric design fires.

ii-A3: Empirical models for charring under parametric fires

The approach implemented in the future revised Eurocode 5 is in context with the method for the development of parametric fires in Eurocode 1, Annex A. Consequently, both the time-temperature and a residual cross-section will be determined. It should be highlighted that parametric fires can only be used if the influence of the mass of the fuel of the exposed timber is accounted for (Brandon 2018, Barber 2016, Barber et al 2020). The fire load contribution coming from the timber will change throughout the fire, meaning that a constant fuel load may not be representative of the temperature-time behaviour of an actual timber compartment fire. To address this, further work by Barber (2016) outlined the development and necessity of an iterative parametric fire curve, by updating this fuel load at each time step of the parametric fire curve calculation as the available fuel load changes.

In general, the parametric fire design method in the fire part of Eurocode 1 considers dimensions of the compartment and openings (expressed via the opening factor, as shown in Figure 9) and thermal inertia of compartment enclosure. However, for timber compartments they are not automatically suitable as the structural fire load is not automatically considered.

This approach uses charring rates observed in standard fires, which are modified for the particular parametric fire. In reality, charring rates of timber can vary both depending on the stage and intensity of the fire and the position and orientation of the mass timber element in the compartment. However, the method is poor at predicting decay and underestimates the charring in the decay phase. Therefore, parametric fire curves may not be accurate for predicting exposed timber compartment temperatures; consequently, conservativeness needs to be addressed accordingly. Furthermore, both parametric fire model (EC1) and especially charring model for parametric fire (EC5) have applicability limitations. For instance, the charring model given by EC5 for parametric fire curve has been shown inapplicable to predict charring in the case of a ventilation-controlled experiment (because the parameter $t_0 > 40$ min) compare Mindeguia et al. (2020).

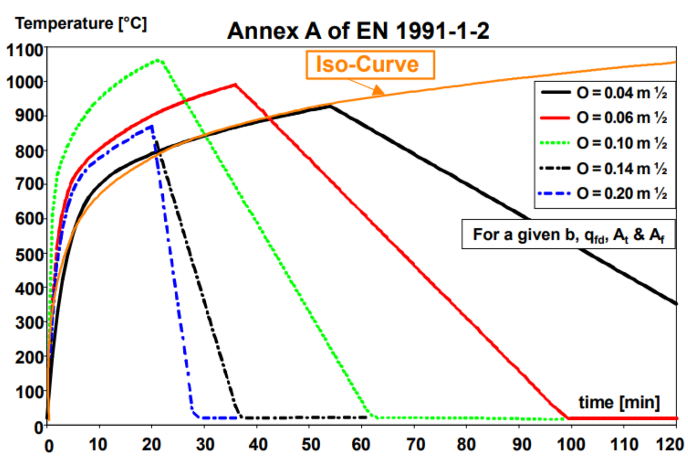


Figure 9: Examples of Eurocode parametric fires for a range of opening factors from Vassart, 2012. This shows that higher opening factors result in quicker calculated temperature-time curves, both in the growth and decay phases.

ii-B: Pyrolysis models

Pyrolysis models can be used to model the charring behaviour and thermal response of timber across a range of scales. These models range in complexity, from single step reaction mechanisms, to multi-step mechanisms. Pyrolysis models commonly assume decoupling of the fire dynamics from the pyrolysis, so the timber response must be assumed e.g. as a parametric fire. However, pyrolysis models do not permit to predict the extinction of flaming-, smouldering- and glowing combustion or the fire intensity enhancement by timber flaming. The key elements that need to be considered are shown in Figure 10.

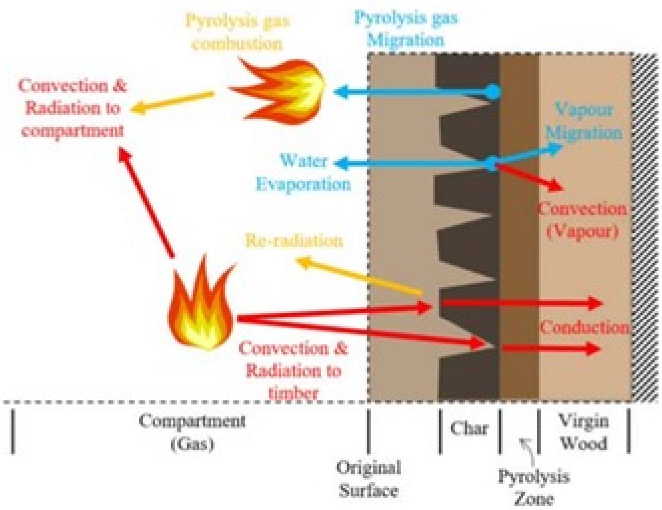


Figure 10: Key heat and mass transfer processes at the surface of a burning mass timber element (Quiquero, 2018). Implementing these processes into a pyrolysis model, parameters including the charring behaviour and contribution of timber to fire behaviour can be determined.

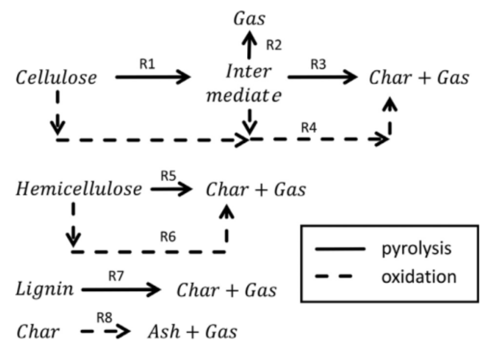


Figure 11: Reaction scheme of the chemical kinetic sub-model (Richter et al. 2020)

Typically, pyrolysis models fail to model all elements shown in Figure 10. A pyrolysis model is only able to simulate a thermally activated reaction. It does not allow for simulating water transport, re-radiation, convection, conduction, gas migration. Richter et al. (2020) described the scheme for the analysis with multiple sub-models, see Figure 11. Pyrolysis models usually rely on the Arrhenius law to represent the reactions approach, which requires a range of kinetic and material parameters to make predictions. Moreover, it is crucial to identify which reaction is the more relevant to calculate charring. Available, general tools to solve the described reactions are PATO (https://pato.ac/index.php/author/jean) or GPYRO (https://www.sciencedirect.com/science/article/abs/pii/S0379711209000332?via%3Dihub) for biomass pyrolysis simulation. Determining the material parameters must be done with care (see ongoing round-robin study about TGA sponsored by the International FORUM of fire research directors), as they can lead to very scattered values. These parameters are highly dependent on the timber species, treatment and even the growth region. For these reasons, an advanced pyrolysis model must be reserved for well-characterised timber structures (eventually considering the particular product) by an appropriate validation process. Smouldering in timber has a major impact on the structure post-fire and may be critical for the operation of the fire brigade, the recovery and repair of timber structures, and the impact on property protection and business. The RR (Reduced Reaction) model proposed by Richter et al. (2020b) incorporates optimised kinetic parameters and a multi-step reaction scheme to predict the behaviour of traditional and smouldering timber fires at meso-scale and timber slabs under a range of prescribed traditional and travelling fires (Richter et al. 2020a).

Simplified pyrolysis models have been coupled to CFD or zone models (see Girardin 2019 or Lardet 2018) to model the gas and solid phase interaction during pyrolysis. These models assume that pyrolysis is governed by surface thermal phenomena, by a pyrolysis activation criteria (temperature or heat flux), and a mass loss rate. These models permit to include easily the timber contribution to fire development in a zone or CFD model but cannot be used to predict charring rates. Structural and mechanical behaviour (e.g. char fall-off) are often not considered in pyrolysis models.

ii-C: Numerical simulations

Typically, FEM models use effective material properties calibrated to a certain heating regime, e.g. the EN/ISO fire. Traditionally, FEM model fail to describe the contribution to the fire dynamics when a combustible solid is heated.

iii-A1: Effective cross-section method for EN/ISO fire:

The effective cross-section method was developed from a simplified approach for simply supported glulam beams that were fire exposed for 30 min, see Schaffer (1984). Schaffer estimated the effective cross-section of a charred timber element, allowing for estimation of structural weakening of timber due to high temperatures. This is achieved by assuming that the char region of a structural mass timber element in a fire provides no load-bearing capacity, reducing the load-bearing cross-sectional area of the element to only the uncharred timber minus a zero-strength layer. By doing this, an effective cross-section can be determined by coupling to charring models (e.g. prescribed charring rates, pyrolysis models, or FEM), to determine the point in time at which the timber element will fail for a given load. This is a simple method that allows for versatile coupling between fire curves and structural response to predict how design fires will influence the structural timber elements over time. In general, the ZSL depends on the kind of design fire, the mechanical state and the type of product (CLT, TFA, glulam…).

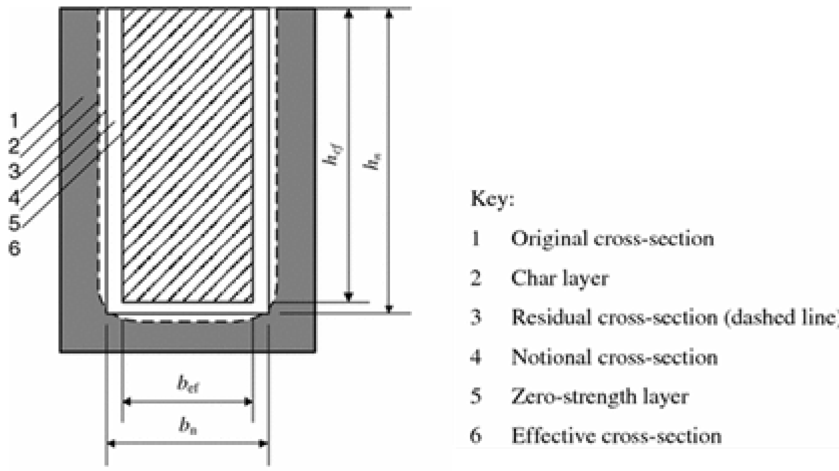


Figure 12: Depiction of a charring timber beam with defined cross-sections from Schmid et al, 2015. This assumption defines how much of a charring timber element cross-section can be considered as providing strength to support structural loading.

iii-A2: Effective cross-section method for general design fires

In the current draft of the revision of Eurocode 5, a method is proposed to modify the zero-strength layer provided for standard fire for the application with heating and cooling rates from general fires. The method is based on the observation that the zero-strength layer is about of the thickness between the position of the 300°C and 90°C isotherm.

iii-A3: Effective cross-section method for selected parametric fires

Lange et al. (2015) developed this further by prescribing two zero-strength-layer thicknesses (15 mm for longer low-temperature fires, 8 mm for short higher-temperature fires), based on a series of timber tests, allowing structural loading calculations to estimate the loading capacity of a given timber structural element. The reduced cross-section method, as highlighted by Brandon et al. (2018b), assumes a homogeneous mechanical behaviour of the timber element over the whole cross section, meaning that this method is not appropriate for members with inhomogeneous layups, e.g. unsymmetrical glulam or CLT elements. Furthermore, uniform charring behaviour is assumed (i.e. the thickness of the char layer will be uniform across the timber element at any given time), which may not apply in non-standard fires such as travelling fires. The reduced cross section method assumes a mechanical behaviour as at ambient temperature beyond a certain depth inside the section. For a long fire duration, the timber's low thermal diffusivity can lead to temperatures above ambient deep inside the structure long after the end of the fire. It might reach an extent where any point in the cross section is significantly heated (>50°C). However, the material reduction curves developed for standard fire exposure are considered not applicable at this stage of cooling.

iii-A5: New effective cross-section method for parametric fires

This method further develops the effective cross-section method, removing the assumption of constant zero strength-layer and charring rates. The charring rate is estimated as a function of the compartment's opening factor and thermal inertia and will linearly decrease to zero during the decay phase. Furthermore, this method modifies the mechanical properties with temperature-dependent reduction factors. The method does not require homogeneous mechanical properties over the cross section, meaning that this approach is applicable for predicting the structural response of CLT elements as well. This approach can be coupled to fire curves to determine the structural response of mass timber in a standard fire, while still offering a level of complexity that allows its implementation in widely available tools such as Microsoft Excel (Brandon et al, 2018b). However, the presented models implies limitations with respect to the type of fire, ventilation conditions and the compartment size.

One of the key assumptions of this approach, similar to the reduced cross-section method, is that the cross-section is uniform (homogeneous) across a particular element; in non-standard fire exposures (parametric fires are specified in application of the approach by Brandon et al, 2018b), a mass timber element may not char at a uniform rate across its surface, meaning that the reduced cross-section is not uniform.

iii-B: FE modelling

FEM including packages such as ANSYS (2006), and LS dyna (Hallquist, 2007), opensees (https://link.springer.com/article/10.1007/s10694-020-01071-0) and Cast3m (https://www.sciencedirect.com/science/article/abs/pii/S0950061817323085). They are tools that provides high flexibility for structural design in general and for timber construction. FEM packages can be used to calculate the heat transfer processes in the timber, and the structural response of loaded timber elements. To achieve this, FEM require further information regarding the fire behaviour (specifically a prescribed local compartment temperature at each time step, the local convection coefficient, and the potentially temperature-dependent thermal and mechanical material properties), which can be sourced from the previously discussed thermal models, depending on the level of complexity required. More advanced models for timber construction have included prediction of crack formation due to material shrinkage (Winter and Meyn, 2009). FEM can also be used to model stress concentrations at connections (Palma and Frangi, 2016). A challenge of connection models is the consideration of the increased heating of sections when metal connectors are installed.

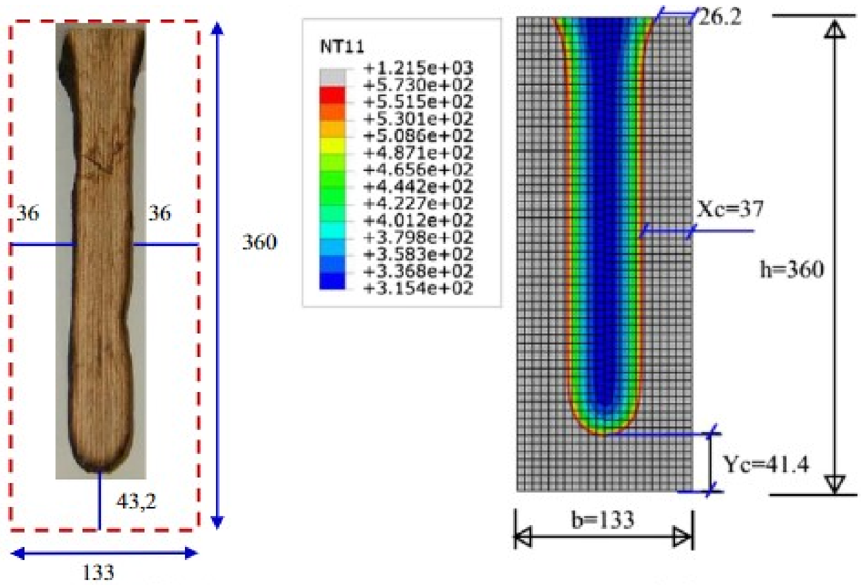


Figure 13: Example of how FEM can be used to predict the heat transfer and charring behaviour of a mass timber element, compared to experiment samples (Thi et al, 2017). A FEM model is shown to successfully predict a charred timber element cross-section. NOTE: Here, the 300°C-isoterm was used to predict the location of the char line which may be a limitation.

In fire design, FEM mainly focuses on the response of the solid to a temperature and does not directly incorporate the gaseous environment surrounding the solid. For timber members, the kinetic response of timber via charring and drying processes is not covered directly but considered indirectly by effective material properties. Currently, the availability of fully coupled thermo-mechanical models is limited (Cueff et al. 2018).

Method applicability for other materials:

FEM software packages typically have implemented material properties for the case of fire for steel and concrete. These material characteristics cover the thermal properties and the mechanical properties.

Concrete: The mechanical response of concrete in fire using FEM is common in research literature but less so in design practice. As solid elements typically need to be used and thermal expansion to adjacent members is not critical for concrete structures, common applications consider single elements rather than completely the entire frame behaviour, e.g. the punching shear of pre-tensioned slabs or buckling of columns. Spalling appears to be the most challenging property to be captured in numerical models. Spalling phenomena are particularly relevant for self-compacting concrete and high strength concrete.

Masonry: FEM is not typically employed for masonry structures under fire conditions in design practice. This is predominantly due to the complexity of the interaction of different materials and the difficult repreduction of the brittle failure in finite element analysis.

Steel: Steel is probably the widest implemented material with respect to FEM for the fire situation. Typical applications are whole frame behaviour analysis to capture load redistribution, modelling of composite slabs to capture tensile membrane action, local buckling of cellular beams, portal frames and 3D modelling of connections (https://www.emerald.com/insight/content/doi/10.1108/JSFE-09-2016-015/full/html). The mechanical material properties (yield strength and stiffness) are often considered reversible in the cooling phase which may not be the case dependent on the production process (e.g. hot vs. cold rolled products) . The complexity of the modelling can range from relatively simple (single beam/column under load) to highly complex (connection modelling).

5.4 Alternative and auxiliary design approaches

The following section lists some tools applied in structural timber designs, which have been used to proof a proposed design; these can be experimental tools or calculation tools. While some tools comprise justifiable elements, the process or the validity should be considered with caution. The limitations and critics are given in the particular section.

5.4.1 Ad-hoc testing on fire resistance furnaces

Recently, for particular larger timber based projects, ad-hoc testing based on fire resistance testing has been observed. An example is the proof of burnout by testing for self-extinguishing of a member after a fire resistance test. The procedure is most likely inspired by the Japanese testing philosophy where a building component is left on the furnace for a certain time. There, after the fire resistance tests, structural elements are left for between three and nine hours on the furnace to allow for an estimation of the component's behaviour directly after the fire during the cooling phase (Kinjo et al 2016). However, it was shown that the behaviour of timber members is significantly depending on the ventilation conditions in the furnace, i.e. the gas environment (oxygen concentration and gas movement).

5.4.2 Ad-hoc testing of compartments

Another tailor made testing ,philosophy that could be observed recently, is the testing of representative compartments of the particular building design prior to production.

5.4.3 Time-equivalence and fire severity

The concept aims for a description of the steel heating in the design fire for a particular project in terms of the standard fire heating to allow for classification and the use of standard fire test results. For steel, the procedure is reasonable due to the high conductivity that, which results in roughly uniform temperatures within a steel section. Consequently, the concept has limited validity for concrete elements. The use of the time-equivalence concept is prohibited by Eurocode 5 for timber structures. Reasons are the different heating (charring depth and heated depth beyond the char line) in design fires and standard fires, which results in a complex comparison of the consequences. Furthermore, the cooling phase does not go along with reversible material degradation. Considering equivalent fire severity for timber structures would require the characterisation of the charring response of a structural member as well as defining the thermal response of the timber slab behind the char zone understood as zero-strength layer (Richter et al., 2020). However, ideas for a time-equivalency concept for structural timber exist, e.g. Barber et al. 2020. As a basis, it is considered that a standard fire would result in a charring depth. Modelling of a natural fire and accounting for the total char depth allows a time-equivalence method to be used, provided the full depth of charring for the whole fire be used. It is not solved how the heating beyond the char line can be translated. A reliable concept would improve the combination of the test results typically obtained in fire resistance tests.

Method applicability for other materials

“The time-equivalence and fire severity” concept.

Concrete: Spalling is not covered and modifications made it possible for a general application.

Masonry: unknown

Steel: applicable. Simplifications with respect to parametric fire design exist and are implemented in the standards.

Timber: similar charring depth and/or thermal penetration and/or load bearing capacity.

Fire protection systems: available if tested acc. to EN 13381-x.

Services: In general, this is not available.

5.4.4 Application of standard charring rates in non-standard fire situation

Charring rates are available mainly for standard fire exposure for various products. A dependency of the moisture content and the density is documented in the literature but disregarded in the currently implemented rules. The heating regime has a significant influence on the charring behaviour, which is – in general – neither a constant value for one fire nor a constant value for all fires. The actually given constant factor to modify the constant charring rate in standard fire to allow the estimation of charring in a parametric fire is based on a very limited number of furnace tests with timber members in parametric fires, see Hadvig (1981).

For laminated products, the charring rate is additionally dependent on the bond line integrity in fire, sometimes referred to as debonding or fire induced delamination. This influence is observed in tests, documented in the literature and is covered by design models (step-model). The application of an averaged charring rate (e.g. 0.9 mm/min as an average of 0.65 mm/min for the first layer and 1.3 mm/min for proceeding layers up to 20 mm) is non-conservative in many cases.

5.4.5 Encapsulation design

Timber framed construction and detailing as well as the essential fire protection of steel elements (e.g. beams or columns) rely significantly on the fire protection by mineral- or gypsum based boards. No time equivalency model is available.

5.4.6 Fall-off from standard fire resistance testing

Fall-off times have been derived from standard fire resistance testing on walls and floor construction. In the first draft of the revised Eurocode 5 (EN 1995-1-2), the 5% fractile values were used. Currently, the use of 50% fractile values is discussed to reduce the implemented conservativeness. These values should then be used as generic product properties. However, it is expected that this will reduce the ambitions of gypsum plasterboard producers to test according to EN 13381-7, which should give more favourable results as they are product related. Currently, no method is available to derive fall-off times for fire protection systems in non-standard fires.

5.4.7 Design for self-extinguishment

See Section “Definitions” above. This term is used ambiguously by the stakeholders. It is considered as a unique characteristic for combustible building materials such as structural timber. Considering a timber specimen, it may be related to the end of the mass loss (correspondingly to the end of any oxidation within the specimen) or the flame extinction at its surface. The end is related not only to an external heat flux but also to the fire exposure comprising the thermal exposure (gas and radiation temperature) and the description of the gaseous environment at the element under consideration (oxygen concentration, gas flow velocity, degree of turbulence). However, some define the criteria just with respect to (1) the avoidance of bond line integrity failure and/or (2) reaching compartment temperatures below a certain threshold, e.g. 200°C. Then, the fire exposure conditions (gas- and radiation temperature and gas characteristics, i.e. oxygen concentration and movement) are typically disregarded.

5.4.8 Travelling fires (Large compartments)

Very limited knowledge currently exists on the fire dynamics of large compartments. This uncertainty is significantly compounded when introducing exposed timber that can introduce new fire phenomena (Rackauskaite et al., 2020). As a result, directly utilising fire models developed for small compartments (e.g. parametric fires) or design tools developed for non-combustible structures (travelling fire methodology) without further validation is not considered appropriate.

5.4.9 Multi-floor fire spread and compartmentation

In some countries, low-rise buildings do not normally require compartmentation floors as it is expected that occupants will evacuate rapidly and the fire brigade will fight the fire from externally. However, typical design practice for medium-rise and tall buildings relies on the concept of compartmentation to reduce the risk of extensive fire spread through a building. Some modern buildings use building designs with atria or open stairs/double height spaces introducing the risk of vertical fire spread to more than one storey at a time. Depending on the fire strategy of the building, passive or active measures may be provided to maintain compartmentation or an engineered solution may seek to justify an open connection (Kotsovinos et al., 2020). When considering engineered solutions for timber buildings where a potential for a multi-storey fire exists, designers need to show caution on the potential of extended durations of heating and charring of structural members.

5.4.10 Unrealistic fire resistance expectations

Where the impact of exposed timber on fire dynamics can be quantified and the resulting thermal and structural response of the timber structure calculated, the designer needs to ensure that their fire resistance specifications are practical, achievable, and consummate to other measures adopted in the fire safety design. For example, a residential building with a large exposed timber ceiling could perform adequately if the timber slab achieves an equivalent fire resistance of 180 min. However, such a fire severity would have a knock-on effect on multiple aspects of the building. For example, questions that the designer would need to consider are: Is a 180 min encapsulation product available for other areas of the ceiling that may need to be protected based on the calculation performed? Is fire stopping for timber structures available for this duration? Can separating elements between apartments achieve this level of fire resistance?

5.4.11 Application of reaction to fire test results for fire resistance

In practice but also in research studies, the charring rate estimation of treated and untreated wood specimens of various species is often based on experiments, where the fire exposure is applied by means of an external heat flux. Those experiments often comprise heat fluxes of up to 50 kW/m^2 only, often applied at ambient air conditions. However, compartment firesreach exposures exceeding 150 kW/m2 in low-oxygen conditions.

5.4.12 Combination of prescriptive and performance based code elements

The performance based design (PBD) concept allows for the design of structures where no prescriptive regulations are existing or applicable (see e.g. Hadjisophocleous 1998). Consequently, this concept is frequently used to replace prescriptive regulations. By doing so, concepts are mixed up which might be non-conservative. Recently, Lange et al. (2021) discussed the actual challenges of fire safety engineering.

6 Enquiry of professionals

6.1 General

This part of the final report was drafted by WP2 under the lead of TalTech and ETH Zürich (A. Just and M. Klippel) and has been revised by external experts. Special thanks goes to S. Schleiner who did his master thesis on this subject, the presented study is based on his studies. Acknowledgements go to N.Werther, D.Barber and J.Liblik for their contributions. The information presented in this part of the report was mainly gathered by means of an online survey. The author(s), the editor(s) and publisher disclaim any liability in connection with the use of this information. Neither the research partners nor the funding partners nor any person acting on its behalf is responsible for the use of the information contained in this publication. Special care should be made when conclusions are developed. No permission to reproduce or utilize the contents of this publication by any means is necessary, other than in case of images, diagrams or other material from the copyright holders. In such cases, permission of the copyright holder(s) is required. To reach the mentioned objectives, TimFix asks the underlying questions:

- What can we design and build safely based on our current knowledge?
- What has to be done to exceed the limitations?

A rough overview of the methodical approach of the pre project TimFix is depicted in Figure 14. The approach is sought to investigate the research hypotheses:

1) Engineers are required to provide evidence that fire safety goals are reached.
2) The methods to deliver the evidence are hardly defined when going beyond prescriptive tabled values.
3) Engineers often lack the tools or qualification to deliver the required evidence.

The hypotheses lead to several research questions that are presented in Figure 12.

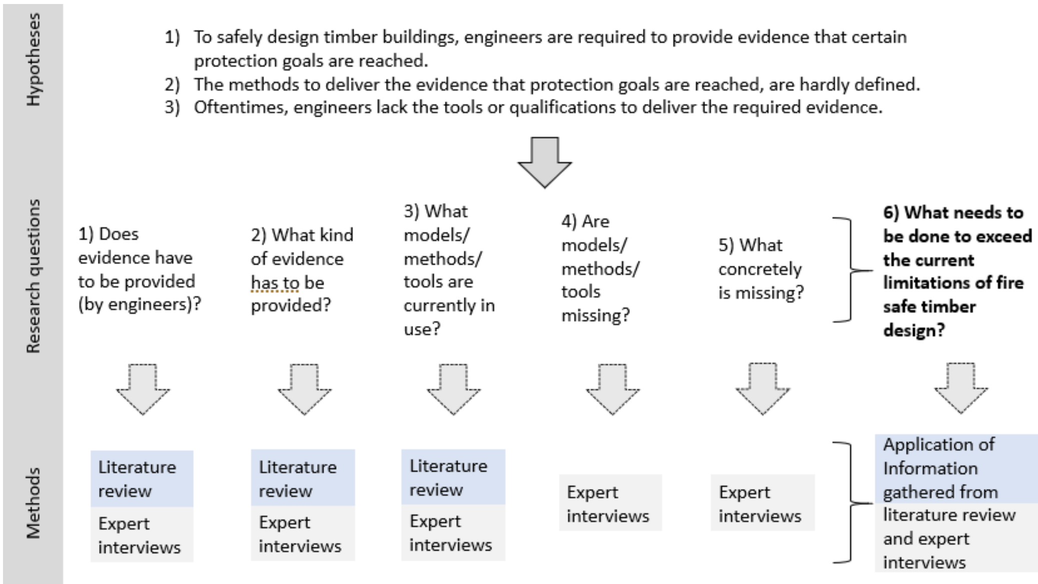


Figure 14: Depiction of the methodological approach deducted from the research hypotheses and questions. (Source: own illustration).

The single most important research question (which is split into sub-questions as seen in Figure 12) that TimFix seeks to answer is:

- What are fire protection engineers currently lacking that would enable them to safely design timber buildings/structures while also complying with building codes in an extent that is equal to constructional materials that are non-combustible (e.g. steel and concrete)?

The literature review creates the methodological basis for the expert interviews that are sought to identify:

- The models, methods and tools that are actually in use within the industry.
- If there are certain models, methods and tools that are missing from a fire protection engineering point of view.
- What concretely is missing in order to handle the challenges of daily work?

The combined findings of the literature review as well as the expert interviews are used to formulate recommendations for future steps in the building industry to favour the use of timber products (such as scientific based revisions of building regulations, design guides, better education, further research and increased testing activity).

6.2 Structure of the Section

The present report is structured as follows:

1. Description of and reasons for the methods used
2. Objective of the expert survey
3. Development and distribution of the expert survey
4. Results of the expert survey (organized in observations and conclusions)

5. Interpretation of the results including derived recommendations

The focus is on points 4 and 5, describing the results of the expert survey and the author's interpretations of said results.

6.3 Limitations of the study presented in this section

It is important to note that this report lists the gathered answers of the experts, even though some might not be in line with the relevant guidelines. Although the results were collected from numerous experts with different backgrounds from all over the world (for details see 8.9.2.1), the sample is not representative. When interpreting the results, the different backgrounds and work environments of the experts must be considered. The responses may include personal opinions and might thus deviate from the relevant codes and legal bases, which could be one explanation for the fact that there are sometimes discrepancies between the answers of experts from one country.

However, the collected responses do provide a good overview of the challenges and problems that professionals from the building industry face in the context of fire safety in timber buildings.

6.4 Method – expert survey

When gathering information from a group of experts by means of interviewing or surveying them, the interviewer usually assumes that the respective group can make assessments and give information that are generally not available in the public domain (Christopoulus, 2009). In contrast to "regular" surveys, expert surveys are often the method of choice when the desired answers cannot be given by public or through common knowledge. Oftentimes, expert surveys or interviews, as interpretative methodical tools are used when special knowledge is needed and reliable data is not available (Hay 2002).

6.5 Reason for expert survey

For TimFix it was necessary to identify existing knowledge gaps and other insights from the timber building industry. It was thus planned from the beginning of the project that interviews or a survey of experts had to be conducted. As opposed to an interview, a survey among the parties involved is more easily distributable and thus more likely to achieve a reasonable number of respondents. With its standardised questions and carefully pre-defined answer options, a survey provides results that are easier to be compared (contrasting interviews with guideline-questions that tend to be slightly adapted with respect to the interview situation and long, individual answers). Along with the Covid-pandemic limiting opportunities to conduct face-to-face interviews, the decision was taken to conduct expert surveys.

6.6 Objective of the expert survey

The general aim of the survey was to gain insight information regarding the following aspects:

- The perceived use and relevance of timber in the building industry
- The perceived difficulties of using timber as a building material
- The differences (in requirements) between timber and non-combustible structures when it comes to
- Fire regulation
- Fire safety concepts
- Methods, approaches and tools

With that in mind, it was necessary to consult a certain sample size so that a large enough number of experts with differing national backgrounds would answer the questionnaire. Relevant literature suggests that a broad range of surveyed people increases the objectivity of a survey (Silzle, A. 2007).

To obtain a broad range of experts, the partners involved in TimFix activated their personal networks of respective experts from different countries. Additionally, the survey was distributed via different social media channels (e.g. LinkedIn).

6.7 Development of the questionnaire

To match the objectives formulated above, the survey questions were developed in an iterative approach with multiple rounds of internal feedback from TimFix project partners.

The next step comprised revising and categorizing the questions. The challenges in the context of revising the questions included:

- Grasping the entire subject but not making the corresponding questions too complex as excessive complexity negatively affects the quality of the gathered data (King and Horrocks 2010),
- Not letting the already quite clear expectation of the survey results bias the questionnaire design (avoiding confirmation bias),
- Bearing in mind that the respondents would give their answers against very different backgrounds as the building code requirements differ depending on the respondent's country.

The revised questions were put in order and assigned to the following four main chapters:

(i) General information and use of timber
(ii) Fire protection and building legislation
(iii) Fire safety concepts and design
(iv) Methods in fire design.

In a last step, the questionnaire was finalized. One part of that was deciding to provide answer options for the respondents and thus use rather closed questions. In contrast to open questions, which minimize limitations for the respondent on the one hand but are complex to answer and complex to evaluate on the other hand, with closed questions the received answers are more easily comparable. It was therefore decided to provide response options, where possible. In order to give the surveyed experts the opportunity to detail their answers where necessary, a commentary field was added to the response options in almost all questions. The final questionnaire comprised 54 questions.

6.8 Distribution of the survey

It was estimated that answering all 54 questions would take about an hour of time. As this was considered inappropriately time-consuming, it was decided that two questionnaires would be distributed. The first was an extended version, containing all 54 questions, which due to their complexity could only be answered by experts with years of experience. To ensure that the respondents were indeed capable of answering the questions, the survey was distributed personally via the private networks of the TimFix project partners. As an incentive to complete the long survey conscientiously, survey participants was offered a financial compensation for their time.

For the second version, the content was revised again, shortened to include exclusively questions that were not too cumbersome to answer, and directly related to timber buildings. The resulting questionnaire now containing 24 questions was distributed via social media with a short complementary note calling for respondents among interested timber experts from the building industry.

6.9 Results – expert survey

The original survey including all questions asked as well as the gathered results are depicted in this section. The results collected are presented in the form of diagrams and supplemented with short descriptions. The descriptions are divided into observations and conclusions.

6.9.1 Participation

The survey (full as well as shortened) was online available via publicly accessible links to lamapoll for seven weeks. During this time, 78 answers have been received (38 people filled out all 54 questions).

6.9.2 Results and comments

In this section, all answers to all particular questions are presented together with explaining comments.

6.9.2.1 General questions about survey participant

Question 1: What is your current profession?

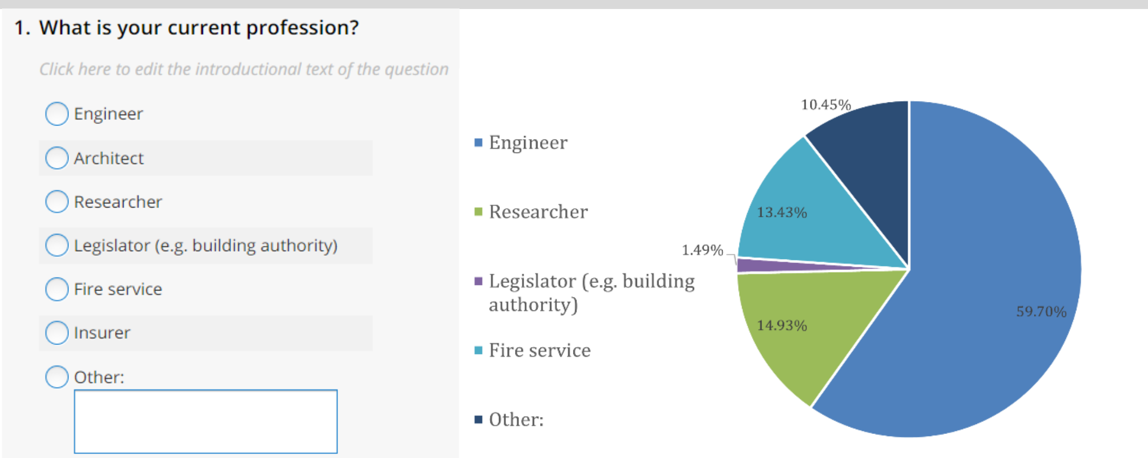


Figure 15: Profession of survey participants

- As shown in Figure 11, the vast majority of the surveyed experts are engineers. The second largest group are researchers, followed by fire services. One person participated as "legislator". Other professions mentioned include fire safety consultant, technical advisor, advisor, influencer, project developer and university professor.

It should be mentioned that insurers and architects are further key professions, which should be involved in the future, as they did not contribute to this study.

Question 2: What country do you currently work in?

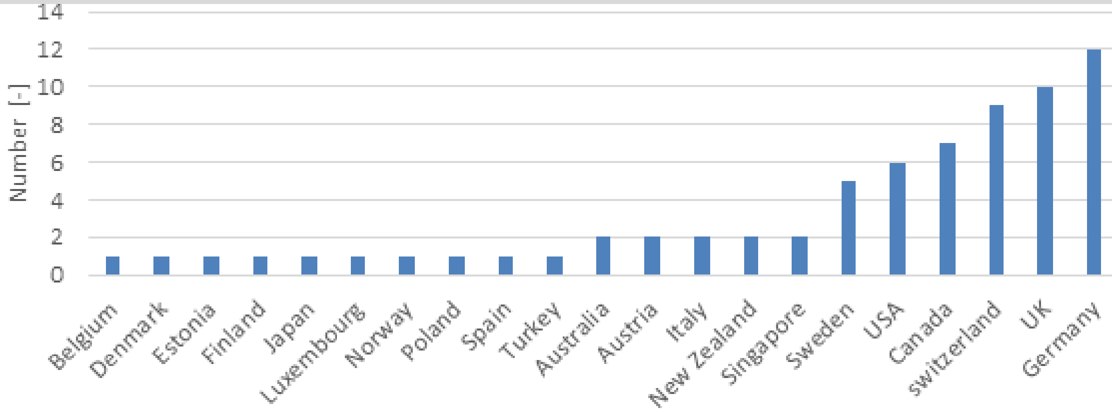


Figure 16: Current place of work

- In total, the survey was answered by people from 21 different countries. Most of the experts that participated in the TimFix survey come from Europe. The largest groups from Germany, UK and Switzerland. Outside of Europe, Canada and USA constitute the largest participant parties. In addition, experts from Australia, New Zealand, Singapore, and Japan gave answers to the questions.

The broad composition of the survey participants is very positive as this leads to a diverse group, whose answers are not only applicable to the situation in a certain country but may be applied to a global scale. It should be noted that mostly experts from Europe have answered together with two American and Canadian experts.

Question 3: How many years of experience have you had in the profession stated above?

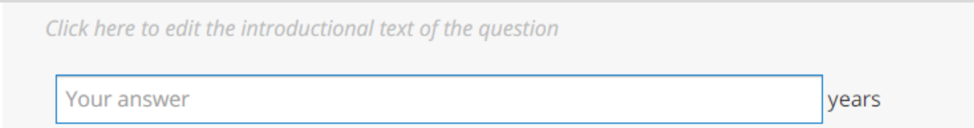
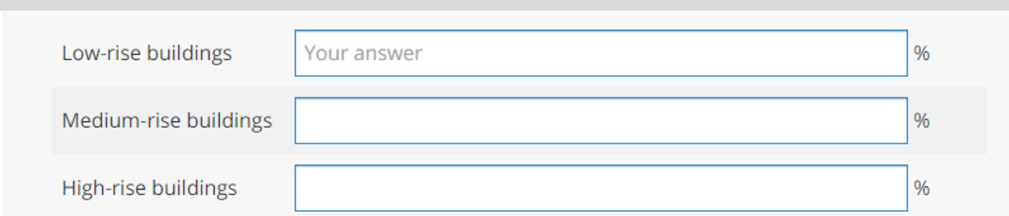


Figure 17: Experience of survey participants

On average, the participants of the survey have roughly 16 years of experience. Roughly, 85% of the survey respondents have more than 5 years of experience in their respective field of work. The term *expert survey* is thus justified.

6.9.2.2 General questions regarding use of timber in construction

Question 4: Please estimate the percentage of new construction from timber for the following different types of buildings



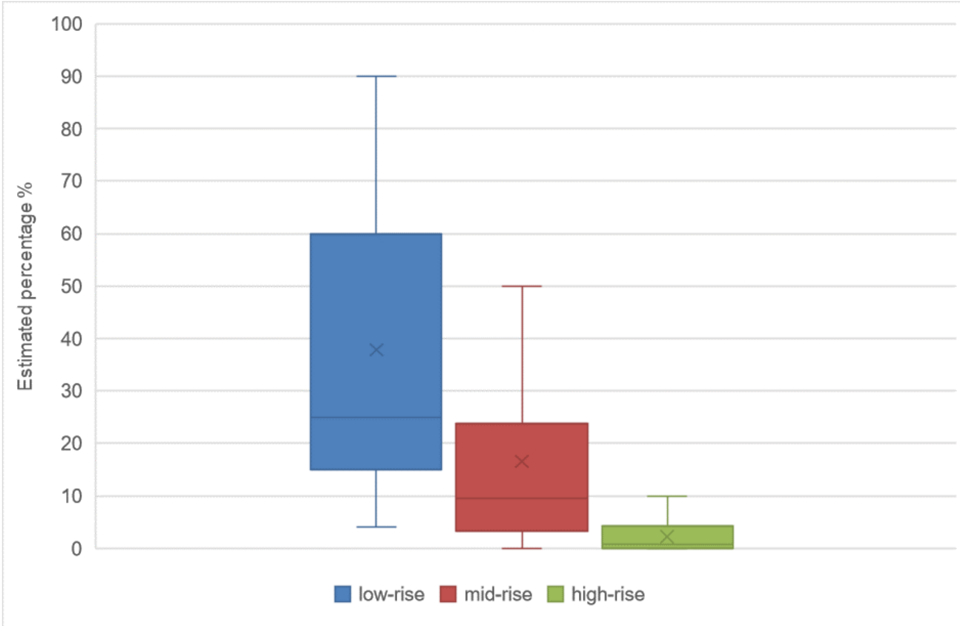


Figure 18: Estimated share of timber constructions in new buildings for different building sizes

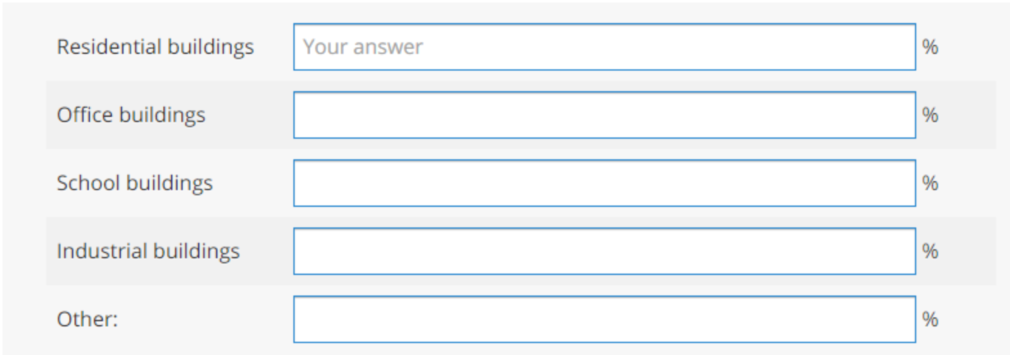
Observations

- The estimated share of timber buildings in new constructions varies widely;
- For low-rise buildings, the answers ranged from 4% up to 90% of all newly erected buildings being constructed in timber. This variation could be explained by different building traditions, regulations, and practice.
- The percentage of timber buildings decreases with increasing building height. The average estimation of timber-share in new buildings decreases continually from low-rise (roughly 40%) to high-rise buildings (2%).
- The definition of different types of buildings vary between countries. Mainly, they are classified according to the number of storeys and/or building heights. See Question 10 for the criteria to categorize a building as "high-rise".

Conclusions

- The scatter of share of timber buildings is large and is different in different regions.
- The estimated percentage of timber buildings is strongly dependent on the precise area of work of the interviewee.

Question 5: Please estimate the percentage of new construction from timber for the following different types of buildings



Residential buildings	Your answer	%
Office buildings		%
School buildings		%
Industrial buildings		%
Other:		%

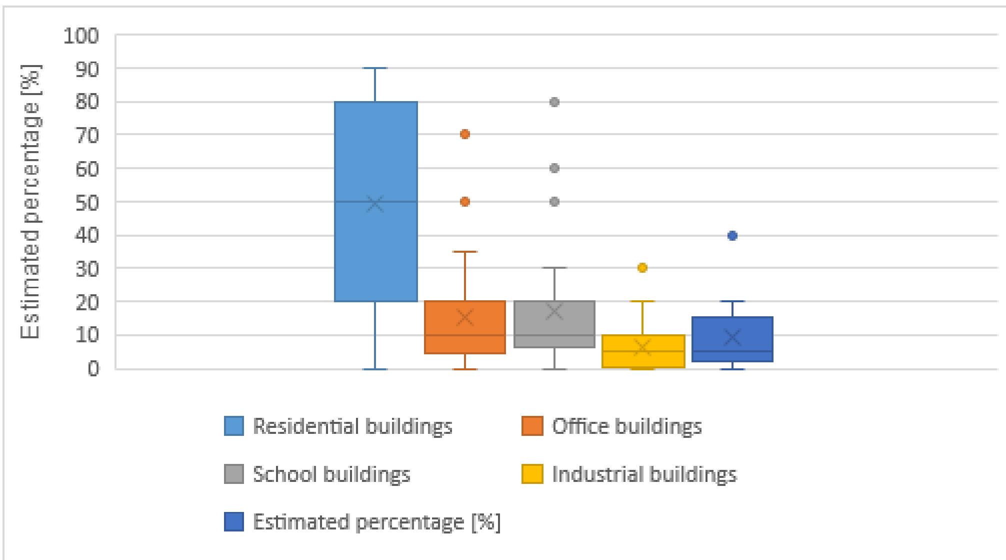


Figure 19: Share of timber constructions in new buildings for different building types

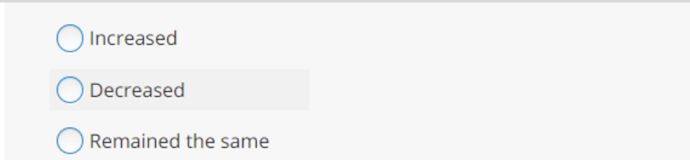
Observations

- The estimation is based on the number of buildings (independent on the size of the building).
- The estimations regarding the perceived percentages of timber buildings compared to new buildings in total vary widely.
- For residential buildings the estimated percentage (an average 47%) is a lot higher than that of all other building types (6% to 16%).
- The smallest share is estimated for industrial buildings (6%).

Conclusions

- The numbers show that the material timber is most widely used in residential buildings.
- In some countries (e.g. Singapore) timber is not used at all in residential buildings; in other countries (e.g. Australia, New Zealand and Canada) timber is widely used (with an estimate of 90%). Most probably it is because mainly residential are mostly low-rise.

Question 6: During the past five years, the share of timber buildings…



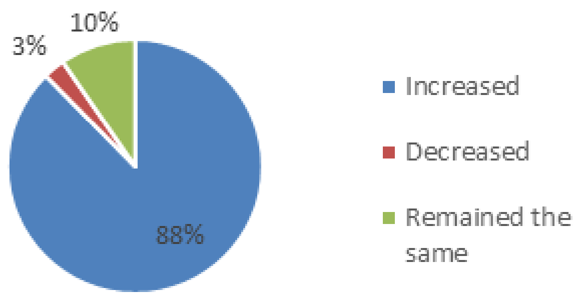


Figure 20: Development of the share of timber buildings

Observations

- The share of timber buildings has increased during the past five years.
- Almost 88% of the experts indicated this fact.

Conclusions

- In the light of questions 4 and 5, it seems clear that even though there are quite different perceptions regarding the frequency of timber buildings in different building types (height and use), there is an agreement that the overall usage of timber in building projects has grown.
- All countries reported increased share of timber buildings during the past five years; however, some experts from Singapore, UK ad New Zealand reported that it has remained the same.

6.9.2.3 Questions regarding legislation in context with timber in construction

Question 7: When was the latest change in fire legislation (and/ or statutory guidance) in your country with respect to the use of timber in construction?

Indicate a year

Your answer

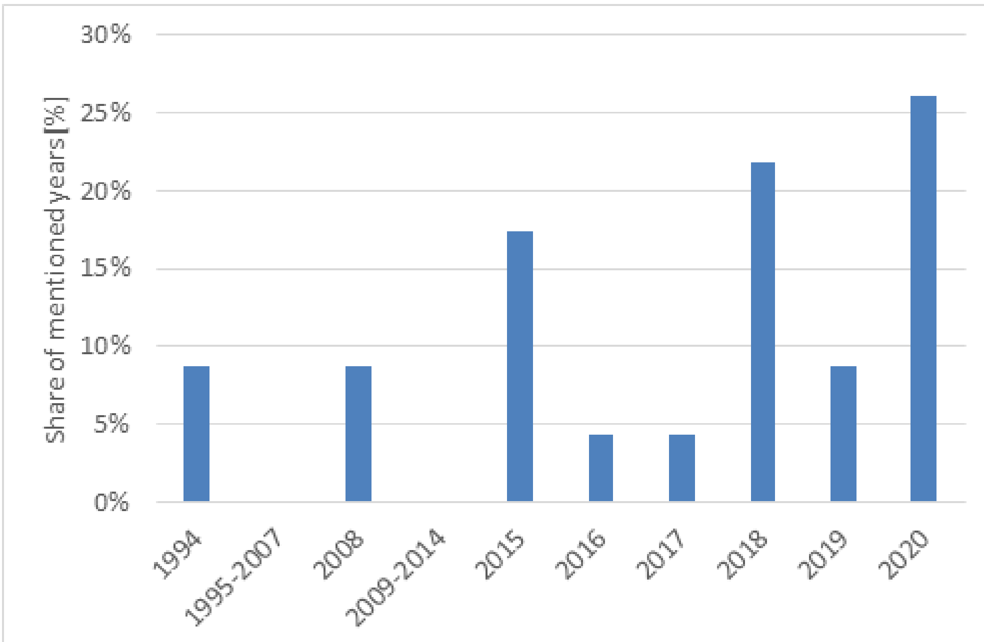


Figure 21: Year of the last change in fire legislation with regard to timber

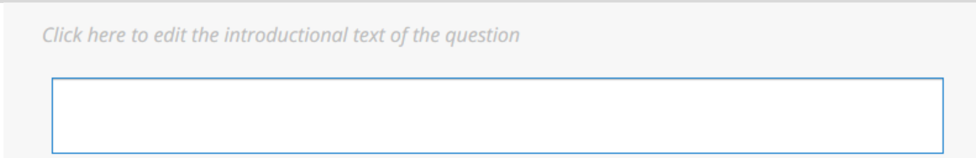
Observations

- 83% of the experts indicated that there had been changes in building legislation with regard to timber within the last 5 years.
- There are discrepancies between experts from the same country.
- For example, two experts from Sweden name 1994 as year of latest changes (small changes every year was mentioned), one names 2019. Year 1994 presents the time when the most significant changes in the fire regulations concerning timber were made. This shows possibly how the question can be interpreted differently.

Conclusions

- Answers to this question are strongly dependent on the respondents' country of residents.
- Discrepancies between experts from the same country hint at the fact that there are not only differences between different countries but also between federal states within the countries.

Question 8: What were the latest changes in fire legislation (and/ or statutory guidance) in your country with respect to the use of timber in construction?



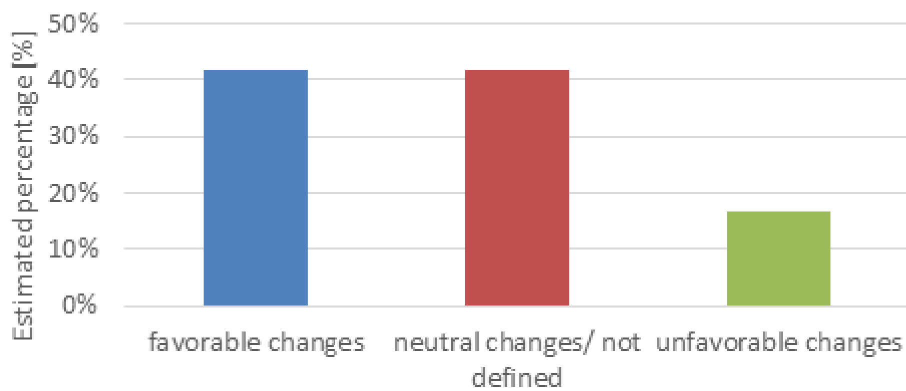


Figure 22: Character of most recent changes

The answers that were received for question 8 were clustered into three categories:

1. Favourable changes – when the response indicated a facilitation for the use of wood.
2. Neutral changes – when the response indicated that the change in legislation did not affect the use of timber.
3. Unfavourable changes – when the response indicated an obstruction for using timber.

Observations

- Only 17% of the surveyed experts mentioned unfavourable changes in legislation.
- Unfavourable changes were mentioned for example in the UK (limitations of combustible building materials in/on external walls in buildings > 18 m) or Belgium (increased requirements for claddings).
- Most answers indicated positive developments in terms of timber applicability.
- For example, the introduction of performance-based regulation that are material-neutral in Sweden or the permission to use encapsulated mass timber in high-rise buildings in Canada.

Conclusions

- Most countries seek to facilitate the use of wood by changing the building code respectively.

Question 9: What are the biggest obstacles in the use of timber in your country?

Drag and drop the most important element to the top, and the least important element to the bottom. Please provide commentary if possible/ necessary.

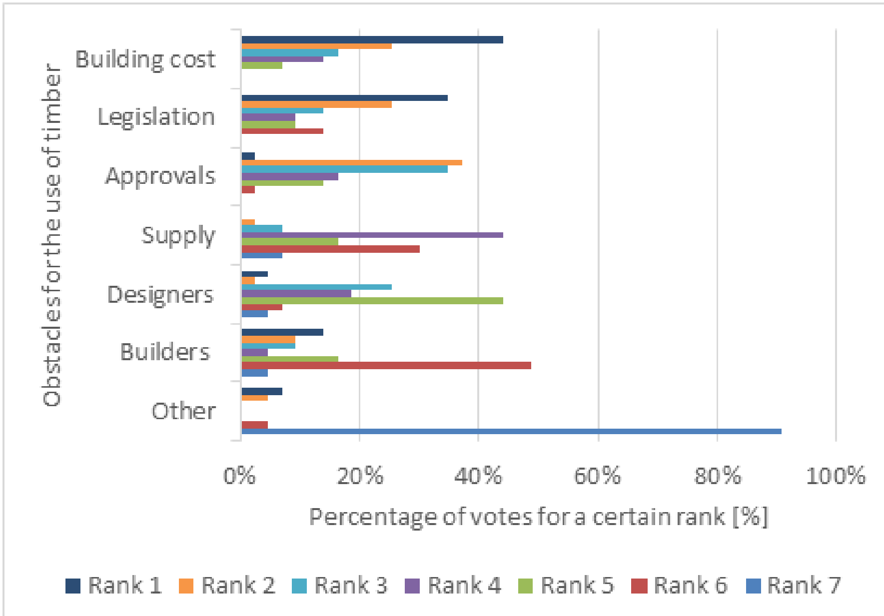


Figure 23: Ranking for obstacles for the use of timber with decreasing relevance[1]

Observations

- Building cost and legislation are voted quite closely on first, respectively second rank.
- Followed by approvals on third and supply on fourth place.
- On the last places are designers and builders.
- From the commentary section, where the experts could explain their rankings, the following statements were made:
- Building cost is generally dependent on the country of application (some countries have to import wood from far away). One reason for high building cost that applies to almost all countries is that encapsulation drives the price of a project: the more wood, the more encapsulation, the higher the cost. Although, it was mentioned twice that maybe the cost is only **perceived** to be higher but is actually similar.
- In terms of legislation, it seems that there is a widespread feeling that surface requirements impede the use of timber. One reason why surface requirements are of such significance for legislators is, according to a respondent, the Grenfell tower fire (London, 2017) which is still in people's minds.
- Approval processes are perceived to be exceptionally long. There are different reasons for that. For example, as legislative requirements can sometimes not be fulfilled,

[1] The ranking was evaluated as follows: Each expert ranked the response options. It was counted, how many times each option was ranked on a certain place. The share of *rank X votes* are evaluated.

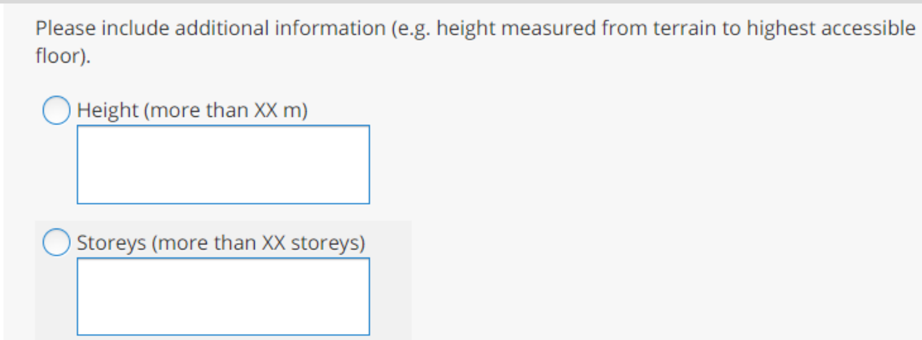
deviations from code must be explained and assessed. Also, both sides: officials as well as project authors (e.g., architects and engineers) are oftentimes not trained enough or not familiar enough with the relevant processes in the context of building with timber.

- Supply is an issue of very different importance in different countries. In some countries like Canada and Austria, this is no issue at all. In other countries (e.g., Singapore), supply is a decisive factor.
- Due to the availability of proven methods and tools, it is usually less cumbersome to erect buildings in steel and concrete (compared to wood). Thus, in order to keep efforts to a minimum, designers and builders might tend to stick to the materials that are thoroughly tried and tested.
- In addition, general unfamiliarity with the product of timber and the connected design process is mentioned as an obstacle when building with wood.

Conclusions

- It seems evident that a lack of qualified personal (designers and builders) is not the biggest obstacle for timber in the building industry.
- Much rather it is the building cost as well as the legislation/ approvals that impede a more extensive use of timber, which is interesting as the results to Q8 suggest that the majority of recent changes were favourable.
- The ranking of obstacles is, again, strongly dependent on the country.

Question 10: What are the criteria to categorize a building as "high-rise" in your country?



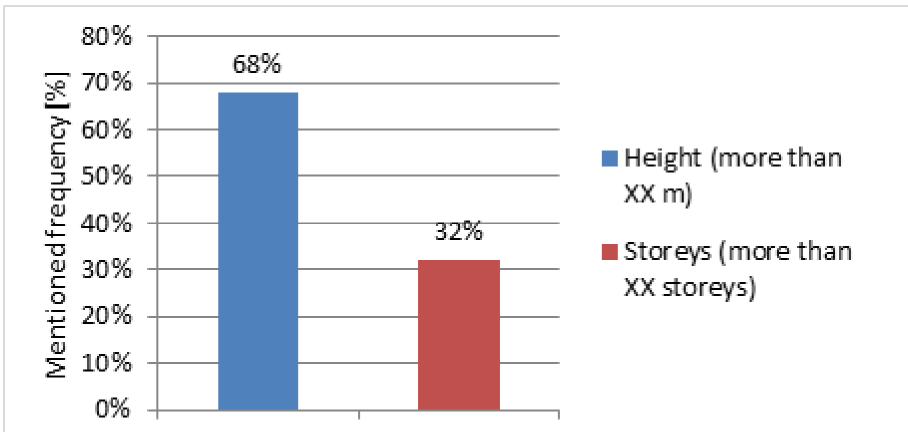


Figure 24: Criteria for classification as *high-rise* building

Observations

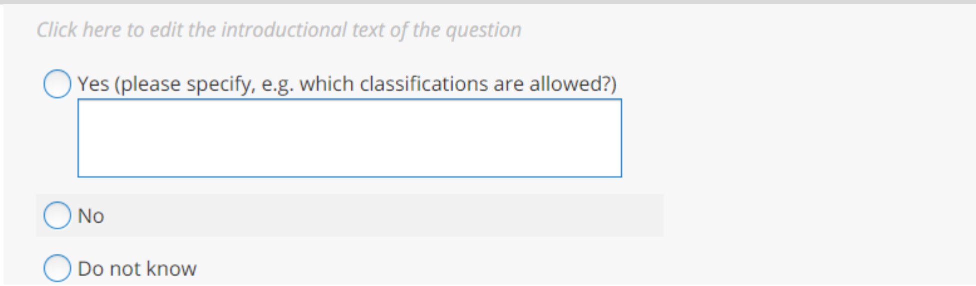
- In most countries, high-rise buildings are characterised by the building heights.
- The heights, from which buildings are considered as high-rise buildings vary from country to country. In Canada, there is even differences within the country: the criteria for high-rise buildings is dependent on the use of the building.
- Usually, the height of a building is measured from terrain to highest accessible floor (however, in Switzerland, the height of the roof is the significant factor).

Conclusions

- There is not a global, commonly agreed upon definition of "high-rise" building.
- The threshold ranges from 18 m (in Canada, for residential/ care buildings or buildings with encapsulated mass timber) up to 36 m (in Canada for all other building uses).
- The height of the upper floor level seems to be one of the main factors to set the limit for building heights in Europe. In Germany and Austria, it is stated 22 m; in Estonia it is 24 m; in Belgium it is 25 m, In Switzerland the full building height is set for 30 m, in Finland and Estonia it is 28 m. In Sweden, 10 storey (35 m) buildings are categorized as 'high-rise'.

- In UK, experts report different categorisations of 'high-rise' buildings: some expert refers to the building height of 18 and 30 m; however, another expert refers to the number of storeys (15 storeys for robustness).

Question 11: Does the fire legislation in your country still allow a classification (fire resistance and/ or reaction to fire) other than European standards?



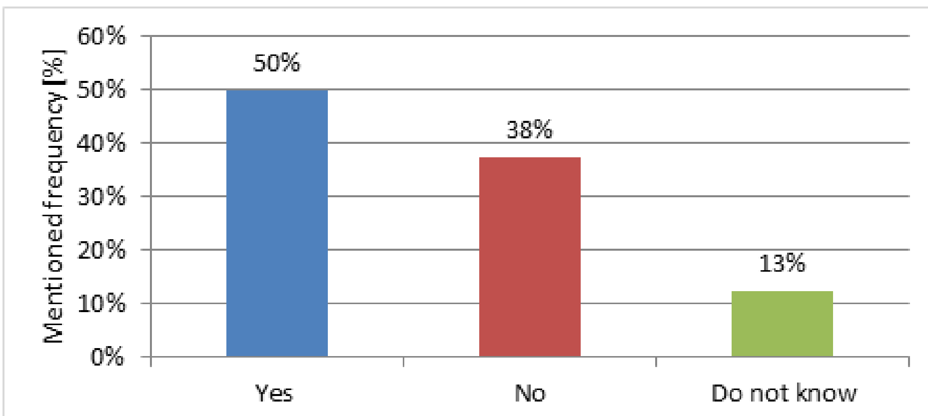


Figure 25: Acceptance of classifications that are **not** European standard

Observations

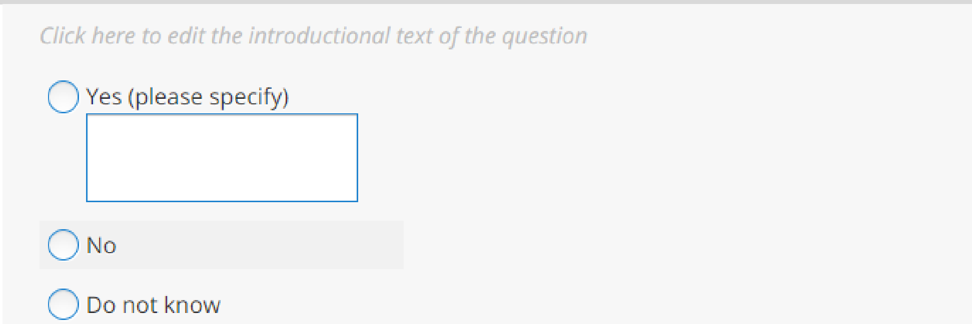
- In most countries, classification is allowed via EU Standards (EN 13501) OR national regulations.

Conclusions

- As not only European countries participated in the survey there are different classification bases depending on the observed country.
- In UK, classification is allowed based on the British Standards for fire resistance and reaction to fire.
- In Italy, some fire regulations still refer to the former Italian classification for the reaction to fire, instead of the European one.
- In Germany, national standard exists for material classification DIN 4102. In case of fire resistance, the F-Classes (F30, F60, F90, and F120) identical to REI-class, no distinction between stability and separating function within the class.

- In the USA and Canada, national standards are followed.

Question 12: Does the fire legislation in your country require criteria that cannot be consistent with the European classification system of EN 13501?



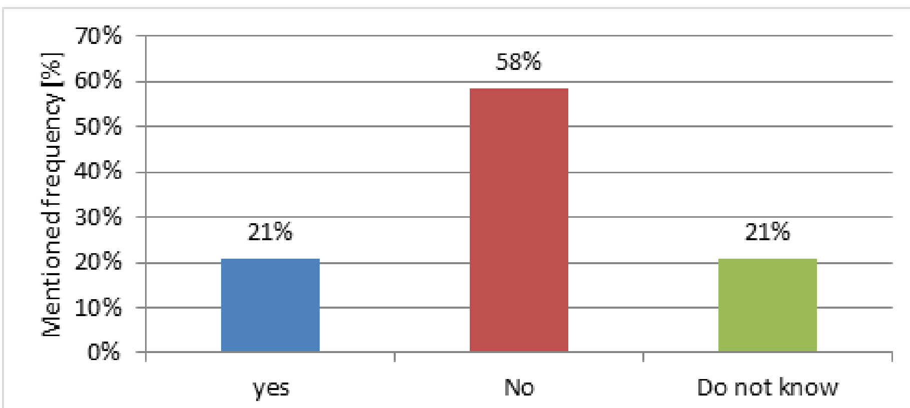


Figure 26: Requirement for criteria outside of EN 13501

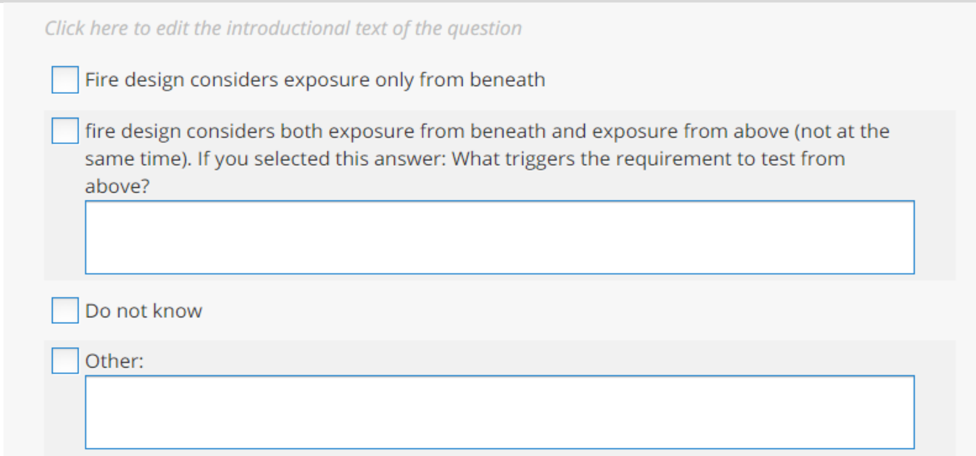
Observations

- Most countries do not require criteria that cannot be consistent with the European classification system (EN 13501).
- Countries from outside of Europe use different guidelines for classification (e.g. AS 1530 in Australia or ULC S114 and S102 in Canada)

Conclusions

- As not only European countries participated in the survey, there are some with wholly different classification standards.
- Most European countries report no criteria that cannot be consistent with EN 13501.
- In Switzerland, the Swiss classification system is allowed.
- In Germany, individual cases may require approval: "Decision in individual cases” (ZiE) approval in individual cases".

Question 13: In some countries, the fire design of floor elements only considers a fire exposure from beneath. Which exposure(s) must be considered in your country?



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- [ ] Fire design considers exposure only from beneath
- [ ] fire design considers both exposure from beneath and exposure from above (not at the same time). If you selected this answer: What triggers the requirement to test from above?
- [ ] Do not know
- [ ] Other:

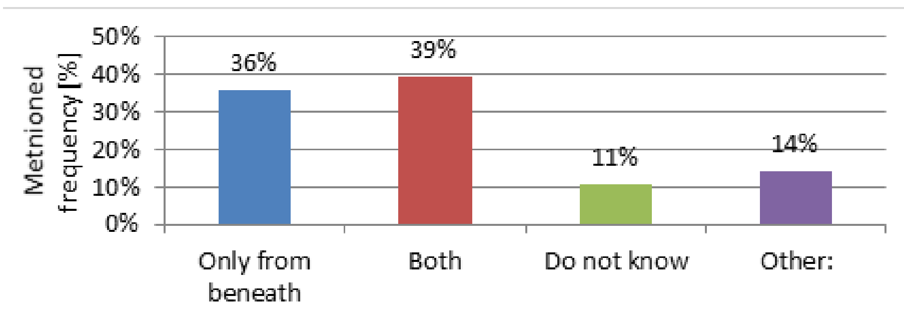


Figure 27: Consideration of fire exposure (from beneath/ from beneath and above) for floor elements

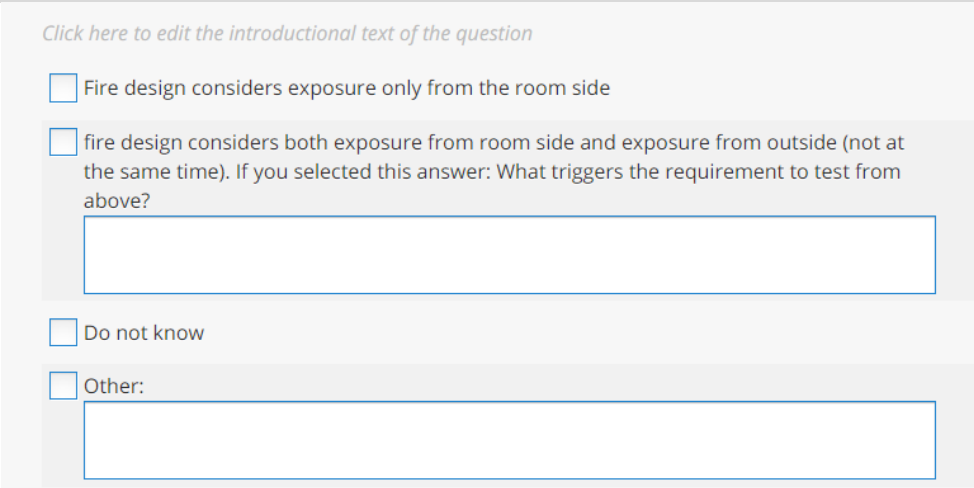
Observations

- 39% of the experts answered that both, exposure from beneath as well as exposure from above must be considered for floor elements.
- 36% answered that only exposure from beneath is considered for floor elements.
- Although exposure from above may not be tested in a furnace, it is many times estimated by means of calculation methods.
- It is mentioned that exposure from above is only necessary to be considered, if wooden structures are applied.

Conclusions

- There is a clear difference for timber structures compared to other materials.
- There is a special need to check the load-bearing capacity of wooden floor element to ensure the safety of fire fighters.
- 11 % did not know, which means that they do not have full expertise.

Question 14: In some countries, the fire design of external walls only considers an exposure from the side of the compartment. Which exposure(s) must be considered in your country?


Click here to edit the introductional text of the question

☐ Fire design considers exposure only from the room side

☐ fire design considers both exposure from room side and exposure from outside (not at the same time). If you selected this answer: What triggers the requirement to test from above?

☐ Do not know

☐ Other:

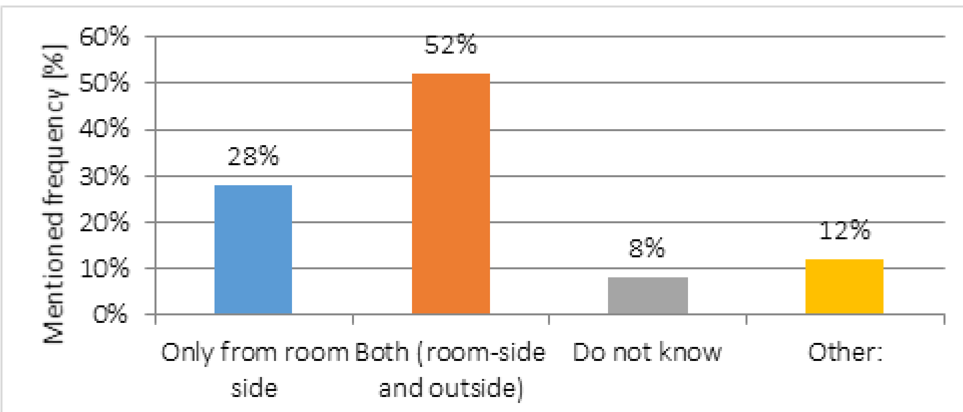


Figure 28: Consideration of fire exposure for external walls

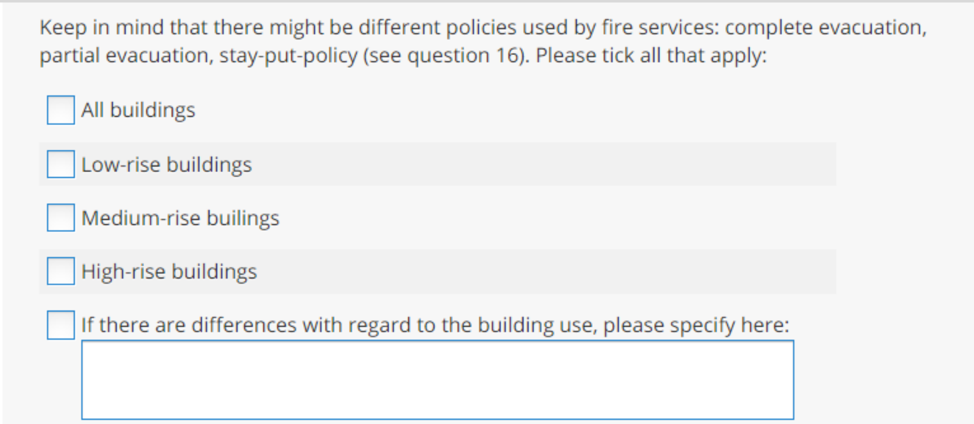
Observations

- In most countries, fire design of external walls must be considered for both sides.
- The experts argue that this is necessary as exterior fires may be significant for the building structure.

Conclusions

- The requirements of outside walls depend on the distance to adjacent buildings, building height and use of the building.
- For external wall reaction to fire performance is very important and many restrictions apply (e.g. the external wall is not allowed to be combustible). Requirements based either on small-scale classification tests or on large scale testing (and now under development) or on both.

Question 15: Which buildings would normally be expected to be evacuated in a fire incident?



Keep in mind that there might be different policies used by fire services: complete evacuation, partial evacuation, stay-put-policy (see question 16). Please tick all that apply:

- [ ] All buildings
- [ ] Low-rise buildings
- [ ] Medium-rise builings
- [ ] High-rise buildings
- [ ] If there are differences with regard to the building use, please specify here:

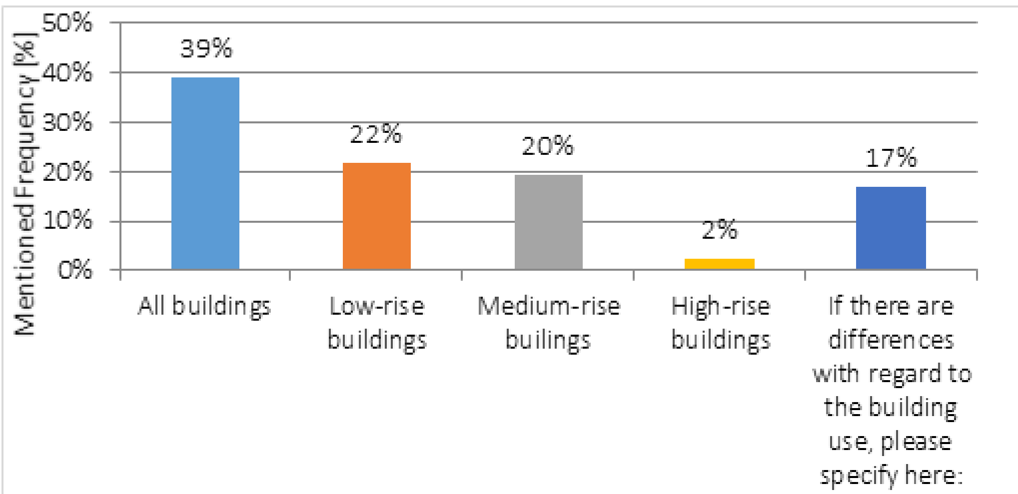


Figure 29: Evacuation strategies for different building types and sizes – part one

Observations

- 39% of the experts indicate that all buildings, regardless of their heights, are fully evacuated.
- 22% say that low-rise and 20% say that medium-rise buildings are evacuated in a fire.
- Only 2% state that high-rise buildings are usually fully evacuated.
- Several experts mentioned that evacuation strategies must be developed in accordance with the layout of the building and in coordination with the fire services.
- Horizontal evacuation (to adjacent compartments) is mentioned multiple times in the context of buildings that accommodate people with limited mobility.

Conclusions

- The comments suggest that generally all buildings are evacuated in fires. The precise strategy must be developed in correspondence to the fire protection concept.
- The evacuation strategy is not exclusively related to building height.

- Experts mention that high-rise buildings are more likely to be gradually evacuated in the event of a fire. In addition, horizontal evacuation (to adjacent compartments) is mentioned in the context of hospitals or retirement homes.
- Different evacuation strategies exist in different countries (e.g. phased evacuation; horizontal evacuation; partial evacuation and stay-in-place policies) dependable on the function of the building (e.g. buildings for vulnerable and disabled people).

Question 16: Which buildings would typically be expected to be only partially evacuated?

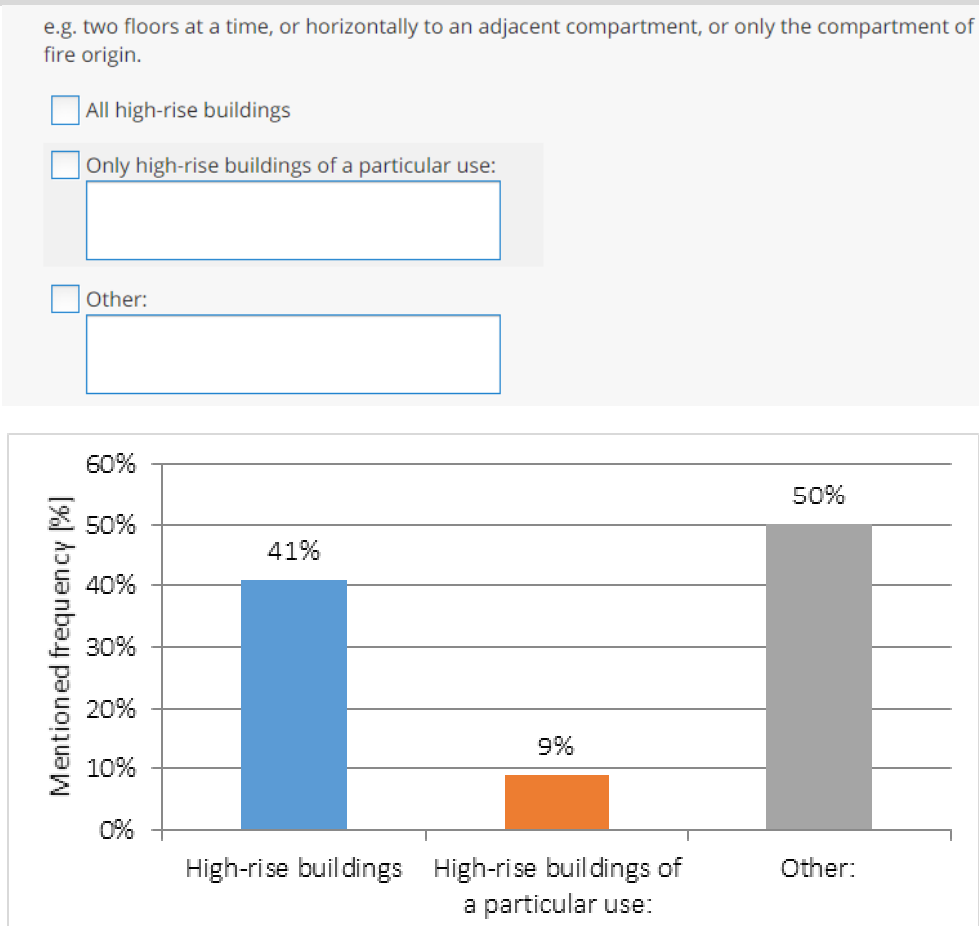


Figure 30: Evacuation strategies for different building types and sizes – part two

Observations

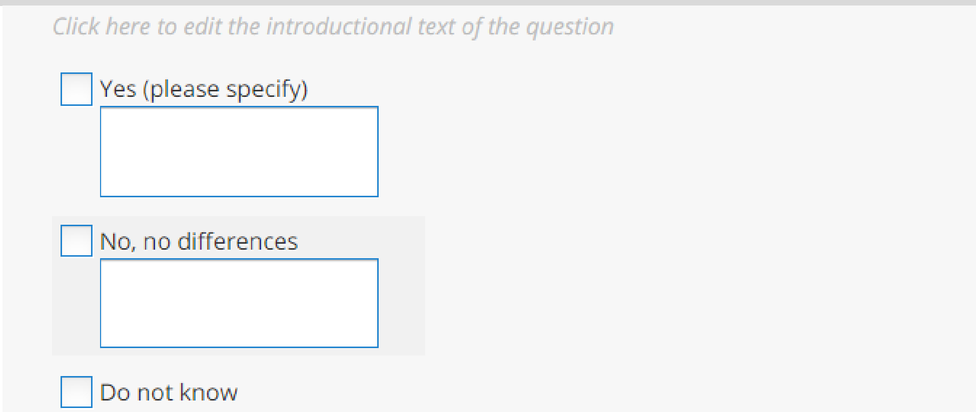
- Multiple experts agree that different evacuation strategies are allowed, and these do not necessarily depend on the building height.
- According to the experts, it is rather important that evacuation corresponds to the fire design in general and building solutions in particular (e.g. sufficient and reliable compartmentation, etc.).

- Again, hospitals and retirement homes are mentioned as most likely to be only partially evacuated.

Conclusions

- Evacuation strategies are dependent on different factors (see above). Combustibility of the structure is not necessarily one of them.

Question 17: In relation to the questions above (15 and 16): Are there any differences in the strategies if the building is constructed in timber?


Click here to edit the introductional text of the question

Yes (please specify)

No, no differences

Do not know

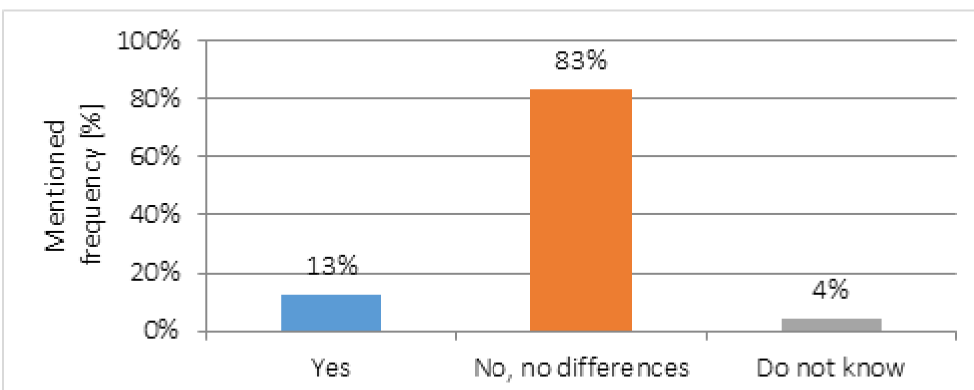


Figure 31: Evacuation strategies for different building types and sizes – part three

Observations

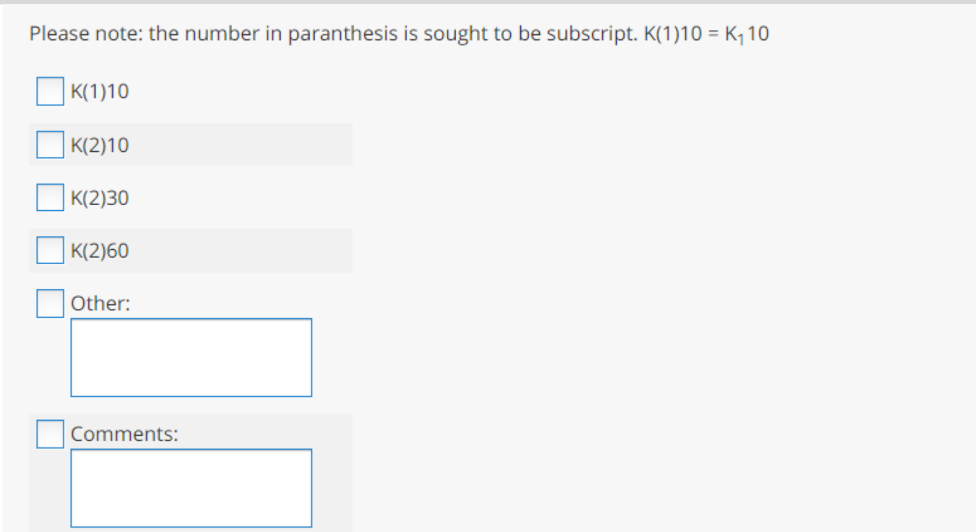
- 83% indicate that there is no difference in evacuation strategy between combustible and non-combustible structures

Conclusions

- The materialisation does not have a direct influence on the evacuation strategy.

- However, two experts (from Estonia and Canada) stated that timber structures are more prone to be fully evacuated

Question 18: Which classes of coverings for fire protection or encapsulation are typically used in your country?


Please note: the number in paranthesis is sought to be subscript. K(1)10 = $K_1$10

- [ ] K(1)10
- [ ] K(2)10
- [ ] K(2)30
- [ ] K(2)60
- [ ] Other:
- [ ] Comments:

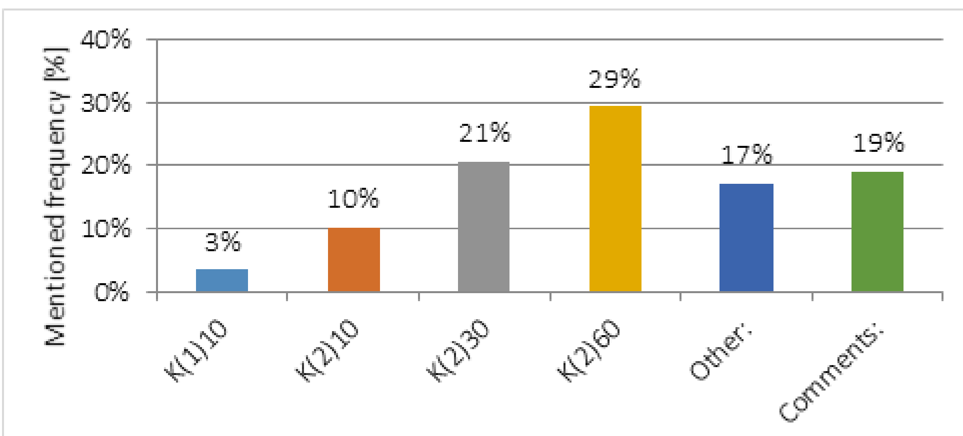


Figure 32: Typically used classes for coverings/ encapsulations

Observations

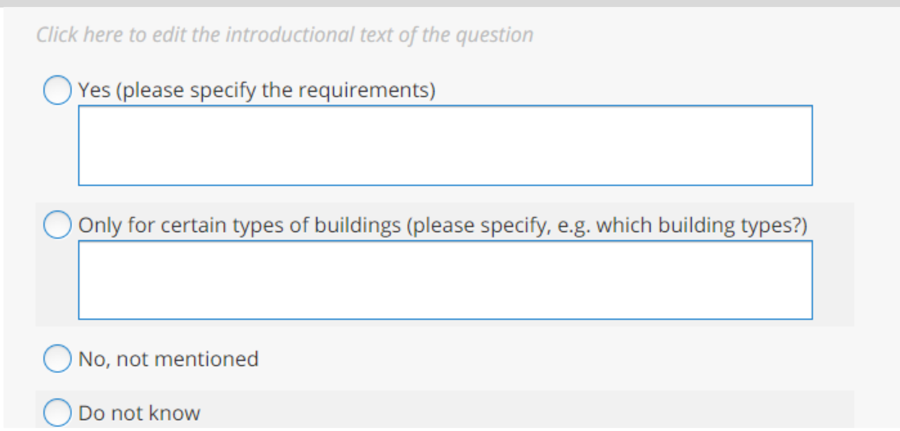
- 50% indicate that either $K_2$30 or $K_2$60 are typically used for encapsulation
- 36% indicate that something else than the proposed classifications are used or commented on the question.
- In total, only 13% state that K110 or K210 encapsulations are in use.

- No comment on the use of sprinklers as a measure to have an effect on the encapsulation requirement was made.

Conclusions

- $K_2$30 or $K_2$60 encapsulations are typically used in Europe.
- In Canada and the US, gypsum board Type X or spray-applied fire-resistant material is used.
- It is stated that height and use of a building play a role in defining the encapsulation requirements.
- In addition, it is stated that the fire load of the respective compartment or building determines the required encapsulation class.
-

Question 19: Are there any reaction to fire requirements for the coverings for the fire protection or encapsulation in your country?


Click here to edit the introductional text of the question

Yes (please specify the requirements)

Only for certain types of buildings (please specify, e.g. which building types?)

No, not mentioned

Do not know

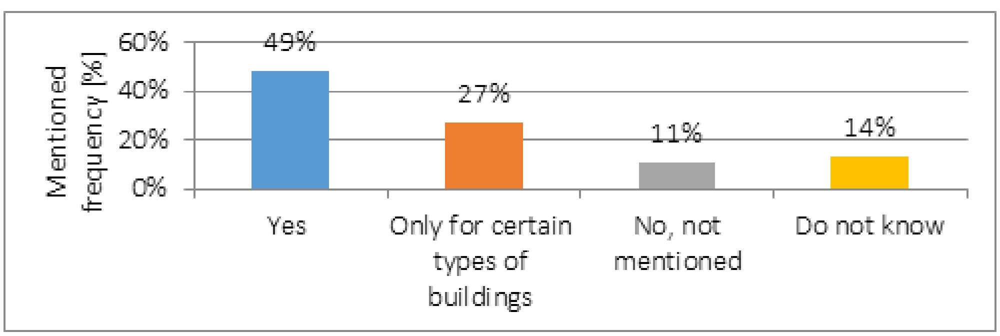


Figure 33: Reaction to fire requirements for coverings/ encapsulations

Observations

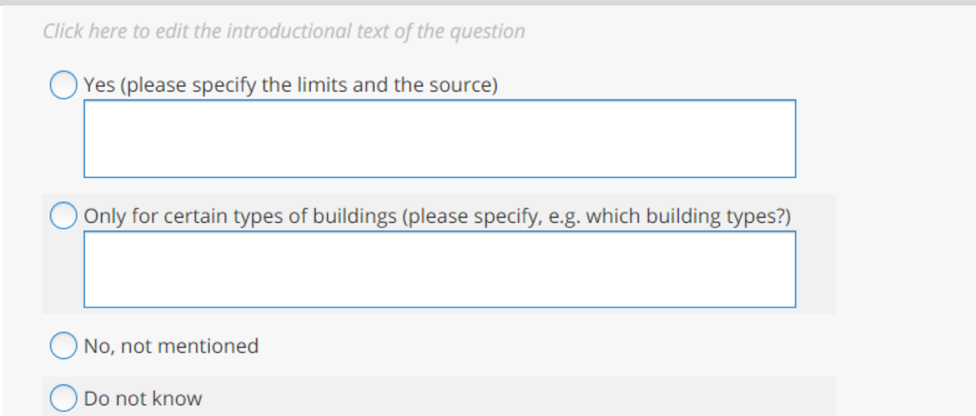
- Most experts indicate that there is a requirement for the reaction to fire of encapsulations

- Mentioned as minimum requirements are A2 and Bs1d0
- In Canada, there is a new Standard exclusively for the encapsulations of timber (CAN/ ULC-S148).

Conclusions

- Encapsulations must generally be classified according to the relevant regulations in the specific country.
- The reaction to fire requirement is usually dependent on the building type and height.

Question 20: Does the fire legislation (and/ or statutory guidance) in your country state limits for the use of visible combustible structures (e.g. exposed timber structures) within the compartment for multi-storey buildings?


Click here to edit the introductional text of the question

- ◯ Yes (please specify the limits and the source)
- ◯ Only for certain types of buildings (please specify, e.g. which building types?)
- ◯ No, not mentioned
- ◯ Do not know

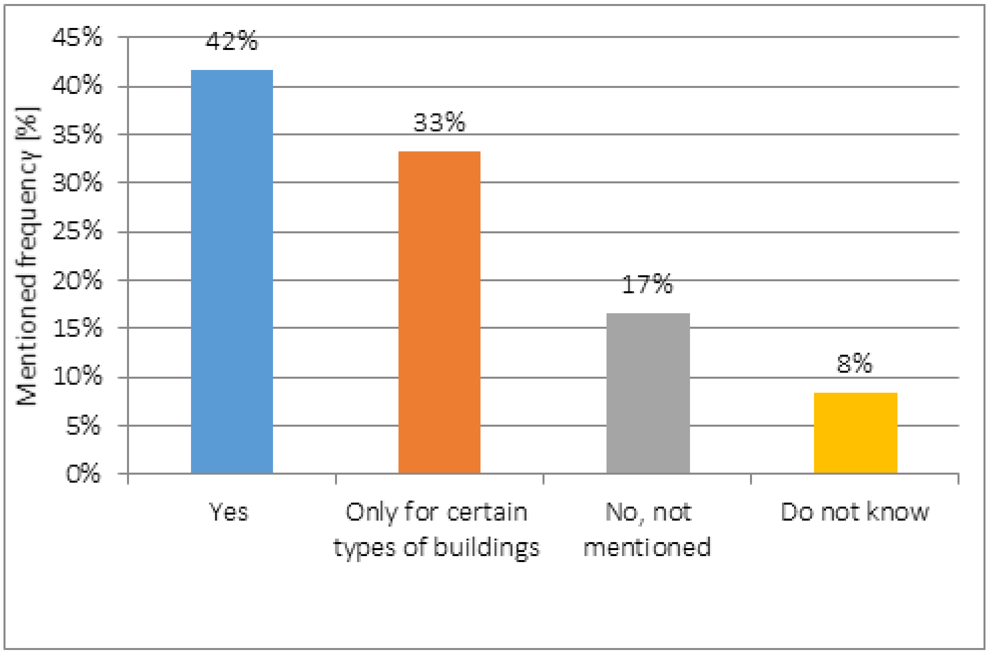


Figure 34: Limits for exposed combustible structures within compartments of multi-storey buildings

Observations

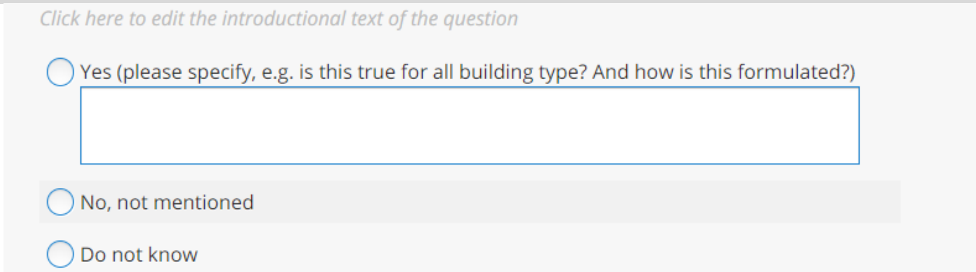
- Almost 80% of the surveyed experts state that there are limits for visible combustible structures (at least for certain building times).
- It was stated multiple times that there must not be visible timber constructions in external walls.
- Exceptions may be granted if encapsulations or sprinkler systems are applied.
- For internal surfaces, depending on the country, the amount of acceptable visible timber differs: In Sweden, the building regulations limits visible timber to 15%, whereas in Germany 25% and in Canada 35% is possible.
- In Finland, the share of visible timber is directly connected to the required fire resistance of the compartment (REI60 = max. 20% timber, REI90 = 20-80 %, REI120 = 100% possible), which are correlated to the building height.
- In most countries, it seems, the limit only applies to walls and ceilings. It is mentioned several times that floor elements are not considered.
- In most countries, the acceptable amount of timber depends on the height and use of the building.

Conclusions

- Visible combustible surfaces are perceived as a risk.
- Visible combustible surfaces in external walls are perceived as especially critical.
- In contrast to walls and ceilings, there are no restrictions mentioned for floors. One expert from Finland states explicitly that there are no restrictions for floors.

- Based on the retrieved data, it seems like floors are considered less of a problem compared to walls and ceilings.

Questions 21 and 22: Does the fire legislation (and/ or statutory guidance) in your country require that (21) any building/ (22) *a timber building* must withstand a complete burnout without a fire service intervention?



Burnout requirement for non-timber buildings | Burnout requirement for timber buildings

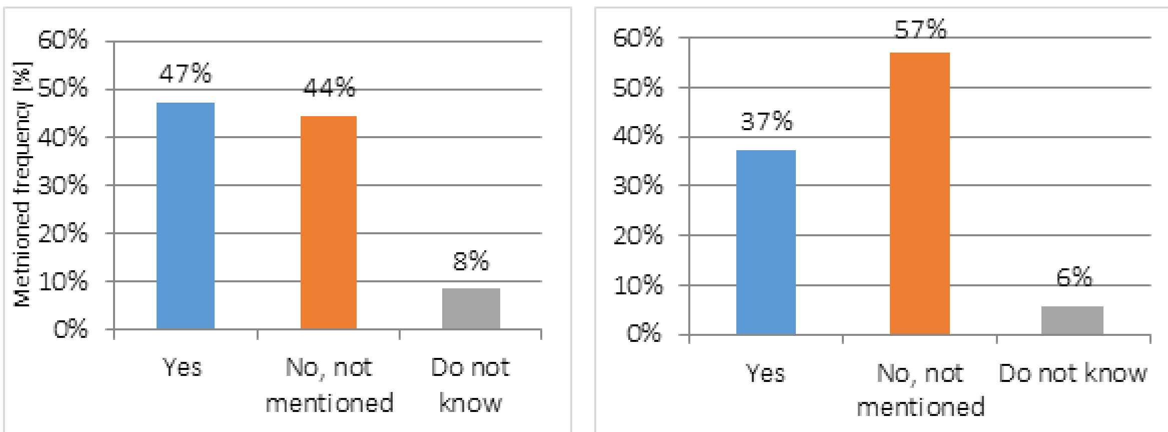


Figure 35: Requirement of resisting burnout without fire service intervention in non-timber buildings (left) and timber buildings (right)

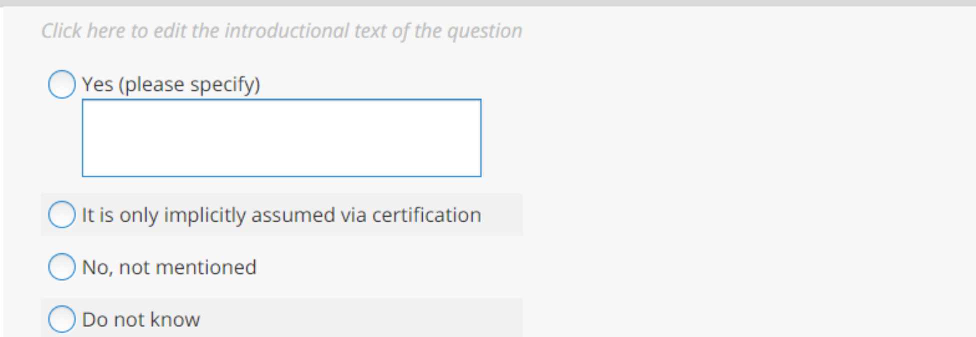
Observations

- Half of the surveyed experts (experts from Australia, Canada, Estonia, Finland, Germany and UK) state that proof for a building's stability in the event of a complete burnout is required in their fire legislation.
- According to the additional comments, the ability to withstand burnout is rather implied than explicitly mentioned.
- The stability might merely be required for a certain amount of time (e.g. if a building is considered feuerbeständig (=fire proof) in Germany, it implies that it withstands a fire for 90 minutes). Burnout is required for building class 5 (maximum height of top floor level of more than 13 m above middle ground level)
- Generally, building height and use as well as compartment size seem to be more relevant than the materialisation of the structure: the figure on the right shows that the majority of the experts state that there are no explicit mentions for proof of stability for timber buildings.

Conclusions

- There would be a need for probability-based limit for burnout.
- It appears that the necessity for proof of withstanding a burnout is not directly dependent on the combustibility of its structure.
- If the proof of withstanding a burnout is required, it is rather dependent on the two major factors:
- Capability of the affected fire brigade
    - Building density of the affected area (=risk of damaging neighbouring buildings)

Questions 23: Generally, the fire legislation (and/ or statutory guidance) requires the limitation of spread of fire and smoke for compartmentation. Is the criterion smoke explicitly considered in your country or implicitly assumed to be maintained for certified separating elements?



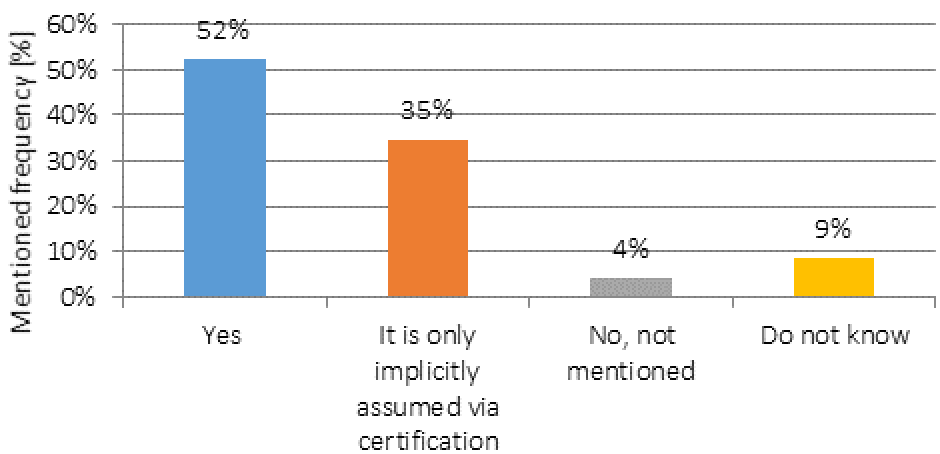


Figure 36: Explicit or implicit consideration of criterion *smoke* for compartmentation

Observations

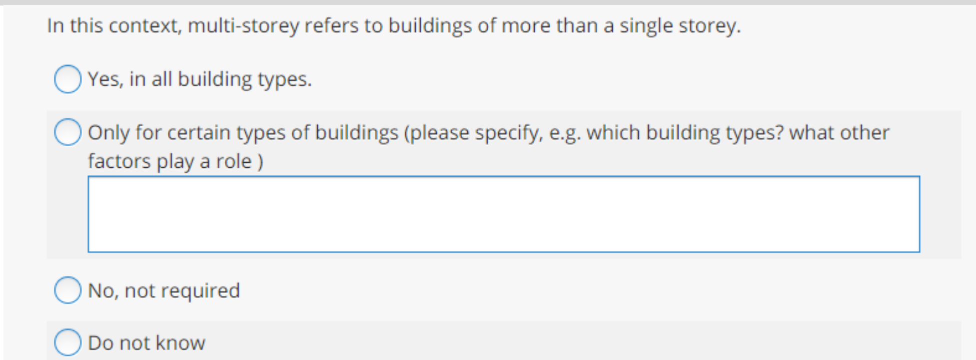
- 52% of the experts (e.g. from Australia, Canada, Sweden, Belgium and Italy) indicate that the criterion smoke is explicitly considered in special applications, such as:
- in fire doors of staircases in high-rise buildings .

- when required according to a performance-based concept.
- 35% (e.g. experts from UK and Finland) say that smoke is rather implicitly considered (via building element certification).

Conclusions

- The data shows that the criterion smoke for compartmentation is an important factor in fire legislation. Depending on the country, it is considered either explicitly in special applications or implicitly as part of the certification process for building elements.

Questions 24: Does the fire legislation (and/ or statutory guidance) in your country require the use of sprinklers for multi-storey buildings?


In this context, multi-storey refers to buildings of more than a single storey.

- Yes, in all building types.
- Only for certain types of buildings (please specify, e.g. which building types? what other factors play a role)
- No, not required
- Do not know

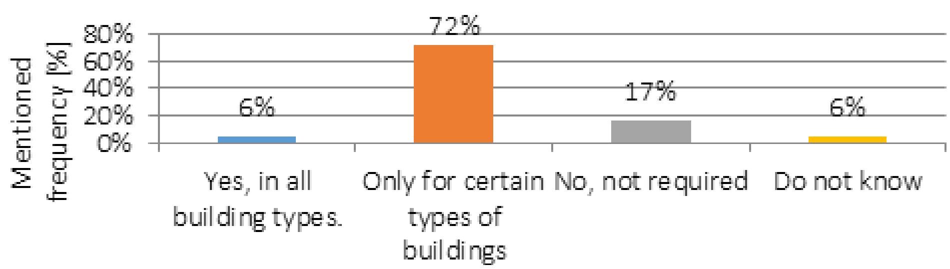


Figure 37: Requirement for sprinklers in multi-storey building

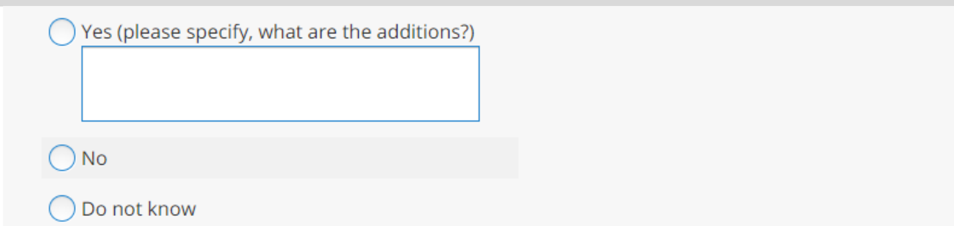
Observations

- 72% indicate that sprinklers are only required for certain building types
- Building height plays an important role for the sprinkler requirement (it is mentioned as a decisive factor for example in Germany, Switzerland and Canada)
- In addition to its height, the use of a building is crucial to the applicable requirements.
- Hospitals, (elder-)care homes and shopping malls with open breakthroughs in ceilings are named as examples for buildings that require sprinklers.
- Moreover, sprinklers can be used as compensation measure, if other requirements (e.g. maximum compartment size) cannot be fulfilled.

Conclusions

- There is no general requirement to install sprinklers in a high-rise building (depending on the actual building regulations).
- The sprinkler requirements are country specific and dependent on the building height, the compartment size and complexity (e.g., extends over multiple storeys), the use and the specific fire risk of a building. Requirements for a number of storeys or building heights are mentioned for timber buildings (e.g. in some countries all timber buildings higher than 2 or 4 storeys require sprinklers).

Questions 25: In relation to question 24: Does the fire legislation (and/ or statutory guidance) in your country have additional requirements for multi-storey timber buildings?



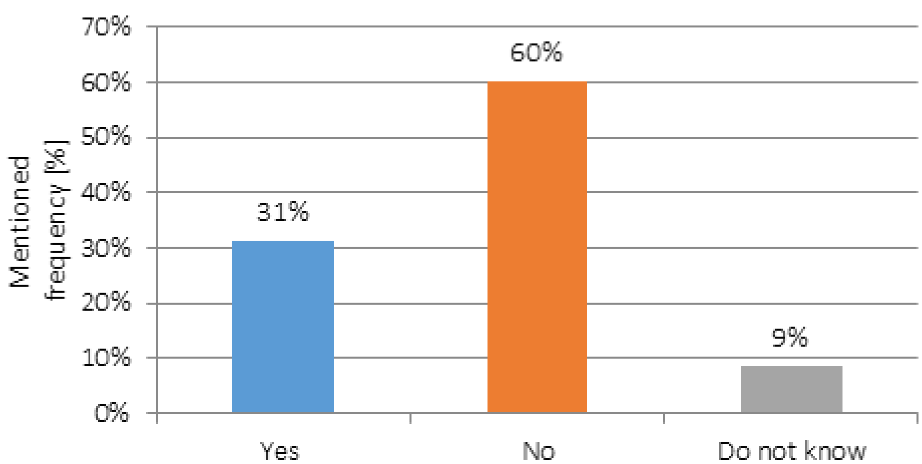


Figure 38: Additional sprinkler requirements for multi-storey **timber** buildings

Observations

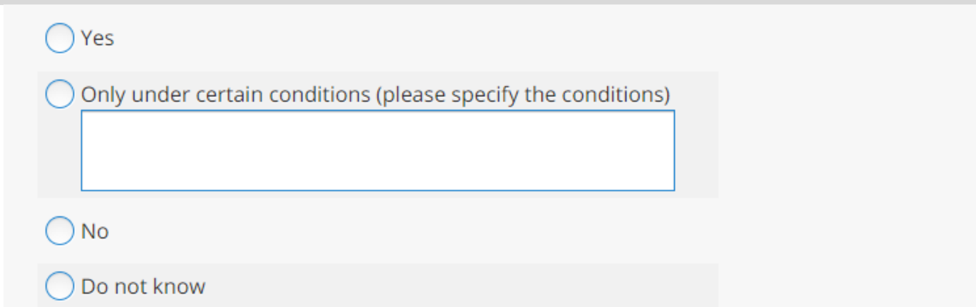
- 60% of the surveyed experts responded that they are not aware/there are no additional requirements regarding sprinkler systems for buildings with timber construction.
- In some countries, like Australia, Canada, Estonia, Finland, Germany and Singapore, the experts shared their opinion that there are additional requirements for sprinkler systems in mass timber buildings.
- The applied sprinkler systems must meet a different standard compared to buildings with non-combustible structure.

- For example, in Canada sprinklers in wooden buildings must comply with NFPA 13 instead of NFPA 13R.

Conclusions

- The combustibility of the structure is one factor that might add to the sprinkler requirement (but does not lead to a necessity).

Questions 26: Does the fire legislation (and/ or statutory guidance) in your country allow to reduce the fire resistance of the structure by adding sprinklers?



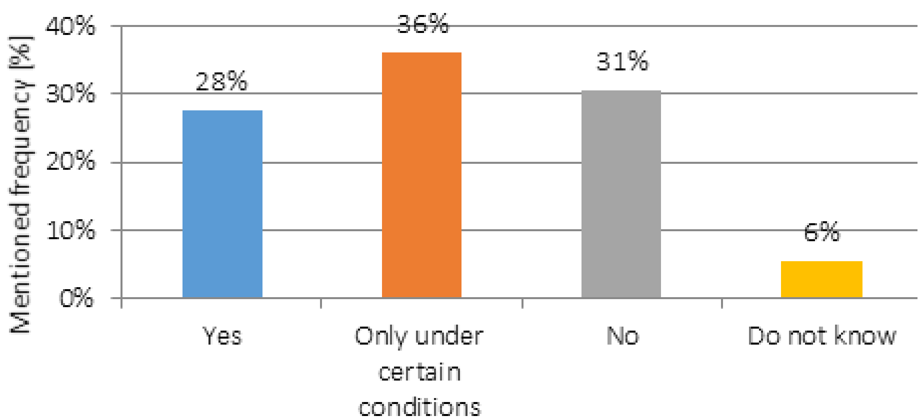


Figure 39: Reduction of structural fire resistance when using sprinklers

Observations

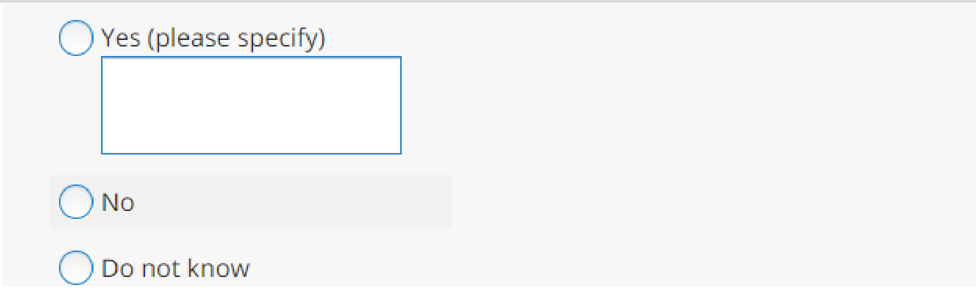
- 64% indicate that the reduction of a structure's fire resistance in buildings with sprinklers is allowed in general or under certain conditions.
- For example, in Germany sprinklers are sometimes used to compensate the feuerbeständig (= REI90) criterion.
- In Sweden, the load-bearing capacity of the structure can be reduced by 30 minutes if suitable sprinkler concepts are applied.
- In Switzerland, it is additionally allowed to reduce the integrity of compartmentation elements (e.g. R60 instead of R90 for the structure and EI30 instead of EI60 for the fire compartments in Swiss high-rise office buildings).

- In Belgium, a trade-off is only possible, if the respective the authorities consent to it as part of a holistic, integrated approach.
- In Italy, rather than the fire resistance, it is the reaction to fire requirements that may be reduced, if sprinklers are applied.

Conclusions

- In multiple countries, sprinklers can be used as a compensation measure to reduce constructional requirements (reaction to fire or fire resistance).
- Fewer countries (like Singapore, Australia, USA, Canada and Austria) do not allow a reduction.

Questions 27: In relation to question 26: Are there any differences for timber structures?


Yes (please specify)

No

Do not know

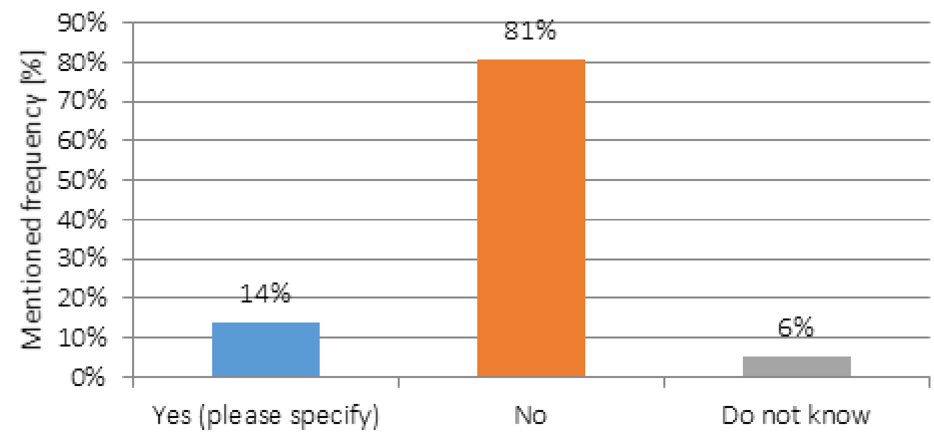


Figure 40: In relation to question 26 - Differences for timber structures

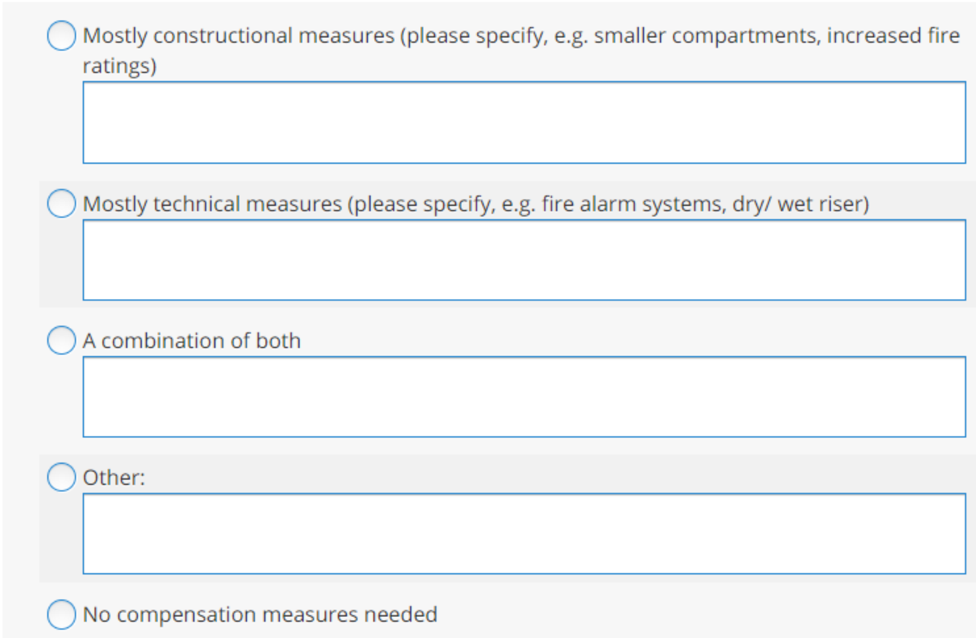
Observations

- 81% of the experts state that timber structures do not generally have an impact on the possibility of reducing the fire resistance due to installation of sprinklers in a building.
- However, especially in countries where the required fire resistance of a structure is directly deduced from the burning load of the building (e.g., Estonia), the combustibility of the structure is important in this context.

Conclusions

- The trade-off between sprinklers and reduced fire resistance of a structure applies to timber as well as non-timber structures.
- Only few countries (e.g. Estonia, Finland and parts of Germany) differentiate between timber and non-timber in this context.

Questions 28: Which typical compensation methods (other than sprinklers) are used in the conceptual fire design process of timber structures in your country?


Mostly constructional measures (please specify, e.g. smaller compartments, increased fire ratings)

Mostly technical measures (please specify, e.g. fire alarm systems, dry/ wet riser)

A combination of both

Other:

No compensation measures needed

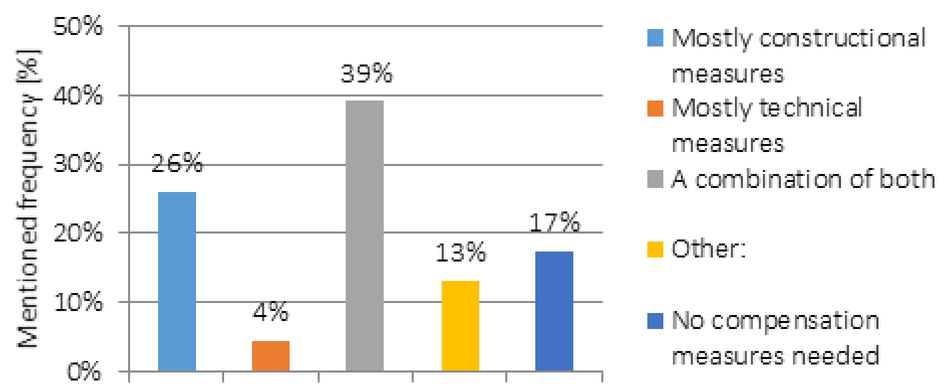


Figure 41: Typical compensation methods for timber structures

Observations

- In many countries buildings require compensation measures, if the structure is built using combustible material such as timber.
- 39% state that a combination of technical and constructional measures is used to compensate for the increased burning loads by combustible structure. Typical means for compensation are:
- Dry / wet risers
- Fire alarm systems
- More fire compartments (= smaller compartment sizes)
- Increased fire ratings
- Limited height or number of storeys

Conclusions

- In addition to sprinklers, there are other measures used to compensate for combustible structures.
- There is no "one fits all" compensation method.
- Different factors play a role in the determination of a solution.

Questions 29: Does the building legislation (and/ or statutory guidance) require smoke detectors as a compensatory feature for timber buildings?

- Yes for all buildings
- Yes for residential timber buildings
- Yes for office timber buildings
- No
- There is no difference between timber buildings and others
- Do not know
- Other:

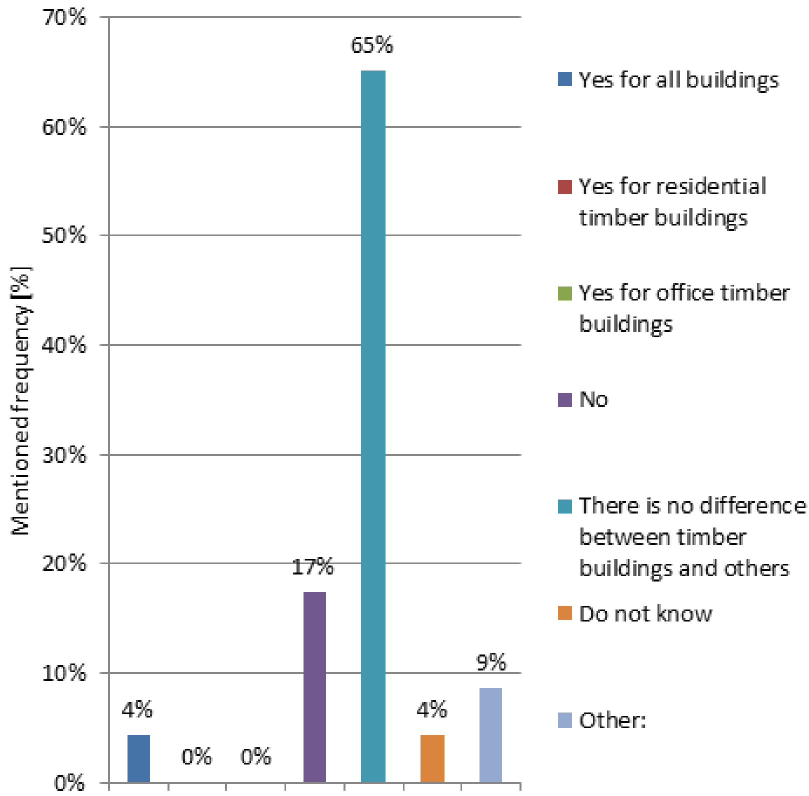


Figure 42: Smoke detectors as mandatory equipment in timber buildings

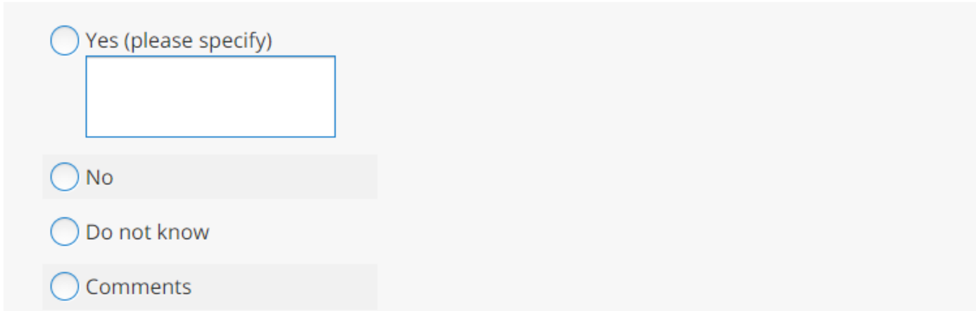
Observations

- Only 4% of the experts (a respondent from Canada) states that smoke detectors are required for all timber buildings.
- 82% say that smoke detectors are not required in timber buildings or if they are, they would be required anyways, regardless of the buildings' combustibility.

Conclusions

- Smoke detectors are no universal compensation measure for buildings with combustible structure.
- The requirement for smoke detectors is not solely dependent on the combustibility of the structure.

Questions 30: Are there any differences regarding fire safety separation distances between buildings using combustible or non-combustible facades?



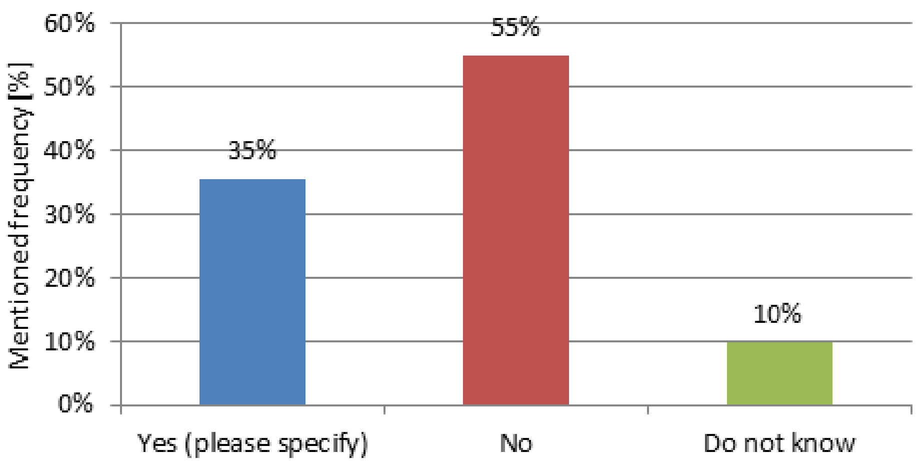


Figure 43: Differences in separation distances for combustible and non-combustible facades

Observations

- 55% of the experts say that separation distance is the same, regardless of the combustibility.
- 35% of the surveyed experts state that there was a difference regarding safety separation distances:
- When using combustible material, the distance between buildings must be increased.
- In Singapore, combustible facades are treated as unprotected openings.
- In Switzerland, there are even concrete values for distances between two buildings of which both (= 10 m), one (= 7.5 m) or none (= 5 m) have a combustible facade.
- In UK, the area of unprotected combustible facades is limited, according to one export. Another UK professional states that combustible facades need a double protected area.

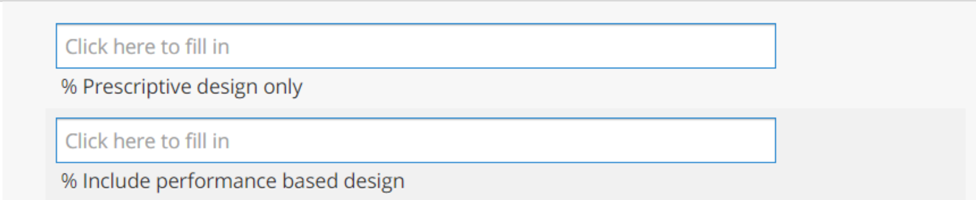
Conclusions

- There are different approaches to determining the separation distance by different countries.
- Difference might occur due to the national or regional differences in fire service capability and population (=building) density.

NOTE: With respect to the rules in UK, it should be noted that different rules in Wales, England and Scotland might apply. Further, design guidance recommends that all external surfaces that are not Euroclass B or better to factored into radiating panel assessment required to assess fire spread risk to adjacent property; the size of the radiating panel is recommended to be taken as 50% of the area of the combustible cladding.

6.9.2.4 Questions regarding fire safety concept and design

Questions 31: How many fire safety designs for timber buildings are you involved with in your country that are based on prescriptive or performance-based design?


Click here to fill in
% Prescriptive design only
Click here to fill in
% Include performance based design

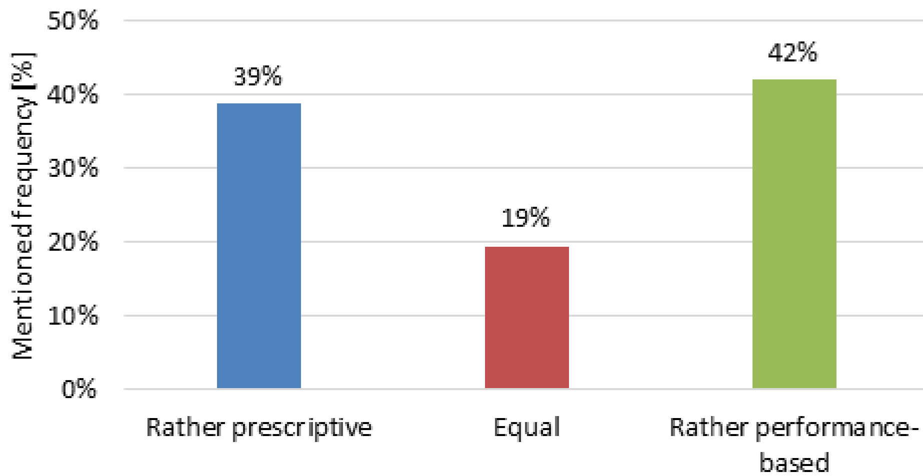


Figure 44: Rather prescriptive v. rather performance-based fire safety designs (timber buildings)

As the ranges vary widely for the different experts, it was decided that the mere tendency (*rather prescriptive* vs. *rather performance* vs. *equal*) should be evaluated. Accordingly, a respondent who indicated that 80% of the timber buildings they are involved with were rather *only* prescriptive-based and 20% rather *included* performance-based designs, was counted as *rather prescriptive* in the figure above. The percentages given by the experts are not subject of closer consideration.

Observations

- The answers are distributed quite evenly.
- 42% say that most of their projects involve performance-based design.
- 39% say that most of their projects are prescriptive concepts only.
- 19% say that they are equally concerned with strictly prescriptive and concepts that involve performance-based design as well.

Conclusions

- The numbers probably relate to the general complexity of building projects: The number of projects that do not require performance-based approaches ("standard projects") and those that do, appear to be relatively equal.

Questions 32: Are there special qualifications required (for engineers and/ or architects) to establish a fire safety concept for a multi-storey timber building in your country?

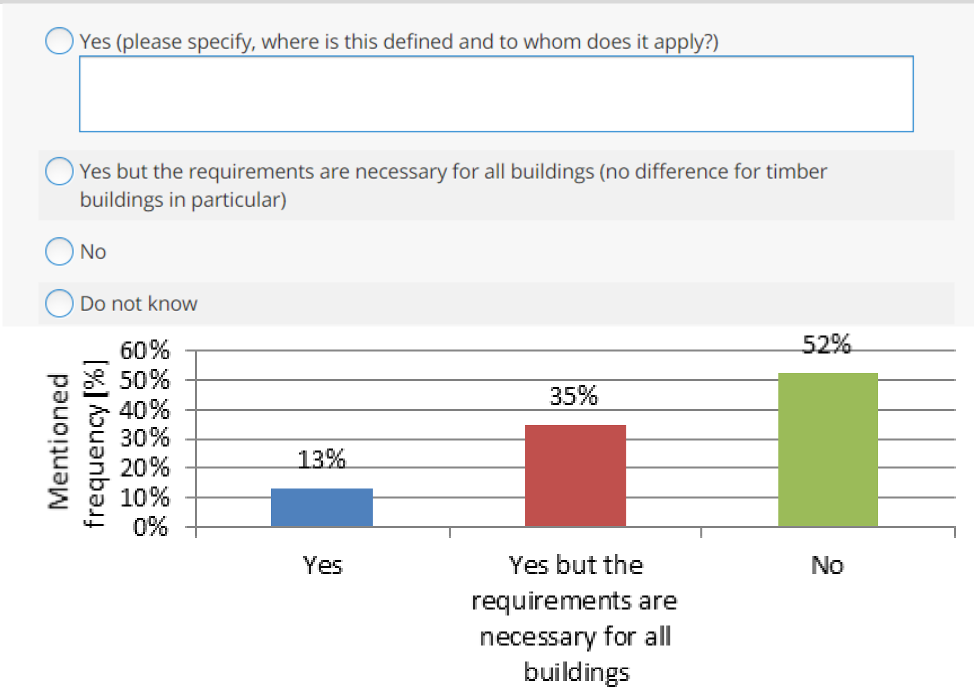


Figure 45: Special requirements for establishing a fire safety concept in timber buildings

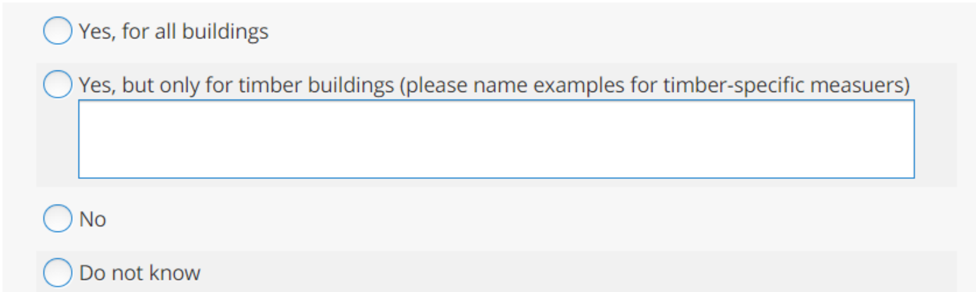
Observations

- 52% of the respondents indicate that there are no special qualifications required for establishing fire safety concepts for multi-storey timber buildings.
- 35% say that there are at least no differences to regular buildings.
- People who indicated that there are indeed special requirements said that they are implicitly required via the determined building class (e.g., in Switzerland and Estonia).

Conclusions

- According to the experts, the presence of combustible structures in some countries leads to an increased quality control standard. Having to fulfil a higher quality control standard in turn requires proof of increased qualifications for the involved parties. Thus, special qualification is rather implicitly required than explicitly demanded.
- The majority of the experts state that there are no requirements for special qualifications of people involved in timber projects.
- No comment was made on the difference between the prescriptive and performance based design of buildings.

Questions 33: Are there quality control measures for multi-storey buildings in your country?



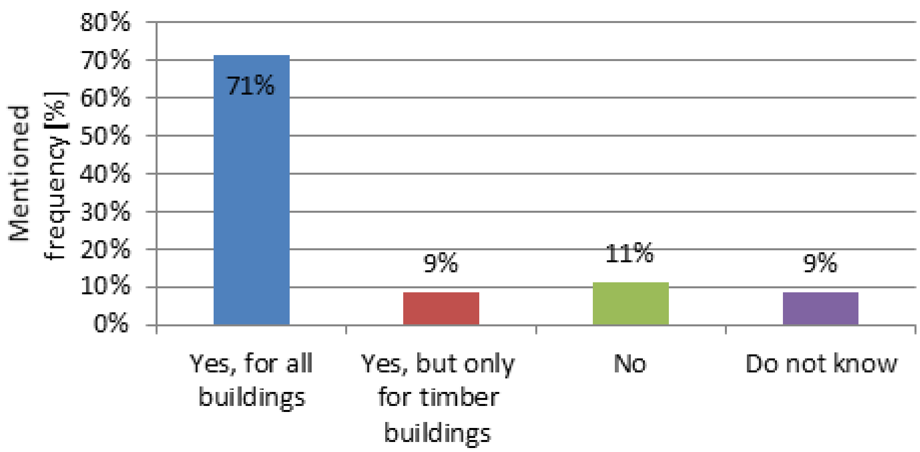


Figure 46: Existence of quality control measures for multi-storey buildings

Observations

- 11% of the experts say that there are no quality control measures for multi-storey buildings in their country.
- 71% say that there are quality control measures for all buildings.
- Only 9% (experts from Canada and Germany) say that there are quality control measures exclusively for timber buildings.
- Specifically, they state that there are additional quality control measures for timber buildings like the timber-specific guideline HolztafelbauRL or the requirement for appropriately qualified site managers who verify the correct execution of work for timber buildings in Germany.

Conclusions

- In most countries, there are quality control measures, but they apply to all multi-storey buildings and are not only focused on timber constructions.

Questions 34: Compared to a "traditional" concrete structure: Do you quantify the complexity of the fire design of a timber building to be…?

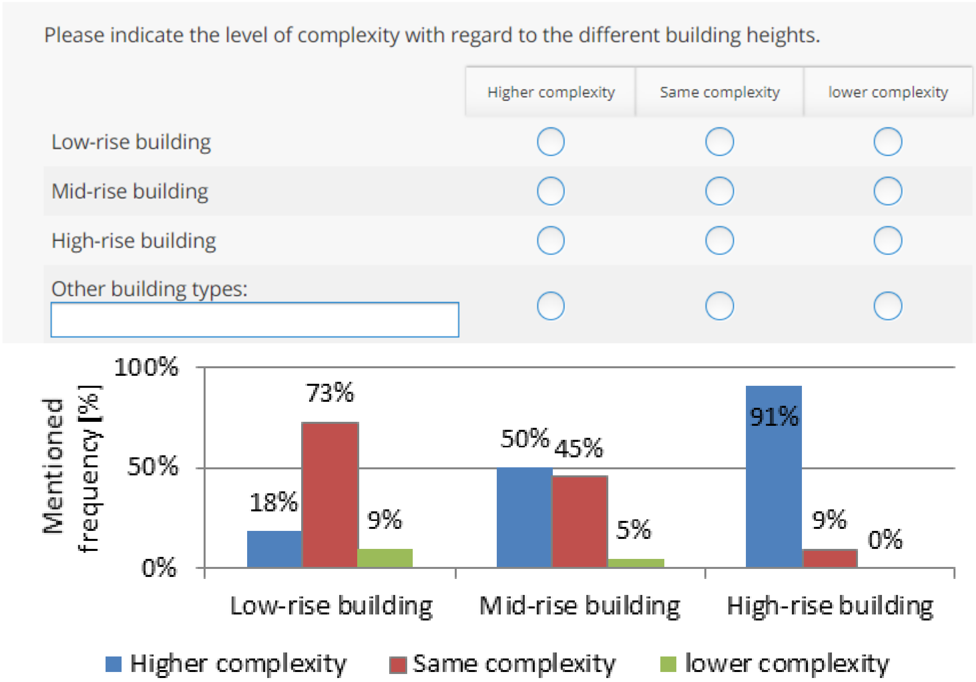


Figure 47: Perceived complexity of timber structures and "traditional" structures

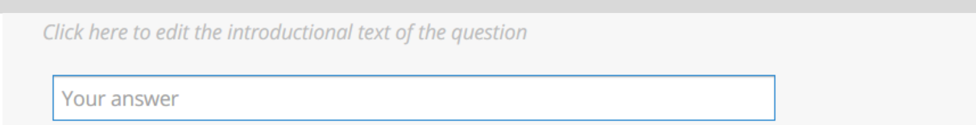
Observations

- In general, only a small number of the survey participants view fire design for timber structures as less complex as for "traditional" structures.
- The percentage of experts, who see timber and "traditional" structures as equally complex decreases gradually from 73% in low-rise buildings to 9% in high-rise buildings.
- The percentage of experts, who view timber structures as more complex than "traditional" structures gradually increases from 18% in low-rise buildings to 91% in high-rise buildings.

Conclusions

- The complexity of timber projects increases rapidly with increasing building height, according to the experts.

Questions 35: In relation to the question above (34), please explain why you made the choices.



Observations

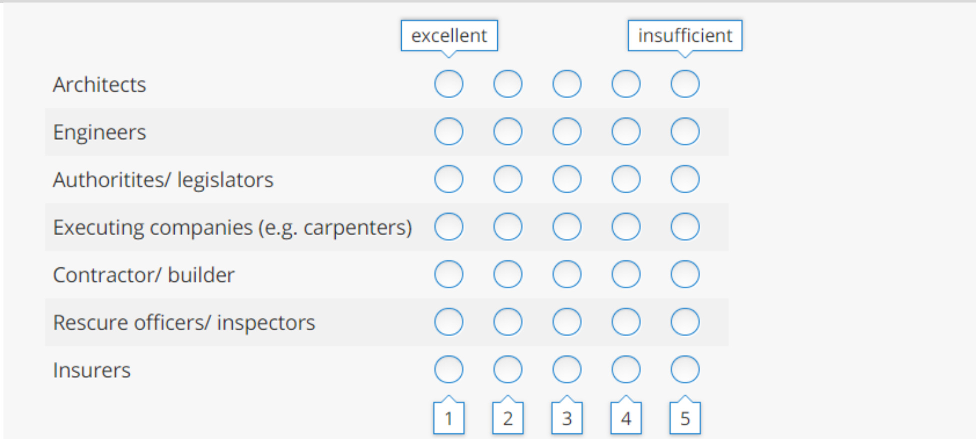
The participants named the following explanations for the indicated perception in the question before:

- Reaction to fire requirements (use of combustible material must be justified more and more thoroughly the higher the building)
- Fire resistance requirements (R-requirement)
- Lack of available prescriptive solutions and thus the necessity for performance-based approaches for many problems (However, it is stated there are prescriptive approaches for timber buildings up to 100 m in Switzerland.)
- Lacking familiarity with timber projects (as stated before, in answers to question 9)
- The fact that large timber projects many times show "special" (meaning complex) architecture adding to the overall complexity of high-rise timber construction projects

Conclusions

- There are multiple reasons for the increased complexity of timber projects in high-rise buildings.
- Limiting authoritative regulations are mentioned repeatedly.

Questions 36: How would you rate the competency with respect to fire safe design of timber structures in your country for the following disciplines/ stakeholders?



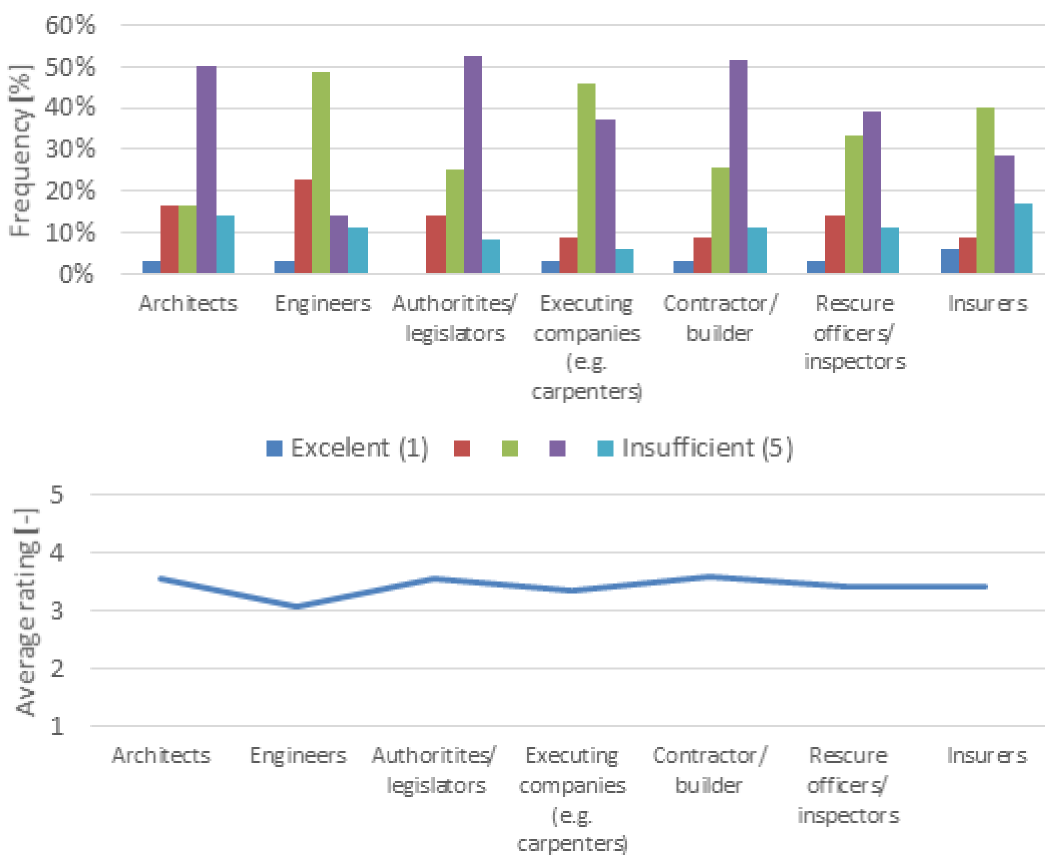


Figure 48: Perceived competence of different stakeholders.

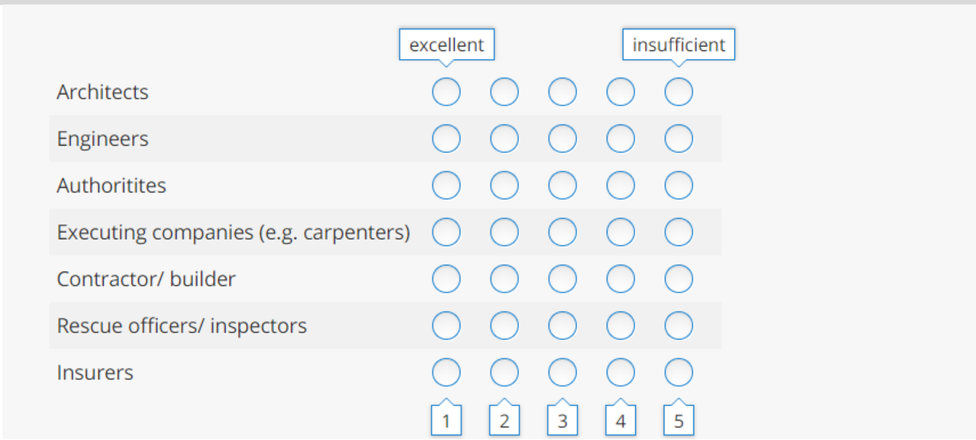
Observations

- The figures show that the respondents view the competency of different disciplines regarding timber structures as too low.
- The average score (bottom figure) for all disciplines ranges between 3 and 4 on a scale from 1 through 5, where 1 is excellent and 5 is insufficient.

Conclusions

- As the average rating ranges from 3.1 (for engineers) down to 3.6 (for architects) it seems overall that the experts see missing competency in all the involved groups dealing with timber projects.

Questions 37: How would you rate the education with respect to fire safe design and timber structures in your country for the following disciplines/ stakeholders?



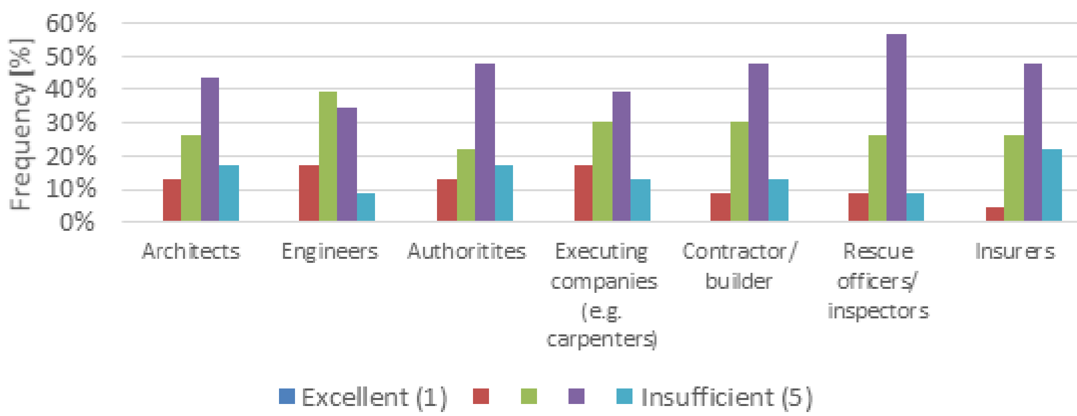


Figure 49: Perceived level of education for different professions

Observations

- Like their competency, the respondents view the education of different stakeholders from involved disciplines as too low with regard to timber structures.
- The average score (bottom figure) for all disciplines ranges between 3 and 4 on a scale from 1 through 5, where 1 is excellent and 5 is insufficient
- The rating ranges from 3.4 (for engineers) to 3.9 (for insurers).
- As shown below, there are only two main differences between the perceived competence and education of different stakeholders:
- Education is even worse than competence.
- Insurers are the only group who perform significantly worse in their perceived education.

Conclusions

- Competence as well as education must be improved decisively.
- It is interesting to note that engineers performed best in both questions, as the majority of the surveyed experts are engineers.

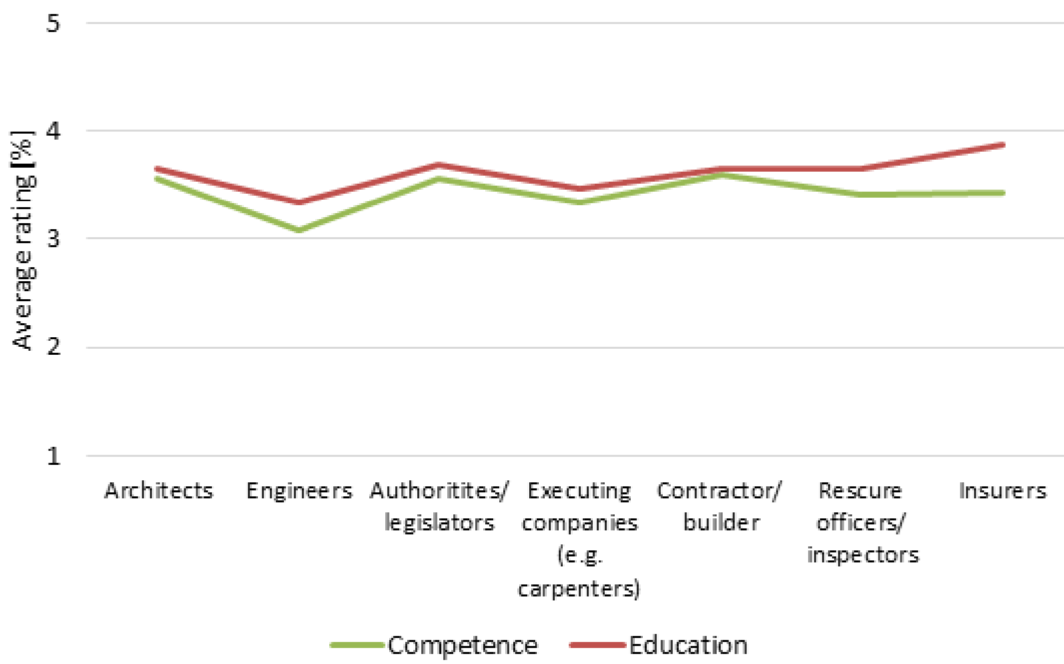
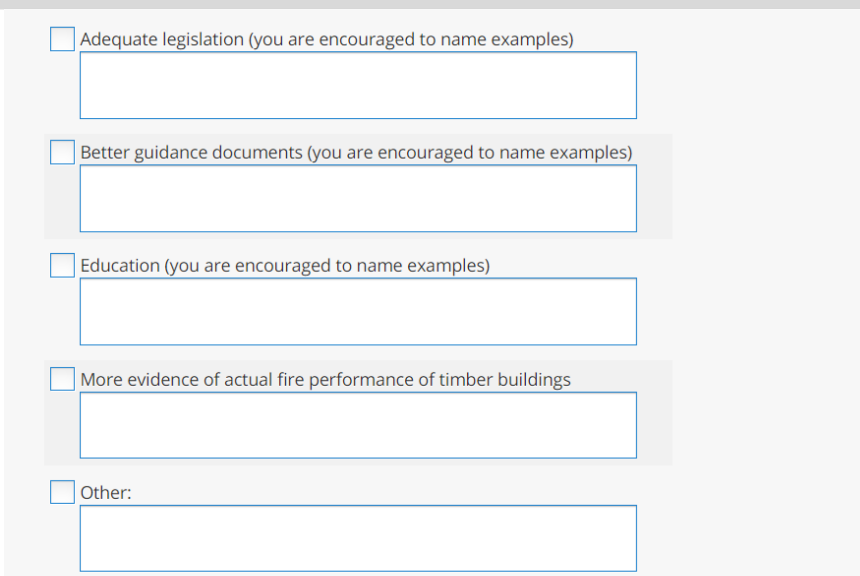


Figure 50: Comparison of education and competence of different stakeholders

Questions 38: In your opinion, which knowledge gaps and obstacles must be bridged in order to improve the fire design process and increase the use of fire safety engineering in the design of timber buildings in the future?



- Adequate legislation (you are encouraged to name examples)
- Better guidance documents (you are encouraged to name examples)
- Education (you are encouraged to name examples)
- More evidence of actual fire performance of timber buildings
- Other:

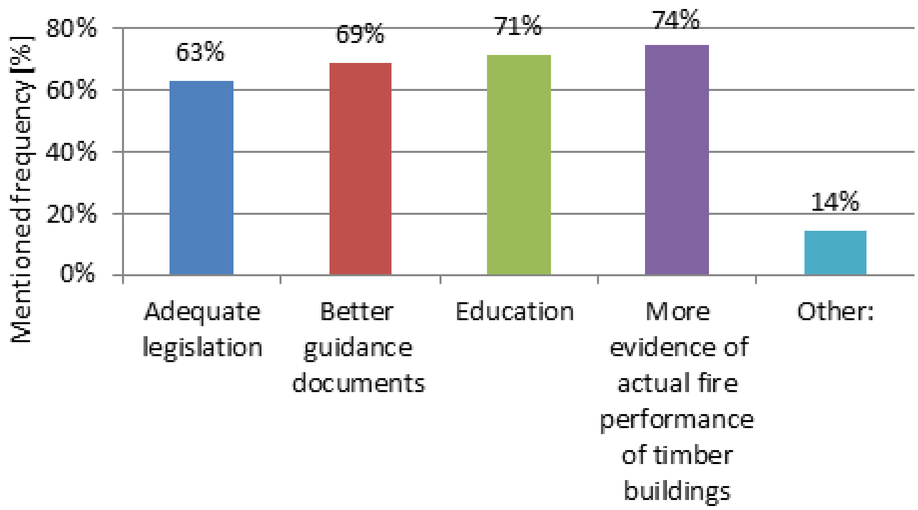


Figure 51: Knowledge gaps and obstacles for increased use of fire safety engineering

(The percentage refers to the number of answers given by the respondents (multiple answers possible). In the figure above, this leads to percentages adding up to > 100%).

Observations

- The surveyed experts indicate that diverse steps of action must be taken in order to improve fire safety design as a discipline and to increase the use of fire safety engineering as a tool.
- 60% of the experts indicate that there is room for improvement within legislation. Such as:
- Make processes more efficient.
- Adopt legislation so that it is not so much focussed on non-combustible structures (e.g. when fire resistance is asked and proven sufficient, reaction to fire shouldn't matter).
- Update EC5 for CLT.
- Reduce reaction to fire requirements.
- Make use of what is already there (CEN committee TC92).
- Develop standards that are more concise.
- 66% of the respondents say that better guidance documents are needed. For example:
- A method for overall risk assessment of wood structures as well as tools for calculation.
- The possibility to develop alternative (not prescriptive) solutions is already present, however more guidance, such as standard solutions for timber frames and a summary of worked examples is needed. This is necessary for the execution as well as for the assessment of construction works.
- Improved education is an important factor for 69% of the respondents (as seen in the results for question 37). Recommendations for improved education are:
- Document lessons learned from previous fires

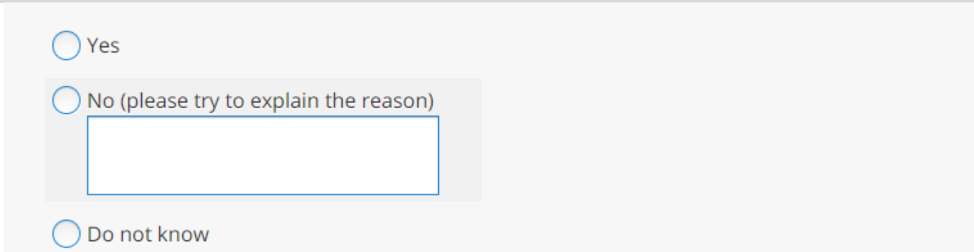
- It is stated that education in fire protection was "learning by doing" after basic education and that fire safety engineering as a discipline should be established at universities.
- Fundamental research focussing mass timber performance in fires
- Improved knowledge for all disciplines on building law as well as the behaviour of timber in fires
- A need for authorities to increase their understanding of timber construction was formulated.
- Most of the experts (71%) indicate that collecting evidence for the actual fire performance of timber is most important in the context of bridging knowledge gaps for timber buildings:
- Examples of timber building successes need to be documented.
- Information, such as statistical data from real fire incidents, is necessary so that insurers can insure confidently and appropriately timber buildings.
    - Research results need to be more publicly present and implemented in education efforts.
- There are efforts to raise actual data (FW München).
- Input from others:
- Involve fire service personnel in the design process to support acceptance and lead to coming closer to best methods for tackling fires in such buildings.
- More marketing is necessary (for timber structures).
- Acceptance needs to be gained on the side of builders that timber constructions can be as fire safe as massive constructions.
- More research is needed on auto-extinction and performance of cavity barriers.

Conclusions

- Among the mentioned obstacles and knowledge gaps, two aspects stand out:
- More research must be conducted. The following aspects should be focused on:
- Fire tests
- Analysis of real fires
- Concise, global standards are required. Maybe the creation of a global overview of "what is already there" would be a good start.

6.9.2.5 Questions regarding fire design and methods

Questions 39: Is the use of EN 1991-1-2 Annex A (parametric fire exposure) permitted within the design process of timber structures in your country?



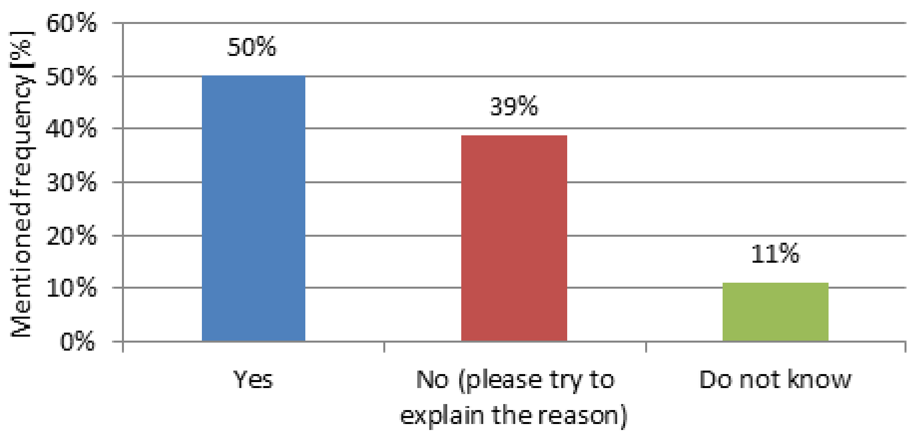


Figure 52: Acceptance of EN 1991-1-2 Annex A (parametric fire exposure) for design process of timber structures

Observations

- 50% of the surveyed experts say that parametric fire exposure according to Annex A of EN 1991-1-2 may be used to design timber structures (which is incorrect when significant surface areas are exposed).
- Those who stated that it is not generally allowed (e.g., experts from UK, Australia, Canada, and Belgium) said that its applicability would have to be proven to the concerned authorities.
- One person indicated that Annex A may only be used for low building classes, meaning when the complexity of a building is limited.
- An expert from Australia mentioned that there were other (national) standards rather used (However, there is no standard in Australia for exposed timber compartment fires. Consequently, this response is incorrect as the Australian Standard is for standard or normative fires only, not PBD).

Conclusion

- Annex A is used in many countries for designing timber structures.

- It should be noted that the Annex A of EN 1991-1-2 was explicitly not developed to be applied in the design of non-combustible structures.

Questions 40: Is the use of EN 1995-1-2 Annex A (determination of parametric temperature-time curves) permitted within the design process of timber structures in your country?

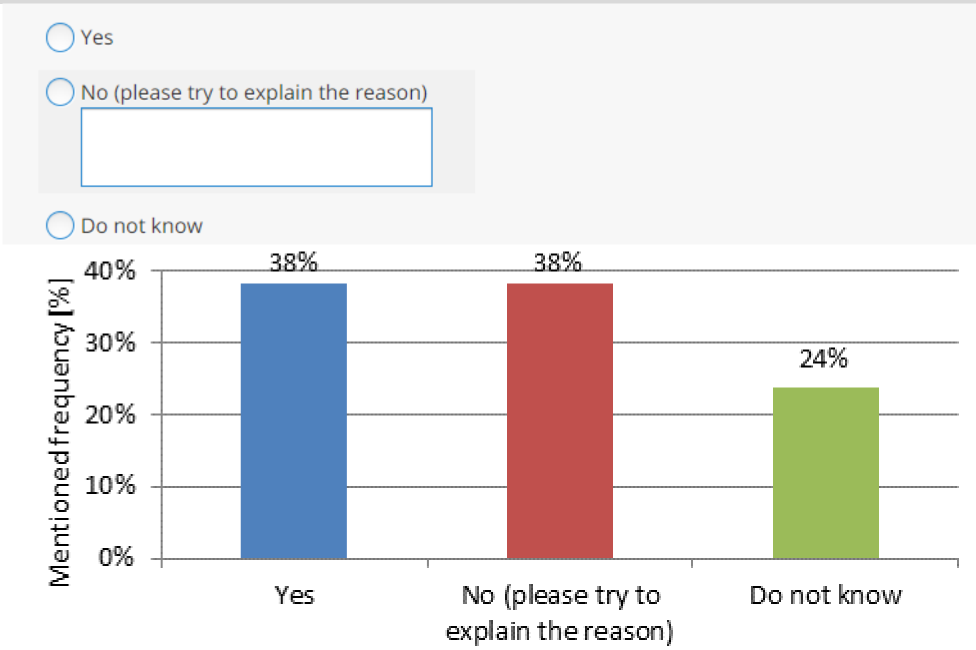


Figure 53: Acceptance of EN 1991-1-2 Annex A (determination of parametric temperature-time curves) for design process of timber structures

Observations

- The results are rather similar to those of question 39.
- Several experts expressed that they did not understand the difference in the questions, which accounts for the fact that a quarter of the participants stated that they did not know the answer.

Conclusions

- In most cases, parametric fire exposure is incorrectly believed to be generally applicable to timber members (and, general, to compartments with exposed timber).
- It should be noted there is an uncertainty regarding the applicability as well as the validity and limitations of EN1991-1-2 and the Annex EN1995-1-2 among the experts.

Questions 41: Which standard or guidance documents are used in your country as the basis for fire safe detailing within the design of timber structures?

Your answer

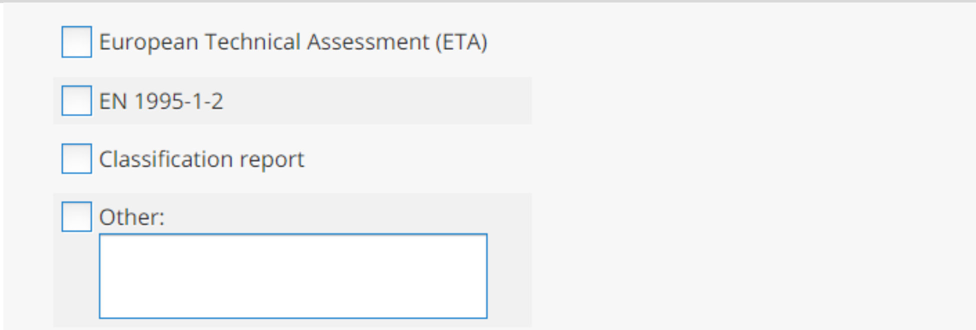
Observations

- In the context of the two questions before, the participants were asked to name the standard and guidance documents used in their countries.
- 18 experts shared the standards/ guidance documents that they typically use in their countries. Mentioned most was Eurocode 1995-1-2, which is not surprising as most experts are from Europe. Other documents cited are:
    - British standards
    - Boverket's Building Regulation (BBR) from Sweden
    - Lignum documentation from Switzerland
    - Manuals from FPInnovations Tall Wood building Guide and Mid-Rise Wood Construction Handbook, Canadian and American Wood Council, CSA-086 Wood Design Manual, CLT Handbook from North America
    - Guidance document by Puuinfo from Finland
    - AS1530, AS1684 and AS1720.1 in the National Construction Code/ Building Code from Australia
    - OIB guidance documents from Austria
    - DIN 4102-4, M-HFHHolzR (Guideline for multi-storey timber constructions) from Germany

Conclusions

- The range of available guidance documents for the fire-safe detailing within the design of timber structures is quite wide.
- There are different standards and guidance documents in each country.

Questions 42: Which methods can be used in your country to proof the fire resistance requirements of structural timber elements?


- [ ] European Technical Assessment (ETA)
- [ ] EN 1995-1-2
- [ ] Classification report
- [ ] Other:

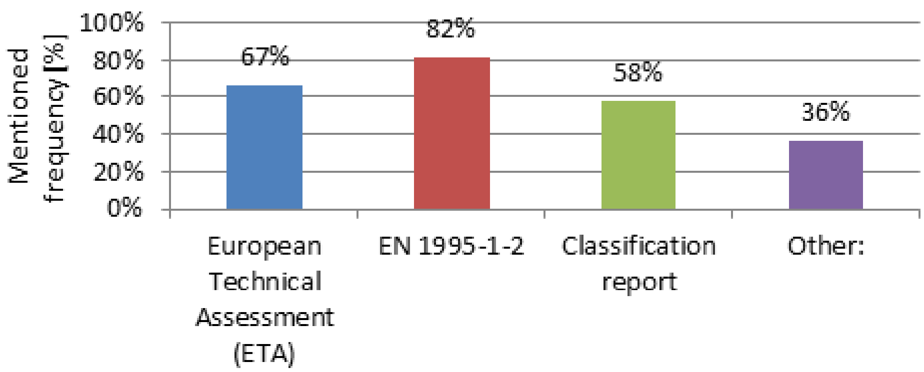


Figure 54: Available methods to proof fire resistance requirements of structural timber elements

(To prevent confusions: the percentage refers to the number of answers given by the respondents (multiple answers possible). In the figure above, this leads to percentages adding up to > 100%).

Observations

- EN1995-1-2 seems to be the favourite method to proof fire resistance requirements. 82% of the experts say that it was used in their country.
- 67% claim that ETA is used.
- 58% say that classification reports are quite regularly used as well.
- Other methods that are especially used outside of Europe include:
  - CAN/ULC-S101 (test reports or listed assembly)
  - Fire test reports in general (including certificate of conformity)
  - Lignum documentation
  - USA National Design Specification
  - International Fire Engineering Guidelines (IFEG) from Australia

NOTE: To the knowledge of the authors of this document, the mentioned document does not list or mention mass timber.

- Guidelines by the Society of Fire Protection Engineers (SFPE)

NOTE: To the knowledge of the authors of this document, the mentioned document does not list or mention mass timber.

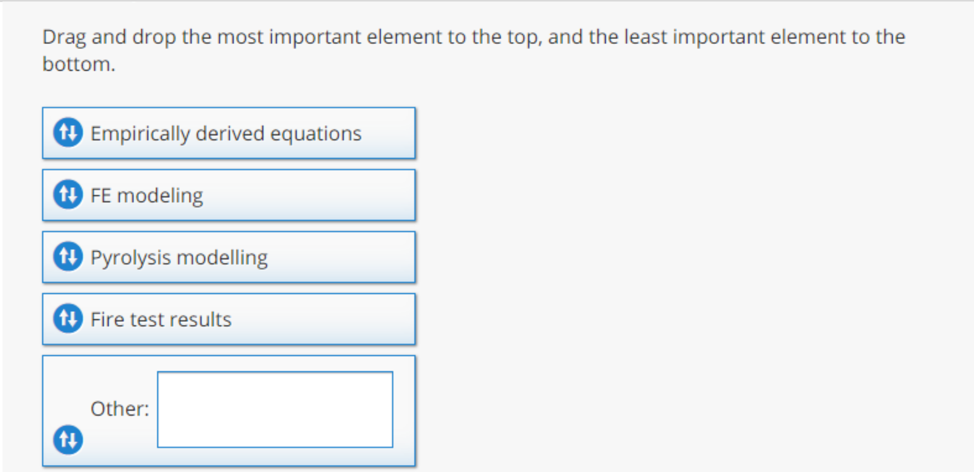
- One expert from Australia mentioned that basically any method (regardless of the country) could be used if it was proven that this is applicable to the present project.

NOTE: To the knowledge of the authors of this document, this statement is not correct.

Conclusions

- The range of available methods to proof the fire resistance of structural timber elements is quite wide.
- There are different approaches in different countries.
- As might have been expected, the EN is not used as widely outside of Europe.
- It should be noted that some guidelines that are not applicable to mass timber constructions are mentioned here (see notes above).

Questions 43: Which approaches (methods/ tools) are used in consultancy to determine the fire resistance of timber elements under non-standard fire exposure (in your country)?



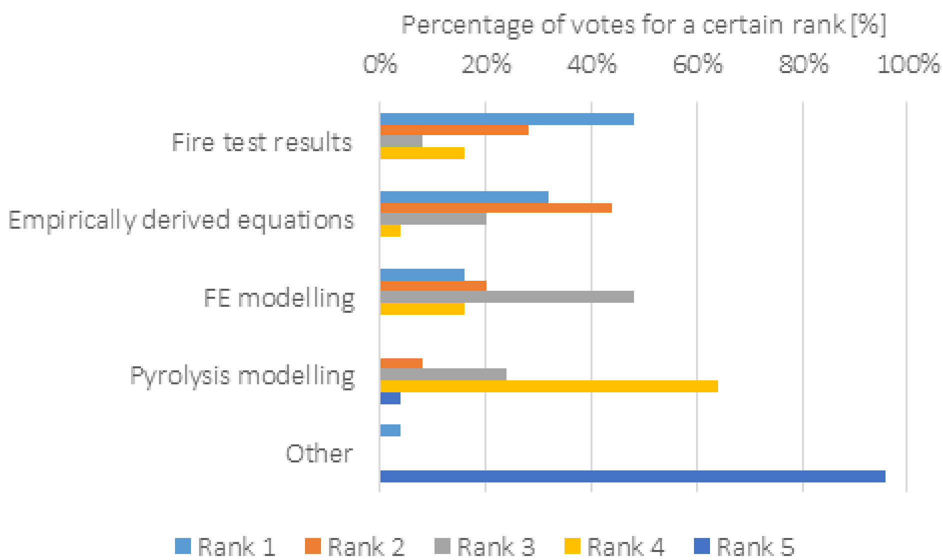


Figure 55: Relevance of approaches used in consultancy to determine fire resistance in non-standard fire exposure[2]

Observations

- 48% of the experts rank "Fire test results" as number one approach to determine the fire resistance of timber elements.
- 44% ranked "Empirically derived equations" on the second position
- 48% placed "FE Modelling" on third place and
- 64% ranked "Pyrolysis modelling" on the fourth and last place

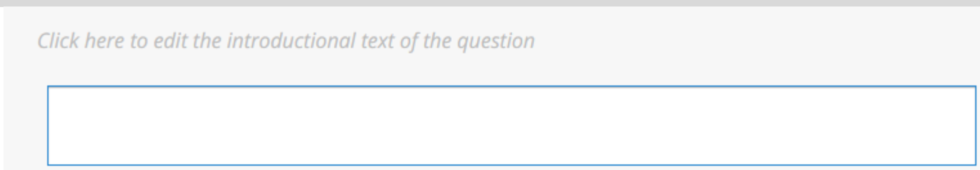
[2] The ranking was evaluated as follows: Each expert ranked the response options. It was counted, how many times each option was ranked on a certain place. The share of *rank X votes* are evaluated.

- One person from Switzerland ranked "Other" as number one and referenced the lignum documentation, indicating that this was the most relevant tool to rate the fire resistance in Switzerland.
- The type of fire test results were not defined.

Conclusions

- The results show that there might be a tendency: the easier applicable the method, the more it is used.
- In addition, it supports the notion proposed by multiple experts in Question 38 that there need to be more valid results of actual timber behaviour in fires.

Questions 44: Which approaches (methods/ tools) are used in consultancy to determine interaction between the structure and the fire dynamics (in your country)?



Observations

- 15 experts gave input regarding the tools and methods that they typically use to determine the interaction between structure and the dynamics of a fire.
- Five of them used none or did not know.
- The following methods were mentioned:
    - Finite elements (FE) modelling
    - Transient heat transfer
    - Fire Dynamics Simulator (FDS)

NOTE: To the knowledge of the authors of this document, FDS lacks proper implementation of (mass) timber. Validation is essential but currently not provided, this concerns flash-over fires, the decay phase including smouldering and glowing combustion and the exterior flaming. (Note also that the question did not ask about timber or mass timber. This method is usually used when analysing situations in which fully developed fire is not reached, such as localizes fires in large spaces.)

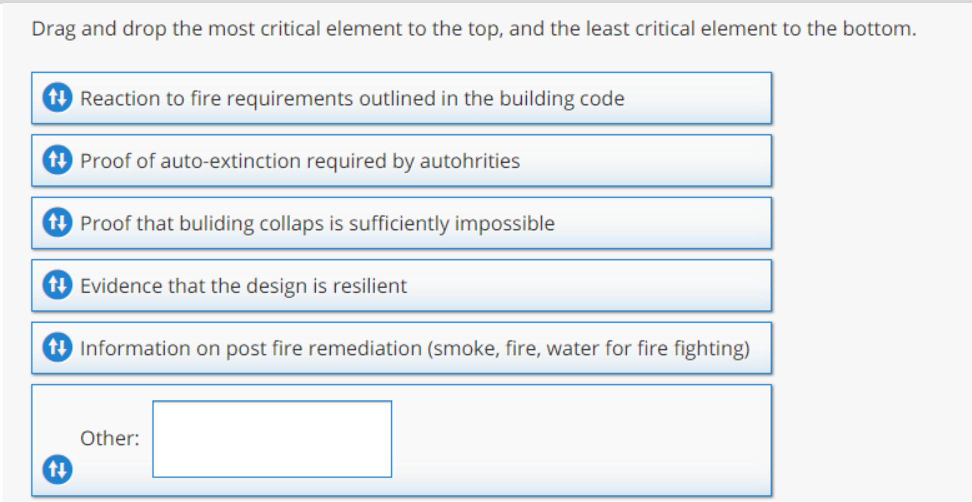
- Heat transfer models using spreadsheets
- Charring calculations

Conclusions

- The approaches seem to differ depending on the question to be investigated. However, it looks like many of the respondents were not sure about the methods and tools to be used.

- Guidance is needed to choose proper methods and tools.

Questions 45: Which aspect(s) do you see as the most critical and difficult in the application of fire safety engineering tools for timber buildings in comparison to buildings with a non-combustible structure?


Drag and drop the most critical element to the top, and the least critical element to the bottom.

- Reaction to fire requirements outlined in the building code
- Proof of auto-extinction required by autohrities
- Proof that buliding collaps is sufficiently impossible
- Evidence that the design is resilient
- Information on post fire remediation (smoke, fire, water for fire fighting)
- Other:

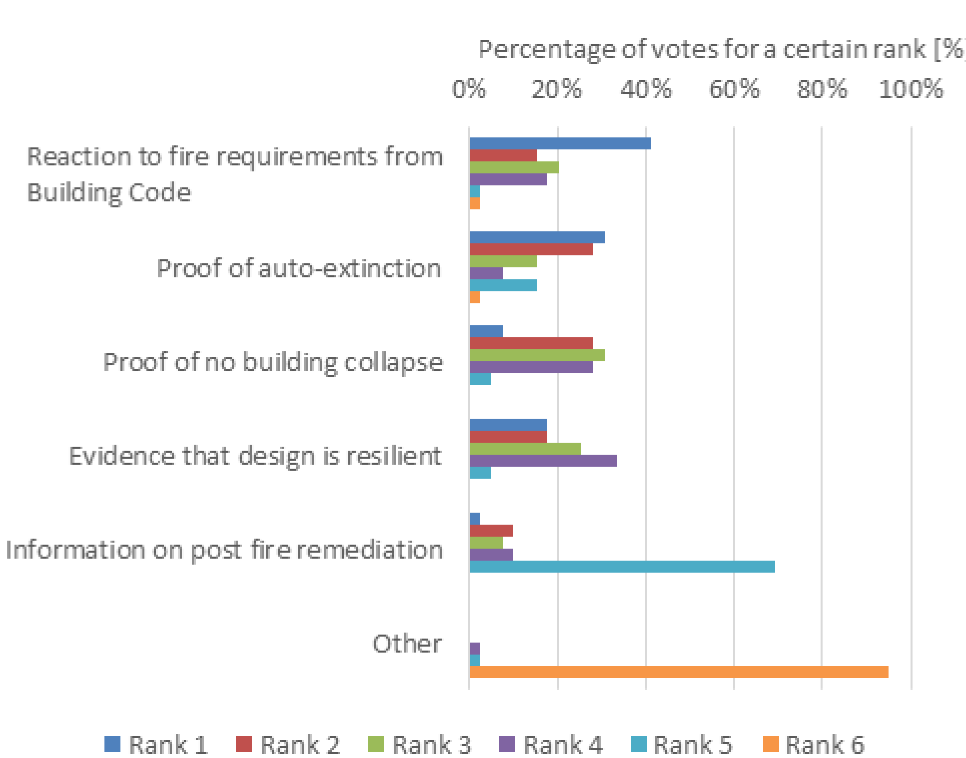


Figure 56: Difficulties in the application of fire safety engineering tools (compared to non-combustible structures)[3]

Observations

- The most critical aspect (41% placed it on rank 1) is the reaction to fire requirements from building codes (this is mentioned multiple times throughout the survey, see for example question 37).
- Almost as difficult is the proof of auto-extinction (28% placed it on rank 2).
- The proof that building collapse is sufficiently improbable ranked on 3rd place with 31% of the expert votes.
- The resilience of the design as well as information on post fire remediation are perceived as less critical.
- Mentioned several times as highly difficult under "Other" was the consideration of delamination for Cross Laminated Timber (CLT).

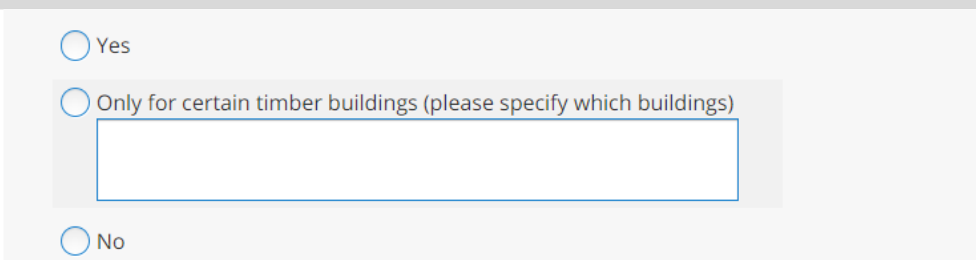
Conclusions

- The difficulty is the complexity of the topic as such as there are multiple complex physical processes (especially heat transfer within and charring or falling-off of timber members) that are challenging to model and thus not easy to deal with.
- Above that, experts identify the building code requirements for reaction to fire as more difficult to overcome than the actual physical challenges.

NOTE: In the opinion of the authors of this document, this is highly surprising as this is easily remedied by surface treatments and a standard test and classification method.

Maybe this reflects the difficulty to convince authorities on possibility to use safely visible wooded surfaces with the aim of engineering tools when authorities have used to handle only A2 materials and surfaces.

Questions 46: In your opinion, is it important to demonstrate that timber buildings reach burnout/ self-extinguishment?



[3] The ranking was evaluated as follows: Each expert ranked the response options. It was counted, how many times each option was ranked on a certain place. The share of *rank X votes* are evaluated.

Figure 57: Importance of demonstrating self-extinguishment

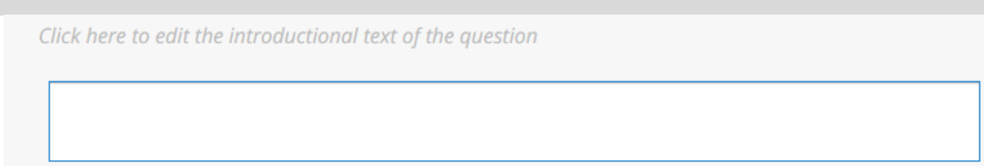
Observations

- It is important to note that the responses to this question differ considerably even among experts from the same country.
- Only 26% of the experts view the proof of self-extinguishment (auto-extinction) as important for any building. See the definition of self-extinguishment in Q47.
- An even smaller share (12%) thinks there is no need to investigate auto-extinction.
- The majority (62%) says it is important to consider burnout but only for certain buildings.
- The propositions as to which certain buildings require proof of self-extinguishment can roughly be categorized in three classes:
  - Building height
  - Building class (use and egress)
  - Neighbouring building vicinity

Conclusions

- Most respondents think it is necessary to consider auto-extinction, if danger to adjacent buildings cannot be ruled out in case of a building collapse.
- Self-extinguishment can be considered, but practical design of real buildings based on that assumption is difficult without other factors with take care of limiting fire development and damages caused if the self-extinguishment fails.

Questions 47: What is the meaning of burnout/ self-extinguishment in your country?



Observations

- Most respondents agree that burnout means that all combustible material from a compartment is burned. This is when self-extinguishment happens (no more "food" for the fire).
- Without external energy, the fire stops without fire service intervention

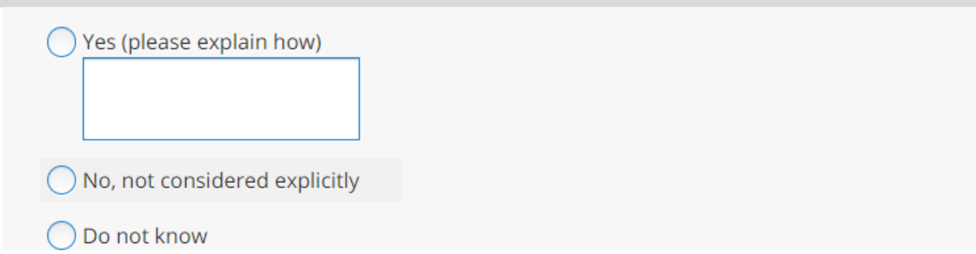
NOTE: In the opinion to the authors, the answers did not address smouldering/glowing combustion adequately.

- Usually, the given definition includes that after complete combustion, the structure is still intact and stable.
- It is mentioned multiple times that burnout / self-extinguishment implies that there was no fire service intervention.
- Two experts from Germany mention that burnout / self-extinguishment refers to a certain time frame: self-extinguishment after 90 minutes.

Conclusions

- There is no precise, widely accepted definition of burnout / self-extinguishment.
- Multiple experts criticize this as it regularly leads to discussions.

Questions 48: Do you consider smouldering/ glowing/ char layer oxidation in the fire safety design of timber buildings?


Yes (please explain how)
No, not considered explicitly
Do not know

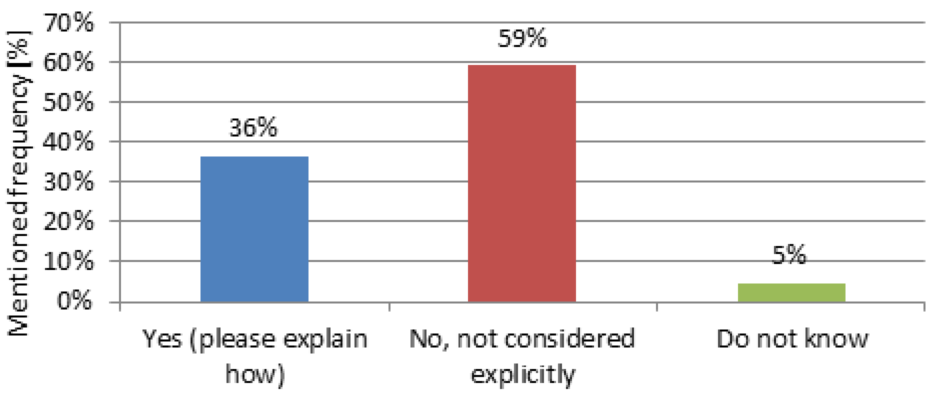


Figure 58: Consideration of smouldering in the fire design process

Observations

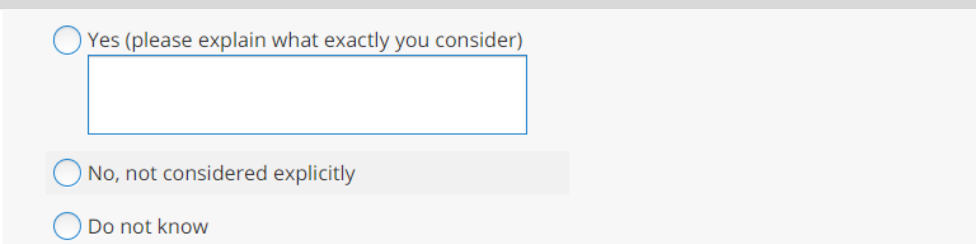
- 59% of the respondents indicate that smouldering is not considered explicitly in the fire safety design of timber buildings.

- 36% positive respondents (including experts from Singapore, Australia, Sweden, Switzerland and Germany) argue that it is implicitly considered in design (considered within temperature curve in furnace for building products). For example, it was stated that charring of wood is taken into account in the design by means of reduced burning depth or zero strength layer.

Conclusions

- Smouldering, like the smoke criterion for building elements with fire resistance (see answers to question 23), is only implicitly considered in the fire safety design of timber buildings and is not explicitly required.
- Smouldering combustion (usually most important for insulation materials) and charring (structural materials) must be kept separate.
- In the responses to question 47, it was noted that self-extinguishment must be considered in some way in certain buildings, according to most experts, while smouldering was said to be not considered. As it is physically hardly possible to consider self-extinguishment without considering smouldering, this shows again a level of uncertainty among the experts.

Questions 49: Do you consider changing and/ or different oxygen concentrations in different phases of a fire and/ or different locations in the compartment?



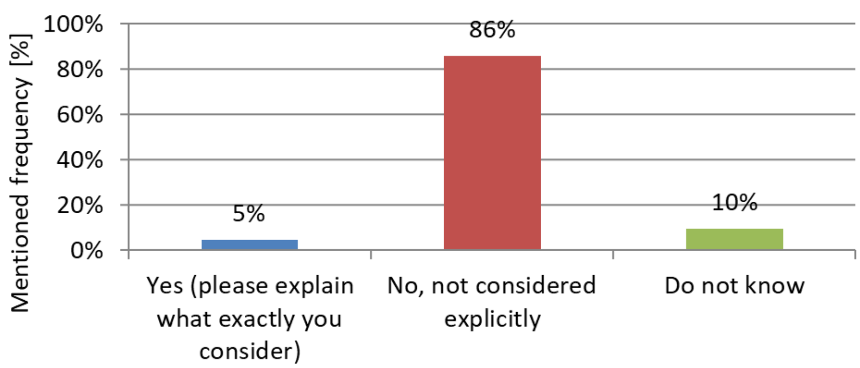


Figure 59: Consideration of different oxygen concentrations (dependent on the fire phase)

Observations

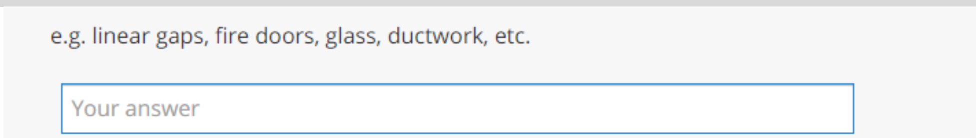
- 86% of the respondents say that different oxygen concentrations are not considered explicitly.

- One person mentions that the oxygen concentration is very different and very dependent on the location of a fire. For example: small rooms with limited ventilation vs. large rooms with broken windows vs. vertical shafts vs. tunnels, etc.

Conclusions

- Changing and different oxygen concentrations are not explicitly considered because it is too hard to account for.

Questions 50: From your point of view, which parts of a structure are most sensitive to smouldering fires?


e.g. linear gaps, fire doors, glass, ductwork, etc.

Your answer

Figure 60: Question 50 sensitivity to smouldering fires

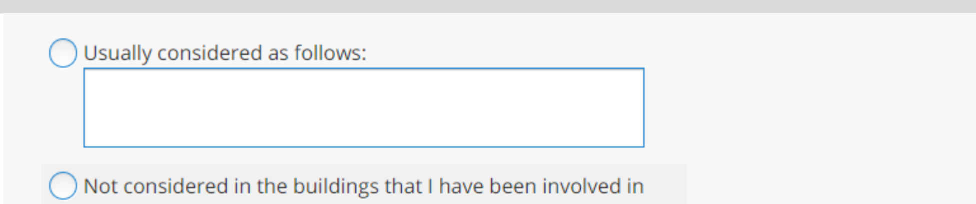
Observations

- The experts identify linear gaps, cavities, and concealed spaces as most vulnerable to smouldering fires.
- Mentioned multiple times are fire doors, intumescent building materials and ductwork.
- One respondent proposed to differentiate between
    - smouldering in the sense of the starting phase of a fire (which is critical for intumescent materials, doors and ductwork)
    - and smouldering in the meaning of post fire (where insulation material and cavities are quite vulnerable).

Conclusions

- Smouldering (as in the starting phase of a fire) is especially critical to all building elements that are dependent on intumescent components to ensure fire resistance.
- Smouldering in the decay phase, however, is much more important in the context of designing exposed timber buildings.

Questions 51: If the contribution of structural timber needs to be considered to the fuel load, how do you usually do this?


Usually considered as follows:

Not considered in the buildings that I have been involved in

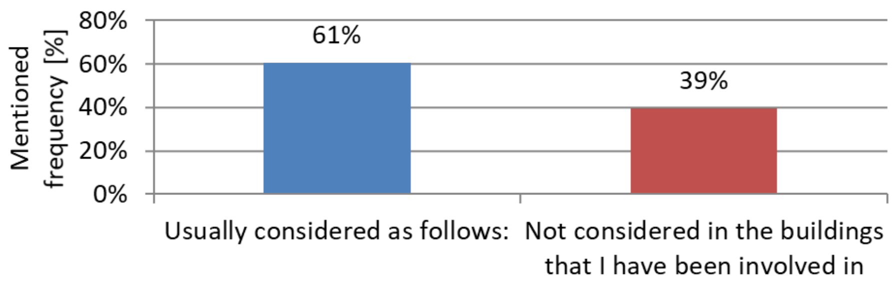


Figure 61: Consideration of structural timber as fuel load

Observations

- Most experts (61%) indicate that, if present, exposed mass timber is usually considered and added to the fuel load.
- The way of estimating the fuel load equivalent differs. The following list is derived from the experts' input:
  - Addition according to EN 1990-1-2 (most likely, the answer intended to refer to EN 1991-1-2
  - Addition to parametric fire calculations (timber is gradually added during each iteration)
  - Calculation of weight loss of timber elements
  - Estimating char depth (based on fire exposure) and determination of the respective contribution to the fire
  - In Germany, there is a way to estimate the fuel load according to the industrial buildings directive.

Conclusions

- Whether the consideration of timber as fuel load is required is decisively dependent on the respondents' involvement in prescriptive or rather performance-based projects.
- When relating the responses gathered here to those of question 31 it was found that 67% of the answers "match". Meaning that respondents who said they were rather involved in performance-based concepts usually considered timber as fuel load, while respondents who were rather involved in prescriptive concepts said they did not consider timber as fuel load. Probably because the prescriptive concepts already include fuel load in the requirements.

Questions 52: Do you have to demonstrate the fire behaviour of timber connections in your country?

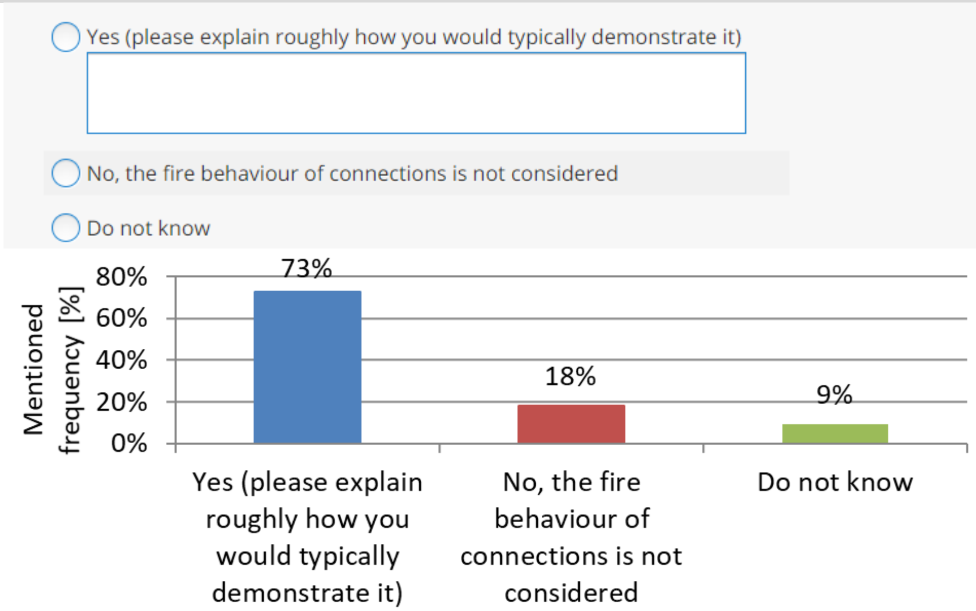


Figure 62: Fire behaviour of timber connections

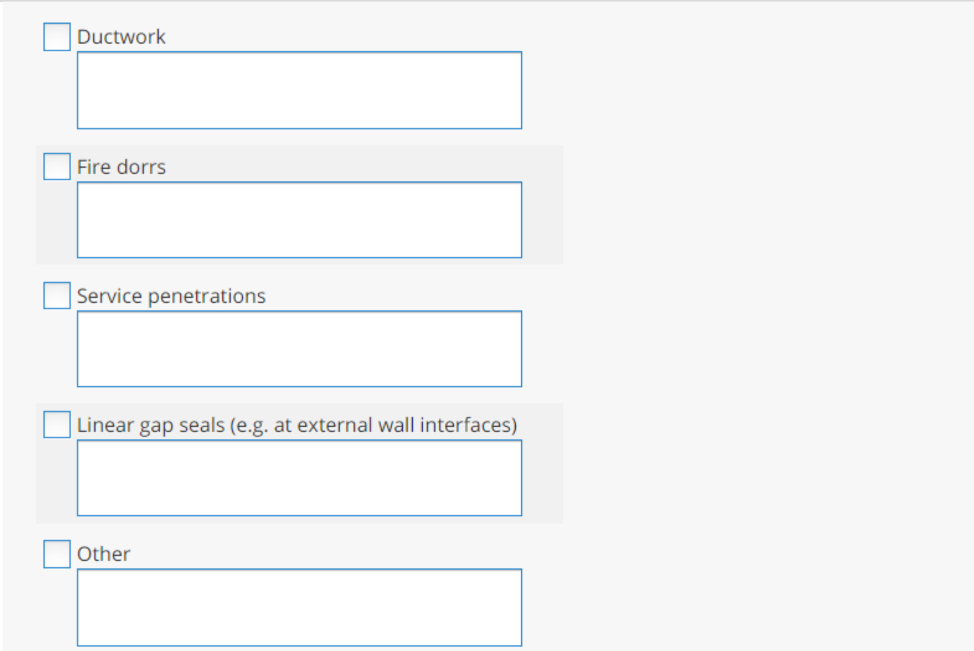
Observations

- According to most respondents (73%), the fire behaviour of timber connections must be considered in their countries.
- Multiple times, it is mentioned that Eurocode is used as a guidance document to consider the fire resistance of timber connections.
- Usually, the connections must provide the same fire resistance as the building products.
- If there are no standard procedures, tests are conducted and analysed to demonstrate the behaviour of the connections.
- To avoid expensive testing, (metal) connections are oftentimes protected by gypsum or timber.

Conclusions

- In contrast to smoke criterion, smouldering and different oxygen levels in compartments (see questions 23, 47 and 49), the fire behaviour must be considered in the fire design of timber building elements in most countries.
- However, this is mostly done implicitly via certifications and tested systems as there are no clear methods available.

Questions 53: Do you have to demonstrate the fire behaviour of interfaces between timber and other systems in your country?



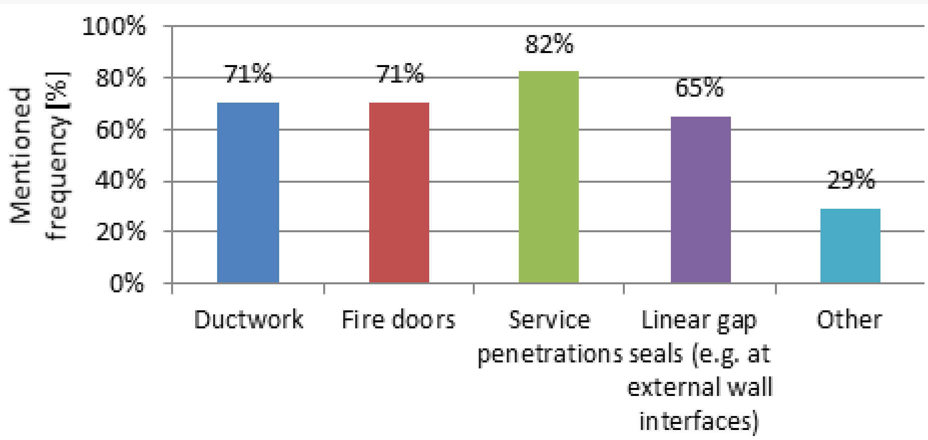


Figure 63: Necessity of demonstration of fire behaviour of different systems

Observations

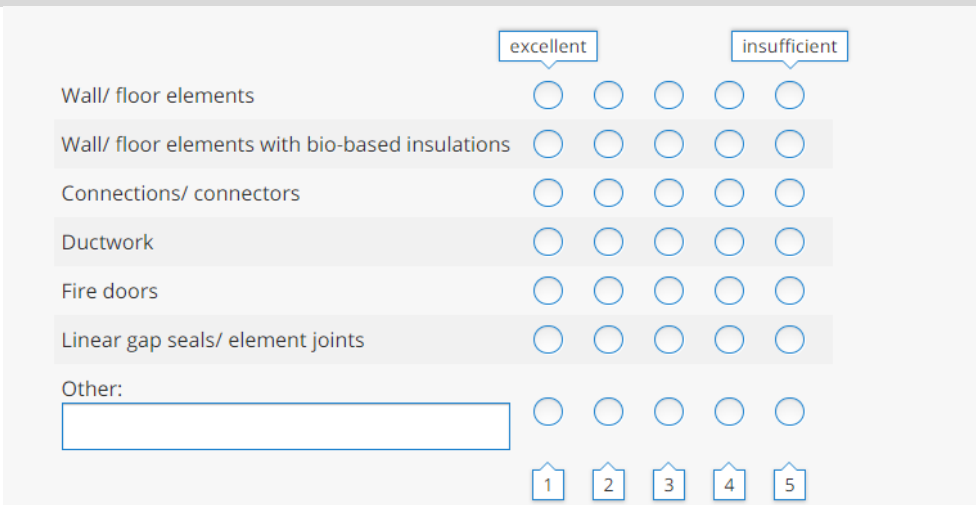
- 82% of the experts stated that it was required to demonstrate the fire behaviour between timber and service penetrations, making those the most relevant in this context.
- Interfaces with ductwork and fire doors are equally relevant, as 71% of the respondents say.
- Closely behind are linear gap seals (65%).
- In the commentaries, most respondents refer to the maxim "installed as tested".

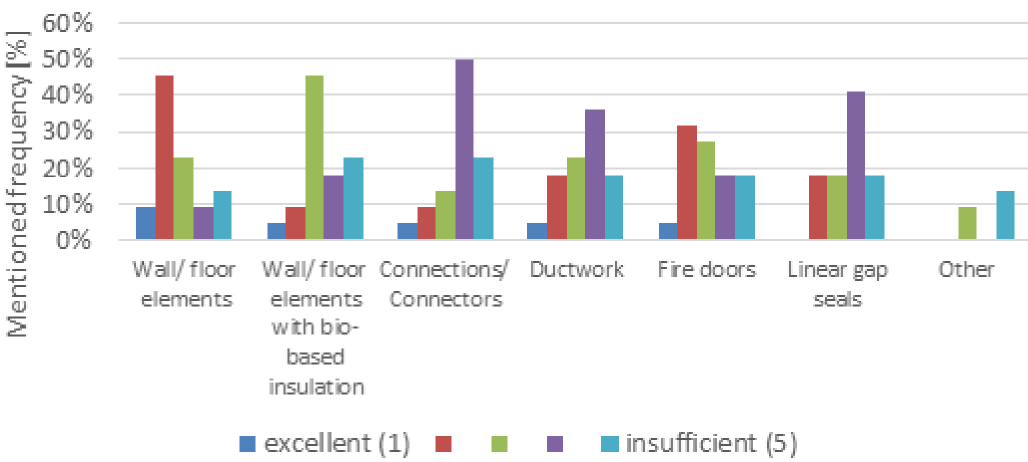
- Thus, all mentioned systems must be tested as mounted on a timber wall to be certified.
- It was also mentioned that this is required for all buildings and building elements, not exclusively for timber buildings and mass timber elements (e.g. walls and ceilings) respectively.

Conclusions

- It is usually required that building elements are installed as tested. Thus, the systems must be mounted on a building element that was tested in a furnace – regardless of the combustibility of the respective element. Problem is that still too few certifications based on testing result on timber elements.

Questions 54: How would you evaluate the existence of approval documents and standards with respect to the proof of fire resistance for following products?





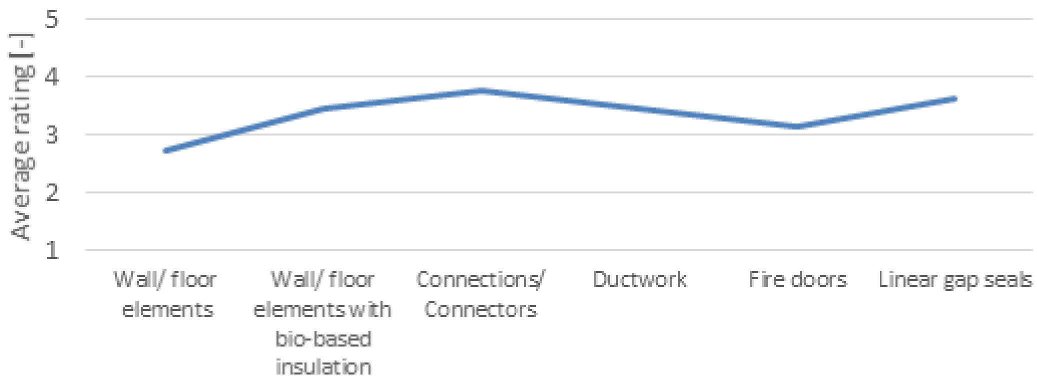


Figure 64: Availability of approval documents/ standards for different building products

Observations

- The availability/ quality of approval documents and standards for the different depicted products is seen as not sufficient.
- The only product for which supposedly sufficient documents are available are wall and floor elements with an average rating of 2.7 (1 = excellent, 5 = insufficient).
- For connections, the average is 3.8 and thus, according to the respondents, hardly sufficient. This point should be compared to Q.52.
- In the input field for other, cavity barriers and interfaces of timber walls and floors with external facades were mentioned.

Conclusions

- As already mentioned in responses to other questions, an increase testing is needed to raise knowledge about actual fire behaviour of timber buildings, building elements, and interfaces with different systems.

6.10 Summary of results

78 experts from 21 different countries responded to the survey (38 people filled out all 54 questions). The experts have an average of 16 years of experience in their respective field of work; 85% of respondents have work experience more than five years.

The use of timber in construction has changed over the last couple of years:

- The share of timber buildings has generally increased during the past 5 years (Q6).
- The share of timber buildings decreases with increasing building height (Q4).
- Smaller buildings, especially residential buildings, are more likely to be constructed from timber (Q5).

Recent adjustments to regulations regarding timber were observed in most countries (Q7). The adjustments were largely but not entirely favourable to the use of wood in building projects.

Regulations are different in different countries. This could be explained by different building traditions, regulations and practice.

Legislation and approvals are – among building cost – seen as some of the most substantial obstacles in the use of timber (Q9). In the context of legislation, especially challenging are requirements that concern:

The reaction to fire of fire-resistant building elements formulated in most building codes (Q19/ Q45).

The limitation of visible, combustible structures that exist in most countries (Q20).

The proof of burnout without building collapse that is required in some countries (Q45) .

To compensate for the combustibility of the structure, a combination of structural and technical measures must be applied (Q28). In addition, the following aspects impede the application of timber structures in high-rise building projects (Q35):

- Increased fire resistance requirements
- A lack of prescriptive solutions for timber projects
- A lack of general familiarity with timber projects

A perception exists that projects involving timber become increasingly more complex with growing building height (Q34). This is schematically displayed in Figure 61.

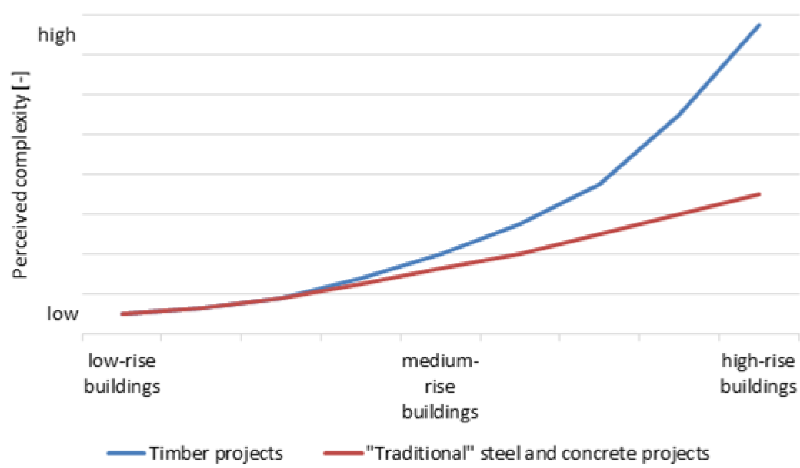


Figure 65: Schematic comparison of the perceived complexity of timber and "traditional" building projects

Most experts state that the combustibility of structures plays only a minor role in the determination of evacuation strategies (Q17), sprinkler specifications (Q25) and other requirements for technical fire protection measures.

The increased complexity of timber projects (Q31), implies that the stakeholders need special qualifications to deal with the challenges. However, countries that explicitly require engineers and architects working on timber projects to have special qualifications are the vast minority (Q32).

Quality control measures are usually required for all high-rise buildings with no difference between timber and non-timber (Q33), which contradicts the fact that as timber buildings get taller, they are considered to be more complex (see Figure 61).

Figure 62 shows that, the competence and education of stakeholders is seen as below average rating (Q36 / 37).

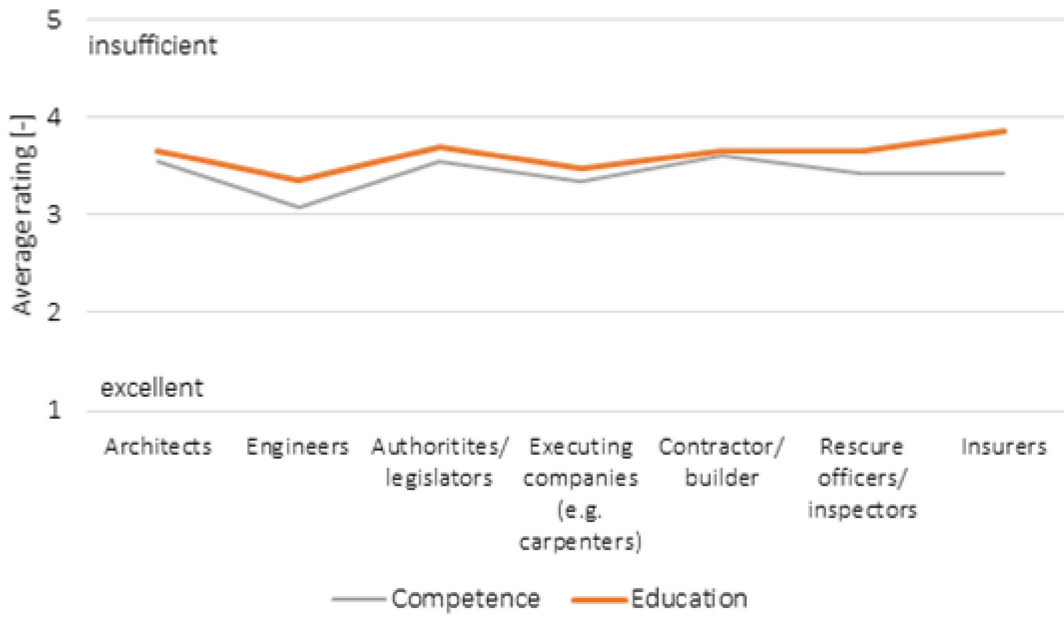


Figure 64: Comparison of education and competence of different stakeholders (1 = excellent, 5 = insufficient) . It should be noted, that the participants were mainly engineers.

The required evidence for fire resistance and other characteristics relevant to the fire performance of timber structures are provided using a variety of standards and guidance documents (Q39 / 40 / 41 / 42 / 43). EN 1991-1-2 (Annex A) is widely used.

In general, the availability or quality of approval documents for various systems in the context of timber construction projects is seen as insufficient, as shown in Figure 65. (Q54)

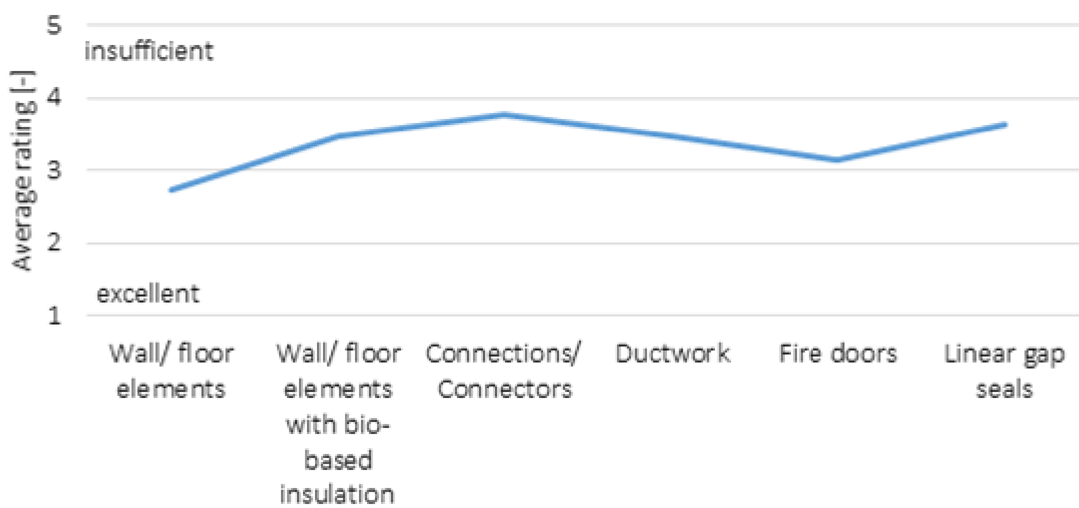


Figure 65: Availability of approval documents for different building products (1 = excellent, 5 = insufficient)

The survey results shows that the research hypotheses introduced in 8.2 are true:

1) The requirements for evidence to fulfil certain fire safety goals is dependent on the country considered (e.g. fire resistance of timber members, the fire resistance of connections, self-extinguishment of timber compartments, etc.)
2) The methods to deliver the evidence are hardly defined. Thus, the respondents name a vast variety of methods and tools when asked for the basis of fire-safe detailing. It should be noted that a number of those tools being applied outside their range of applicability.
3) Engineers often lack the tools or qualification to deliver the required evidence. There is high level of uncertainty regarding the applicability and the validity of documents or methods and tools.

6.11 Challenges

There are apparently several challenges in the use of timber in buildings. The most challenging and problematic aspects are:

- Reaction to fire requirements in general
- The limitation of visible combustible surfaces
- Lacking approval documents
- Lacking guidance documents
- Lacking competence and education (on all sides, building as well as approval and even with the respondents)
- Lacking knowledge regarding the applicability and limitations of existing guidance documents
- Lacking familiarity with the product

Increased fire resistance requirements impede the application of timber structures in high-rise building projects (Q35). There is limited overview about the use of sprinklers and increased performance and reliability requirements.

Challenges that despite their important role in the fire dynamics of wooden elements are not or only implicitly considered in the design process:

- Smouldering / glowing and char layer oxidation (Q48)
- Changing oxygen concentrations during a fire within a compartment (Q49)

There are challenges which, even though there is no or no sufficient guidance available, must be considered in the fire design process in various countries. These challenges include:

- The proof of burnout / self-extinguishment (Q46), which is, according to most experts, only relevant for certain buildings and situations. Although, there is no commonly agreed upon definition of burnout or self-extinguishment, the term generally means that after all combustible material is burned the structure is still intact. (Q47)
- In the context of legislation, a challenging requirement concerns the proof of burnout without building collapse that is required in some countries (Q45). It is not enough to consider only burnout. The non-collapse criteria can be also given. In this probability approach also sprinklers are taken account but not necessarily the fire brigade intervention.

- The estimation of a fuel load equivalent that visible mass timber structures add to the compartment fuel load. The estimation usually involves an iterative approach using software like FDS (Q51). However, FDS can only be used for timber structures, if highly detailed but significant changes are made. It seems like FDS is oftentimes not used correctly.
- Demonstrating the fire resistance of timber connections (Q52),which is oftentimes avoided by merely protecting (encapsulating) the connections in the first place.
- Demonstrating the fire behaviour of timber with other systems such as ductwork, fire doors, service penetrations, linear gap seals and others (Q53)

A common perception that construction with wood comprises a higher risk than construction with concrete and steel. The lacking comprehension of issues connected to fire design of mass timber buildings might in part lead to a skewed risk perception because, risks that are un- or badly known are rather overestimated (cf. Covello 2001 S. 385, Fischhoff 1978 S. 133, Walaski 2011 S.51).

There is a lack of reliable data regarding the specific fire performance of timber building products, especially mass timber elements. Challenges are the following:

- Physical challenges (e.g. modelling and calculating specific processes like changing oxygen conditions, smouldering, delamination mechanisms and determining fuel load equivalents for mass timber)
- Uncertainty about actual fire behaviour that cause the process of developing accepted methods and tools to calculate fire resistance and other relevant characteristics to be lengthy and elaborate.
- Evaluating the extent to which it is appropriate to transfer existing tools and methods (for other building products such as steel and concrete) to wood structures is difficult

Besides the need for additional data and research about compartment fires involving timber structures and or mass timber, there is a need for extensive additional communication within the fire design community. A wide variability of knowledge exists amongst the experts. An extensive additional communication could help to ensure that there is a common understanding about the gathered data and what it means for fire safety design.

The exchange and availability of standards, guidance, approval documents, fire test data and research is not efficient amongst the experts and countries. There are vast national differences regarding the typically used documents. In many cases, guidance that is not valid for exposed mass timber is used for fire safety design. This needs to be avoided.

In the search for solutions to the problems and challenges described, it is important as well as challenging to consider different perspectives:

Merely proposing to remove legislative obstacles that limit the use of timber in any way is neither desirable nor favourable for the building industry.

Suggesting that approvals and permits for mass timber constructions should be granted more easily does not solve the problem, as in the worst case this could lead to large fire outcomes that are detrimental to mass timber buildings on a global scale.

6.12 Research needs and outlook

The objective should be to redefine regulations to make building with wood easier (and thus cheaper and more attractive) without lowering the current standard of safety.

There are three major areas that could be enhanced in order to improve fire safety design efficiently:

1. Research and testing
2. Communication and exchange
3. Education

1) Research and testing

Continuous increased and targeted research efforts regarding the fire performance of timber building products and mass timber compartments will contribute to improve guidance for fire safety design of timber structures.

More research and fire testing are needed to understand the influence of timber on fire dynamics of non-standard fires. Currently, design specifications for structural beams and columns are applied and widely accepted (e.g., National Design Specifications for Wood Constructions in America or the Lignum documentation in Switzerland). However, these specifications are mainly related to structural elements like columns or beams and based on charring rates under standard fire exposure.

Important areas for further research and testing are the fire design of timber floor elements (consideration of fire exposure only from beneath or from beneath and above, see Q13), fire design of external walls (consideration of fire exposure only from room side or from room side and outside, see Q14), and the investigation of the interface between timber building elements and other systems (e.g. connections, service penetrations and ductwork, see Q52 and Q54).

There is a need to clarify the definition of self-extinguishment in timber compartments and the need to prove it (Q47).

The research and testing efforts could be collected in a global database for fire tests and simulation approaches to:

- Profit from results gathered from tests all over the world.
- Quickly identify knowledge gaps and chose test set-ups in a way that the gaps are bridged.

2) Communication and exchange

The applicability of existing standards, methods and tools need to be discussed thoroughly. There are significant gaps among the experts when it comes to understanding the validity of present standards in the design process for timber structures. For example:

Applying parametric curves from EN 1991-1-2 to timber buildings or using Annex A of EN 1995-1-2, see Q39 and Q40).

Applying tools like FDS to combustible compartments without the necessary changes to the software (see Q44 and Q51).

A global set of guidance would be favourable. As there seem to be numerous national guidance documents, a promising approach might include cumulating and comparing national guidance documents and approval strategies. This could help to determine the state of the art (see Q38).

Extensive communication and exchange could help to develop a common understanding about the limitations of existing guidance.

3) Education

The education and competence of the stakeholders is rated below average expectations (Q36 / 37), Figure 64.

Among others, degree programmes such as the International M.Sc. in Fire Safety Engineering (University of Edinburgh, Ghent University and Lund University) or the MAS Fire Safety Engineering (ETH Zurich) show that there already are efforts to promote fire safety as individual discipline. However, these efforts need to be enhanced by:

- Developing targeted programs to prepare engineers and architects for the challenges of designing fire safe buildings.
- Including fire safe design of timber buildings in the curriculums of structural engineers.

There are obvious gaps in knowledge among experts need to be addressed:

- The complexity of the fire dynamics of exposed mass timber is underestimated. Only a small handful of researchers and engineers can do this compactly and for limited scenarios. An incompetence leads to poor engineering and poor approvals that could result in a large fire outcome that is detrimental to mass timber buildings globally.
- Similar lacks as listed for engineers may be found in firefighting education and –tactics.

7 Development of a database

7.1 General

The aim of this section is to describe the created database that allows the collection of national and international existing fire tests results of timber structures in a systematically manner.

Based on a comprehensive analysis (Annex D) of the feasibility of a web based online solution of such a database, it was decided that in the context of this pre-project to focus on the structure and possible contents of such a database as well as their implementation in principle.

A professional online database service can only be realised in a further project. In the pre-project the database structure, links and the general content was created, visualised and made available via a Microsoft Access database. Microsoft Access enables establishing a full database and a future transferred to each professional online database system. Even if Microsoft Access is not intended to have a user specific online access, a full workable database was established including the predefinition of type of each input variable or for which specific data filter functions may helpful and needed. The data and metadata can be exported via CSV to any other database and imported in the future.

7.2 Content of the database

Typically, the fire tests are carried out with different objectives to give answers to specific knowledge gaps, often to confirm national perspectives or to allow the use of timber in a specific application. Even if these tests are known and cited in the literature, a general overview of the conducted tests is missing. A compilation of the existing test setups and the test results may be an essential step to allow for a worldwide interpretation and use of such data and helps to avoid unnecessary testing.

Within the database developed in this project, the main focus was on the following four groups of tests:

1. Compartment Fire Tests (indicated as type CO),
2. Façade Fire Tests (indicated as type FA),
3. Furnace Tests of Assemblies (indicated as type FU),
4. Fire Tests for Joints (indicated as type JO).

The homepage of the developed database is shown in Figure 66.

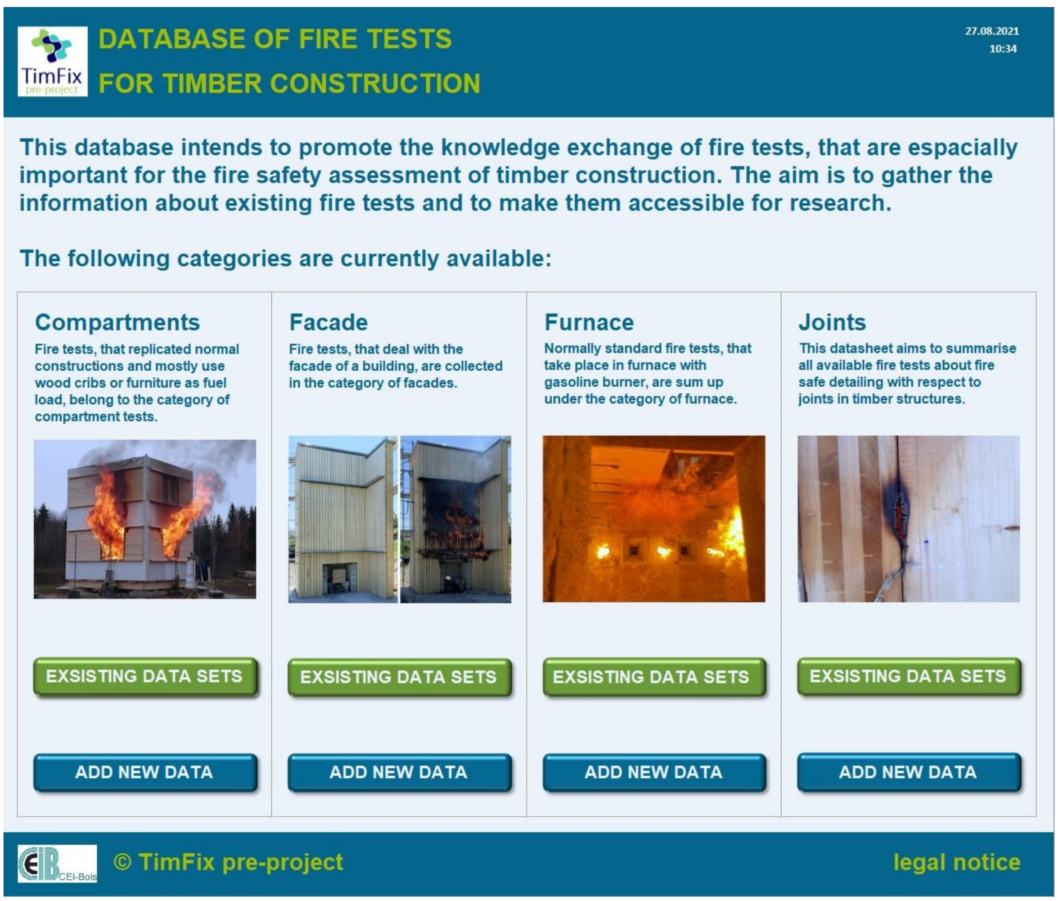


Figure 66: *boarding page for input of the TimFix database.*

An extension to other specific test results or categories, such as connections or service installations for timber structures is always possible.

In addition to the input of new data, the system also allows the view of already existing data sets in all categories, as shown in Figure 66. Further, the tabulated data can be filtered by specific attributes as shown in Figure 67.

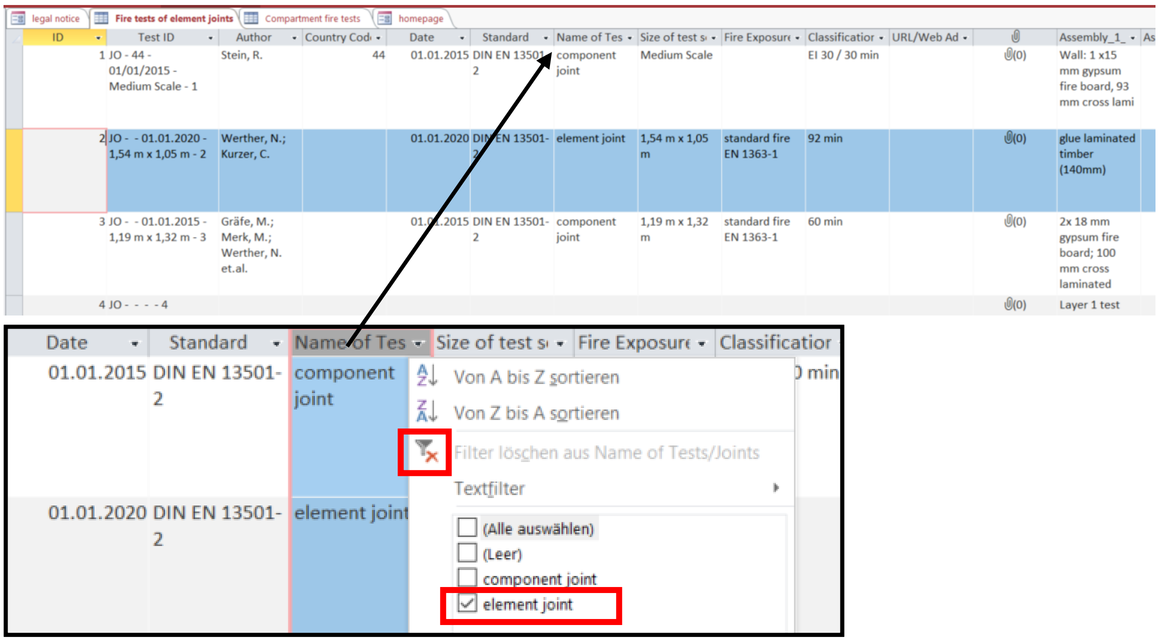


Figure 67: database structure of the listed data for the category “fire tests for joints” and option to filter for specific attributes.

7.3 Setup and content of the database and datasheets

The following sections give an overview of the content of the database and datasheets for the each category.

Each implemented data set is assigned to a unique test ID, which serves as a general identifier. This automatically generated specific test ID helps to avoid duplication of data and thus helps to uniquely assign the data sets. This test ID is composed of the type of test (e.g. CO, FA, FO, JO), the international country code of the country where the test was conducted, the date of the test and a reference to the size or type of exposure.

In order to guarantee the unambiguous assignment within the data sheets and for a clear navigation, explanations and navigation aids were integrated into the each data sheet and at the queried items, as shown exemplarily in Figure 68.

Figure 68: measures for a clear navigation in the datasheets (example)

Since, despite the four categories, even in one category there can be strongly varying quality of information about the test. Each data set contains the possibility to upload supporting documents like pictures, test data, test reports or URL links.

7.3.1 Compartment fire tests (CO)

All tests that replicated normal constructions and mostly use wood cribs or furniture as the fuel load, belong to the category of compartment tests and can be added to that category in the database. The data sheet is structured in the sections “Test Data” and “Results”. These ask for the following information.

Test Data (as shown in Figure 69):

This category includes the general information and the aim, the dimension and setup of the assemblies of the fire compartment but also the openings and ventilations, fire load and the type of extinguishing.

Results (as shown in Figure 69):

Includes the test results, information about the occurrence of flashover, charring depth, protection ability of the linings, additional measurements and further additional comments about the results.

Test Data | Results

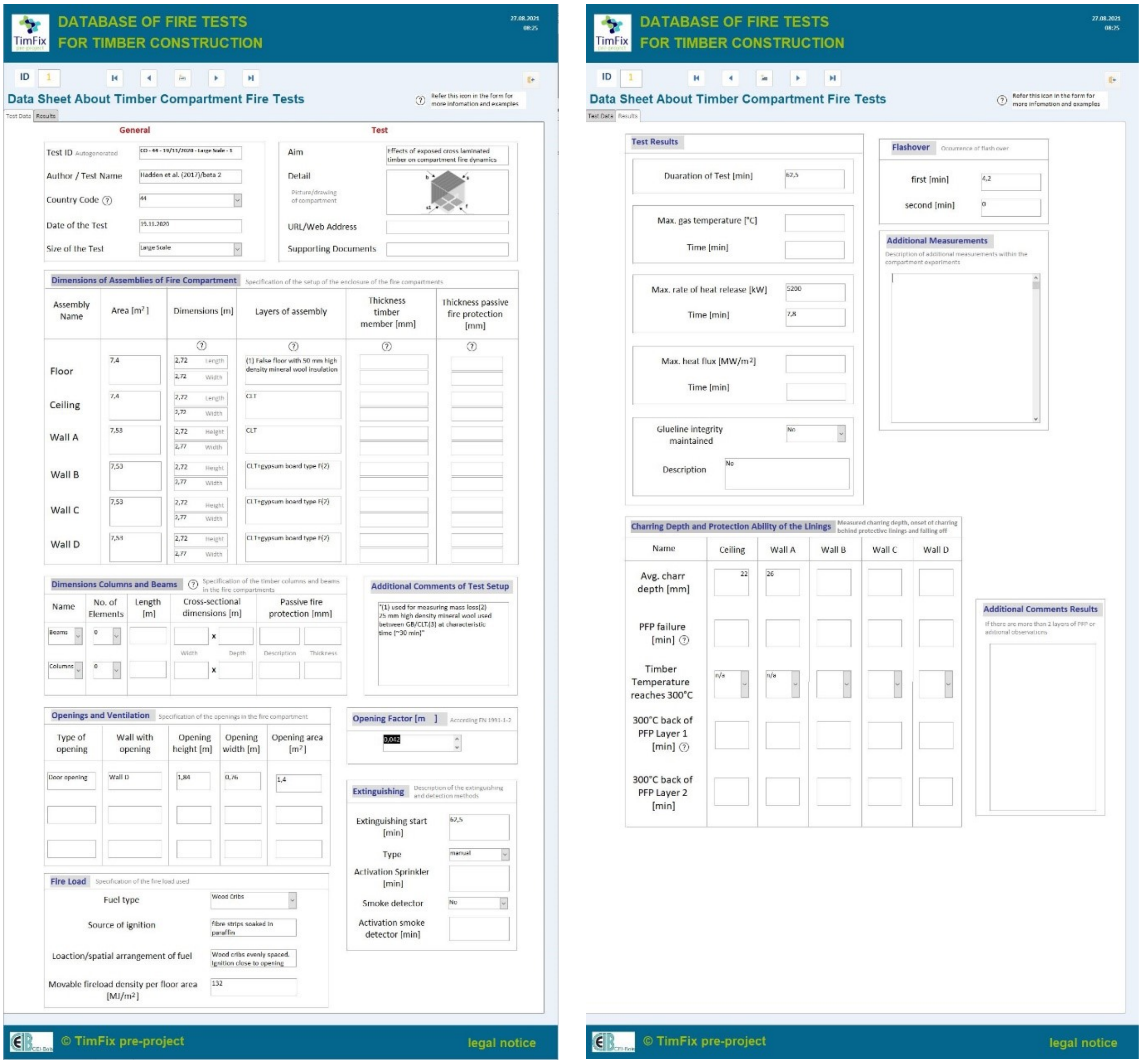


Figure 69: input mask in MS Access for the test data of compartment tests

7.3.2 Façade fire tests (FA)

All existing fire tests that deal with the facade of a building are collected in the category of facades.

The data sheet is structured in the sections “Test Data” “Fire Exposure” and “Measurements and Results”. These sections ask for the following information.

Test Data:

This category includes general information, the design and dimension of the tested specimen, the openings design, information about the material and setup of the façade and information and description of existing fire stops.

Fire Exposure:

Describes the fire source with type of fuel and heat release but also includes information about the fire extinction methods in the conducted tests.

Measurements and Results:

Includes the information about the conducted measurements during the tests, like the overall heat release rate, gas temperatures and heat flux but also measured temperatures in the specimens. Further information about the falling of part, debris or droplets can be assigned to each test.

An image of the datasheet is given in the Annex D.

7.3.3 Furnace tests of assemblies (FU)

Standard fire tests, that take place in the furnace with gasoline burner, are sum up under the category of furnace. Alternative fuels are considered.

The data sheet is structured in the sections “Test Data” “Loading”, “Measurements” and “Extinguishing and Results”. These sections ask for the following information.

Test Data:

Summarizes the general information about the test, the specimen description and setup, the fire characteristic and exposure and further includes information about the used furnace.

Loading:

Describes the external loading type (hydraulics or dead load), its application (linear load or point load), its control (displacement or force controlled) and the eventually performed changes of the loads (e.g. increase after a certain time). Further, the failure criteria are included.

Measurements*:*

This category includes information about the conducted measurements for the temperature and gas concentration, including the type of used measurement device. Further relevant observations from the tests can be implemented.

Extinguishing and Results:

Includes information about the termination of the test, measured char depth and/or mass loss.

An image of the datasheet is given in the Annex D.

7.3.4 Fire tests for joints (JO):

This category of tests aims to summaries all the available fire tests about fire safe detailing with respect to joints in timber structures.

The data sheet is structured in the sections “Test Data”, “Measurements” and “Results”. These sections ask for the following information.

Test Data:

Summaries the general information about the test, the specimen description and setup of the assemblies forming the joint. Further description of the joint and potential sealing measures is given.

Measurements*:*

This category summaries information about the conducted measurements for temperature, leakage or gas analysis. Further information about the used measurement device is queried.

Results:

Includes information about the failure time of integrity at the joint, measured critical temperatures, gas concentration and allows for additional comments and observation.

An image of the datasheet is given in the Annex D.

7.4 Other databases available and under development

There are various databases available, which consider some of the listed characteristics. These are either well established, under development or have been left without maintenance.

A frequently used database of construction based on test results is www.dataholz.com (Austrian database), which was recently elevated to a German-Austrian level by means of a longer certification process in Germany, the result is www.dataholz.eu.

A database essentially needed for computer fluid dynamics validation (e.g. FDS) is provided and maintained by NFPA, who is the developer of FDS. The database contains numerous entries used for the setup of compartment and buildings to predict the fire development. (https://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Fire-Safety-Challenges-of-Tall-Wood-Buildings-Phase-2, https://www.sfpe.org/publications/magazine/fpeextra/fpeextra2021/fpeextraissue63).

Currently, the STA "mass timber project" is developing a database for compartment tests where structural timber is (partly) involved in the fire dynamics. Funding of the database after the creation is not defined (yet).

In the US there is a glulam to glulam fire testing database underway. It is proprietary testing though and that is the problem with some of the testing. But once the database is available, basic information can still be recorded.

Exterior use of timber is currently not implemented in a database as incidents are rare. However, a common database should be established, a first version is available on Wikipedia (LINK).Façade fire data is included in the EU Fire Data project EUFireStat. A connection to the database should be implemented. A similar database is US Fire Incident data. In Finkland, a database is available (https://prontonet.fi/Pronto3/online3/OnlineTilastot.htm).

Beside the failure reports about fires and fire extinguishment work it would be also essential to evaluate the factors that lead to success stories. Unfortunately, this is not properly reflected in failure-focused databases of fire accidents.

8 Gap analysis and design strategies

8.1 General

Various gap analysis documents are available with respect to the fire design of structural timber (e.g. Gerard et al., 2013; Brandon and Östman, 2016). In the following, a gap analysis is presented based on WP2, WP3 and WP4 of this TimFix pre-project. In contrast to previous gap analyses, the gaps are related to building categories, distinguished by certain building properties, such as degree of complexity, consequence class, or the building height.

~~As important element of an action plan required steps to address the gaps are suggested.~~ The final action plan shows the recommended steps to address the gaps.

For each recommended action, the following is included:

- The time period for the action is recommended, where the recommendations will be categorised into short-term (within 1 or 2 years), middle term (within 5 years), or long term (within ten years). Argumentation of the recommended time period will be provided in this document.

- If needed, a recommendation to perform the action simultaneously with other actions if they are interlinked.

The suggested actions of this report will allow national or international research or industry projects to systematically fill the gaps to achieve the related goals.

8.1.1 Building types

In this report proposed categories of building types are not based on building regulations as significant regional and international differences exist. Some definitions deviate between regions and nations. A further specification of building categories is foreseen for the main project that is to follow up the pre-study of this report. In Eurocode, EN 1990 (CEN 2002) a rough classification using three consequence classes exist, as shown in Table 1.

Table 1: Consequence classes and example in line with Eurocode [CEN 2002].

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

8.1.2 Expected European classification for buildings and construction

Already today consequence classes, more specific than the ones specified in Table 1, are typically used by regulators, e.g in the UK where further division of CC2 can be observed. In the proposal for the revision of Eurocode (published between 2025 and 2027), the concept was refined and five consequence classes as well as sensitivity classes are suggested, see Table 2.

Table 2: Consequence classes proposed in Eurocode [Palma et al. 2019].

Consequence class	Indicative qualification of consequences	
	Loss of human life or personal injury [a]	Economic, social or environmental consequences [a]
CC0 – Lowest	Very low	Insignificant
CC1 – Lower	Low	Small
CC2 – Normal	Medium	Considerable
CC3 – Higher	High	Very great
CC4 – Highest	Extreme	Huge

[a] The consequence class is chosen based on the more severe of these two columns.

CC4 buildings/structures are nuclear structures, buildings containing significant amounts of hazardous substances, geotechnical constructions whose integrity is of vital importance for civil protection, e.g. underground power plants, road/railway embankments with fundamental role in the event of natural disasters, earth dams connected to aqueducts and energy plants, tailing dams and earth dams with extreme consequences upon failure (very high risk exposure), etc. and are therefore not often considered for structural timber.

8.1.3 Building classification in this document

In the following sections, building types related to the occupancy and building height are categorized as shown in Table 3. Further, the building types consider the building technique, i.e. if they are built as timber frame assemblies (**TFA**) or from mass timber products such as solid timber panels or cross-laminated timber (**MTP**). Linear elements such as glulam beams may be used together with both types as post and beam construction (**PBC**). CC0 is not further considered as these buildings are not expected to be designed for fire safety. The highest consequence class CC4 is left included in the analysis although typically associated with extreme consequences (e.g. nuclear power plant, large span highway bridges), as it is possible that constructions made from a combustible building material are used in building of this consequence class.

Table 3: Consequence classes and building types used in this report

CC1	Buildings with low possible loss of human life
CC2	Buildings with medium possible loss of human life
CC3	Buildings with high possible loss of human life
CC4	Buildings with extreme possible loss of human life
<4	Buildings up to 4 storeys
<10	Buildings up to 10 storeys
>10	Buildings over 10 storeys

R	Residential buildings
O	Office buildings
TFA	Timber frame assemblies
MTP	Buildings constructed from mass timber products such as solid timber panels or cross-laminated timber
PBC	Post and beam construction

Following the above classification, the identified gaps are intuitively associated with this list, exemplarily shown in Table 5 (where CC0 has been omitted). The "X" symbols in Table 5, and following tables, indicate the building types for which the identified gaps are relevant.

Table 4: Example of gap analysis target group with the classification of building types used in this document.

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
		X	X	X		X	X	X	X	X	X

8.2 Gap analysis concerning fire dynamics

8.2.1 General

This section was drafted under the lead of RISE (D. Brandon) based on the evaluation of fire incidents with combustible e structures and a corresponding workshop in the framework of the pre-project TimFix. The aims of this section are to:

1. Identify aspects, that are important in practice*, of safe robust design strategies for buildings of mass timber or timber frame construction.
2. Identify regulation gaps, concerning the implementation of safe and robust design strategies.
3. Identify knowledge gaps, concerning the implementation of safe and robust design strategies.

Only aspects that are related to reduced safety or high property loss of real building fires or fire tests of realistic buildings are aimed to be identified.

To fulfil these aims, this work package has the following objectives, which are all performed with the help of a group of experts in the field.

a) Objective A: Create a data set of real fires and fire tests of realistic structures and identify the factors that had a significant influence on fire safety (from the identified factors listed in Work Package 3).
b) Objective B: Compare the identified fire safety factors with current regulations in a number of countries with a large share of timber construction and, wherever possible, identify gaps in these regulations.
c) Objective C: Compare the identified fire safety factors with currently available tools and, wherever possible, identify gaps in the current set of available tools.
d) Summarize the gaps of knowledge (this report)

8.2.2 Objective A – identify the most significant factors in real/realistic fires

A list has been generated of 23 real fire accidents in buildings of timber construction and 80 real scale timber compartment fire tests. Consequently, 103 real fires in timber compartments were analysed. For each fire, the factors that had the most significant impact on fire dynamics, fire development and damage were identified during a workshop with a small group of invited experts. The contributing experts were:

- D. Barber, Arup
- J. Schulz, Arup
- D. Brandon, RISE
- J. Schmid, ETH Zurich
- N. Werther, TU Munich
- E. Mikkola, KK-Palokonsullti

The seven most significant factors identified are:

1. Sensitivity to cavity fire spread
2. Glueline integrity failure of mass timber
3. Lack of robustness against re-entering of external flaming & high external radiation
4. Lack of sprinkler systems
5. Size of compartmentation
6. High percentages of exposed timber & configuration of combustible surfaces
7. Insufficient gypsum board protection on protected surfaces

These factors are expanded with comments in Table 5.

Table 5: Most significant negative identified factors in real fires

	1	2
1	**Identified factor**	**Comment**
2	Sensitivity to cavity fire spread	In the majority of large damage fires in real buildings, there was some form of cavity fire spread.
3	Glueline integrity failure of mass timber	Although real fires in which glueline integrity failure has had a significant influence were not identified, a significant number of full scale fire experiments show the very significant influence that glueline integrity failure can have on the fire dynamics and the damage caused by the fire.
4	Lack of robustness against (re-) entering of external flaming & high external radiation	In a significant number of real fires analysed, the fire re-entered the fire compartment after spreading externally. This often happened through the eave. The external radiation of fires can be increased by the presence of exposed timber inside the compartment. This may compromise the fire brigades' ability to extinguish the fire, and may cause fire spread to neighbouring buildings.
5	Lack of, or malfunctioning of sprinkler systems	Most significant fires in the database took place in buildings without sprinklers. Based on the information available, the experts at the workshop expect that the fires would have had a significantly different outcome if sprinklers were in place and activated successfully.
6	Size of compartments	In fire safety designs it is essential to prevent fire spread out of a compartment. If the fire compartments, however, are large, the allowed fire spread is large.
7	High percentages of exposed timber & configuration of combustible surfaces	As timber is combustible, it can act as additional fuel during a fire, especially if the timber material is exposed to the fire (i.e. no fire protective encapsulation is present). In addition, the location of exposed timber surfaces with respect to each other has been shown to have an influence on fire dynamics of a compartment. Effects of a radiative feedback loop have been observed, especially on vertical exposed surfaces in close vicinity
8	Insufficient gypsum board protection of protected surfaces	Gypsum board fall-off can have a significant influence on fire dynamics and increase the fire intensity, fire duration and consequences of the fire. Charring behind gypsum boards can cause smouldering that is difficult to extinguish.

Real fire accidents in multi-storey residential buildings with timber structures have been further analysed in a parallel study led by RISE named SAFITS, which stands for *Statistical Analysis of Fires in Timber Structures*. In 18 fires of residential buildings of three or more floors, where at least 3 fire compartments were involved, the paths of fire spread were fully or partially identified using mostly fire accident reports, but in some cases news articles or other reports. The fires included in the analysis took place in the USA, UK and Sweden and excluded fires that occurred during construction. A result of the analysis of SAFITS, useful to identify main gaps and details is the diagram of Figure 70.

The study indicates that main causes of large fire spread in residential timber buildings of 3 or more floors are:

1. Attic fire spread (14 of 18 fire accidents)
2. Cavity fire spread (8 of 18 fire accidents)
3. External fire spread and fire spread into the building, commonly through the eave or roof detail (7 of 18 fire accidents)

Although, the attic can act as a *super-spreader* (path of fire spread that leads to fire in significant parts of the building), ignition rarely takes place in the attic (1 of 18 fires in the SAFITS study). The main paths of fire spread into the attic are (1) via the façade or balcony through the eave or roof detail and (2) through cavities with combustible surfaces in assemblies. The study therefore indicates that the most important details to prevent large damage fires in buildings of the scope are of (a) the eave and roof (b) the construction cavities and (c) fire barriers/protection in the attic.

Fire spread directly from fire compartment to fire compartment has only been identified in one of the fire incidents, because of a complete absence fire barrier. It should be noted that the study only included buildings with timber structures and that the indicated paths of fire spread can also occurred in buildings with non-combustible structures.

Out of 18 fires that involved at least 3 compartments (fires with identified fire spread paths only)

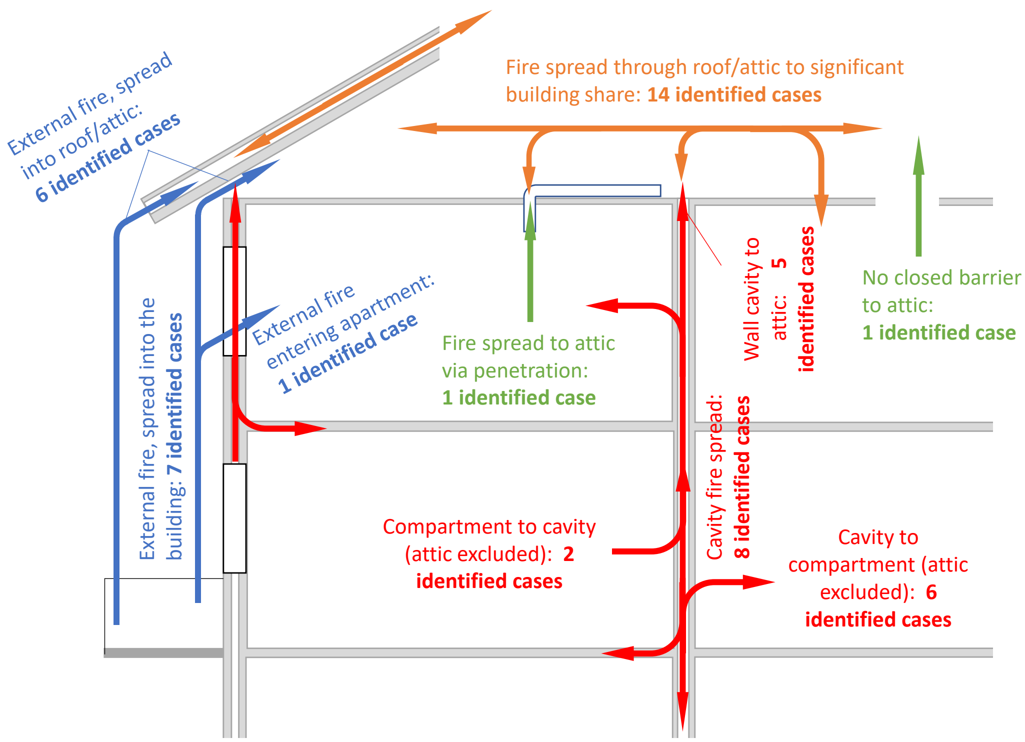


Figure 70: identified paths of fire spread in 18 real fire accidents in buildings with timber as the main structural material.

8.2.3 Objective B – identify gaps in regulations

A survey of experts conducted within Work Package 2 of this project, with participants from UK, Finland, Belgium, Switzerland, Italy, Sweden, Norway, Estonia, France, Austria, Germany, USA, Canada, Australia, New Zealand, Japan and Singapore, indicated that most of these countries changed fire regulations that concern timber buildings within the last 5 years. There are, however, some countries in which the last regulation changes were in the 90s or earlier.

The survey responses describing building regulation changes were analysed and categorised into changes that allowed an (1) increased or (2) decreased field of application for timber as a structural material. Nine responses indicated an increased field of application by regulations (allowing timber to be used as a structural material in an increased number of building types). This is the case for Canada, where buildings with wood frame construction are allowed up to 6 storeys high, since 2015. In Canada, mass timber construction will be allowed up to 12 storeys in 2020. In the USA, the height limit for mass timber buildings was increased to 18 storeys (or 12 storeys with some exposed surfaces allowed). In Switzerland, timber as building material can be used in any kind of building types, incl. high-rise buildings, since the new fire regulations were released in 2015 (VKF 2015). Four responses within the survey indicated a reduced field of application for timber buildings.

These reductions were caused by:

- Increased requirements for reaction-to-fire performance, from Euroclass D to Euroclass C or higher, not allowing exposed untreated timber (e.g. Sweden);
- Implementation of performance-based requirements, with restrictions regarding the combustibility of materials (which explicitly rules out timber) (e.g. Germany);
- Ban of combustible materials for certain elements in certain buildings (UK).

Although it is not mentioned, specifically in the survey, the changes of reaction-to-fire requirements may be to control the early fire spread in the growth phase of a fire, or they may be to limit the contribution of combustible building material to the fuel of the fire, or to take a conservative stance related to lack of knowledge. The exclusion of timber in a performance-based approach is presumably related to the lack of performance-based methods that are suitable for the fire safety design and structural fire design of timber buildings. Further, suitable test methods are not available that will properly evaluate the performance of loadbearing timber in an external wall.

8.2.3.1 Differences between countries

The survey indicated that some countries had implemented small changes which allow realising more timber buildings, but some other countries had significant regulation changes with arguably opposite effects. Further significant differences between countries indicated by the conducted survey include, among others:

- differences in allowable height of timber structures varying from 11 m for certain occupancies to unlimited height for similar occupancies.

> *Discussion by select group of experts indicated in 8.2.2: the differences of allowable height of buildings with a timber structure are likely related to a large number of aspects, such as: significant historical events; quality assurance; implementation of a performance-based or prescriptive approach; sprinkler requirements and other prescriptive requirements; fire performance requirements of engineered/mass timber products. Further, the feasibility of*

external firefighter intervention is not clear and the boundary conditions to allow for required actions are not set. A historical factor that is expected to have caused some of the major differences is that some codes have updated mass timber provisions that have evolved from light frame provisions, while others have mass timber provisions that were developed separately.

- differences of protection times of fire protective cladding, varying from 10 minutes in Europe ($K_2$10) to 80 minutes in America (IBC 2021).

Discussion by select group of experts: differences between levels of protection could indicate different intended purposes for the protection, such as only reducing the contribution of the combustible structure to the fire as fuel in the developing phase, reducing the risk of flashover or increasing the time to flashover. Higher levels of protection can be implemented to completely avoid contribution of the combustible structure in the fire, which would eventually lead to a sufficient cooling phase (decay) of the fire after the combustible content burns out. Additionally, it is expected that regional differences of expectations and experiences in relation to fire service intervention played a role.

- differences of required reaction-to-fire classes, which are generally dependent on occupancy and/or height. Exposed wood is allowed in relatively tall buildings in some countries, while other countries do not allow any combustible materials in buildings over a certain height.

Discussion by select group of experts: differences between required reaction-to-fire classes indicate differences of allowed contributions to the fire as a fuel. As the reaction-to-fire class is most often only required for the exposed surface of materials, this measure only concerns contributions of the combustible materials to the fire load during the initial fire development.

- differences of sprinkler requirements. In a relatively small number of countries such as Finland and the USA, different sprinkler requirements hold for different building or construction types, which are categorized based on, among other things, the combustibility of the main structural material. However, in many countries, material-dependent requirements do not exist.

Discussion by select group of experts: as evidenced by the relatively small number of large damage fires in buildings with installed sprinkler system. The implementation of sprinklers is considered to have a very significant effect on the overall safety levels. However, as the effectiveness of sprinklers cannot be guaranteed statistically, it is also considered important to consider the event that sprinklers are ineffective.

- dependence of minimum distance between buildings on the combustibility of facades.

Discussion by select group of experts: knowledge of external fire exposure is mostly limited to knowledge from standard façade fire tests. It is known that external fire exposure can also be dependent on the fuel load inside the burning compartment, which includes the fuel provided by exposed structural timber. External fire exposure also depends on the amount of combustion taking place outside the ventilation openings, which will be greater with exposed wood internal surfaces, Building regulations have been formed mostly based on experience and historical events (Östman et al. 2010), which is different in different countries, making it difficult to give reasons for differences between regulations in different countries.

8.2.3.2 Comparison of performance-based and prescriptive design methods

It is clear that the implementation of either a performance-based or a prescriptive approach causes significant differences in design methods and in the final design solution of a timber building. For especially tall and large buildings, whether a country implements a performance-based approach or a prescriptive approach, is arguably one of the main causes of significant differences in the regulations. Lack of generally accepted performance-based design methods and knowledge about such methods (Östman et al. 2010) may limit the design of timber buildings, even in those countries with performance-based requirements. Some countries implement a purely prescriptive code, in which buildings are categorized and requirements are given for each building category. For building categories, which include a large range of possible building designs, the requirements need to be relatively conservative to ensure an acceptable level of safety. For example, the American IBC 2021 allows relatively tall buildings with a timber structure. However, they have stricter fire performance requirements for mass timber products, mass timber adhesives, levels of fire protection by gypsum or other boards, and levels of sprinkler protection, than most other countries. Table 6 gives a summary of the advantages and disadvantages of prescriptive and performance-based regulations.

Table 6: Advantages of prescriptive and performance-based approaches.

	1	2	3
1	**Design Approach**	**Advantages**	**Disadvantages**
2	Performance-based approach	- Increased potential to have material independent performance criteria. - Large field of application	- Lack of methods for structures of combustible materials - High complexity - Strong dependence on the competency of the design team and enforcing authorities. - Round-robin studies (Rein et al. 2009; Johansson et al. 2020) indicate significantly different outcomes from different practicing engineers for the same assignment. - Relatively difficult to check by authorities
3	Prescriptive approach	- Relatively simple - Outcome is relatively independent on engineer. - Relatively easy to check/control by authorities	- A large field of application requires relatively conservative rules. - Likely material dependent regulations are required to achieve similar performance. Example of this could be a required level of fire protection or limitations of exposed timber.

Table 7: Summary of gaps in typical prescriptive regulations.

	1	2
1	**Identified fire safety factors.**	**Typical Prescriptive regulations**
2	Sensitivity to cavity fire spread	Most prescriptive regulations deal with fire spread beyond the compartment of origin, using insulation and integrity requirements for fire resistance ratings. In many countries, there are no requirements regarding the robustness[4] of fire resistant structures, or requirements to prevent fire spread beyond the compartment of origin. In some countries, prescriptive rules specify required fire protection of combustible surfaces in all cavities, or subdivision of cavities as a function of the reaction-to-fire performance of the surfaces facing into the cavity (applies in UK for example), which increases the robustness, but may increase the costs significantly.
3	Glueline integrity failure of mass timber	USA and Canada include prescriptive requirements for bond line performance of mass timber structures. This is in the product manufacturing standards - rather than in the building codes. Recent research (Brandon et al. 2021) showed that delamination during a fire leads to an increased potential to expose large surface areas of timber, while ensuring a continuous decay of fires. As far as known, no other countries have such requirements. However, efforts are being made to include such requirements in future standards.
4	Lack of robustness against (re-) entering of external flaming & high external radiation	As far as known by the authors, there generally are requirements that aim to lower the risk of fire re-entering a fire compartment because of external flaming. However, in practice these requirements are often not fulfilled. A statistically common path for fires to re-enter a building is through the eaves. Some codes implement increased minimum distances between buildings, which have combustible facades. Most countries do not have such regulations. The authors do not know of countries where the minimum distance between buildings is dependent on the presence of exposed combustible materials inside the building.
5	Lack of, or malfunctioning of sprinkler systems	Prescriptive requirements for the implementation of sprinklers differ significantly. Of the large-damage fires identified for objective A, the vast majority of buildings did not have automatic sprinklers installed.
6	Size of compartments	Limits for maximum compartment size differ significantly in different countries. By allowing relatively large fire compartments, relatively large fires are permitted, which can have consequences for safe evacuation and fire service interventions.
7	High percentages of fully exposed timber & configuration of combustible surfaces	Some countries do not allow any exposed timber surfaces, while others have strict prescribed limits of exposed surfaces. There are, however, countries that allow the use of exposed surfaces without any prescriptive limits, and limited or no prescriptive measures to allow for the resulting large areas of exposed timber. With only a few exceptions (such as the US building code), most countries do not specify specific allowed configurations or areas of exposed mass timber surfaces.
8	Insufficient gypsum board protection on protected surfaces	Prescriptive regulations in some countries include requirements for fire protection (qualitatively, eventually quantitatively) or encapsulation of timber members. In some parts of Europe so named K-classes are used to indicate a protection time of 10 to 60 minutes in fire resistance test conditions. In the USA the required protection time for type IV-B and IV-A buildings (i.e. tall timber buildings) is two-

[4] In this report robustness of fire protection system refers to its ability to limit fire spread even if the one or more fire barriers are compromised.

	1	2
		thirds of the required fire resistance (which most often equates to 80 minutes). In most other countries such requirements do not exist.

8.2.3.3 Objective C – identify gaps in available design tools

The list of available design tools generated by Work Package 3 is compared with the identified fire safety factors (identified by analysis of previous fires for objective A of WP5) in Table 8. In this table, orange shading indicates a lack of identified performance-based design tools to prevent negative consequences as a result of identified factors, where dark orange indicates no available tool was identified and light orange indicates very limited available tools. Green shading indicates that there are tools available that are identified to allow design approaches that can help prevent negative outcomes of the identified most fire safety factors.

It is recognised that the fire resistance framework can ensure a certain level of safety if combined with a number of prescriptive rules, such as prescriptive gypsum board protection, prescriptive limits of exposed surface areas and prescriptive glue line integrity performance of mass timber members. In this table the ability of using standard fire exposure (for example according to ISO 834) as a performance-based design tool without additional prescriptive regulations is assessed.

Table 8: Identified tools for performance-based design versus identified fire safety factors in real fires.

	1	2	3	4	5
		Identified factor considered by:			
	Identified fire safety factors.	**Standard fire exposure**	**Parametric fire**	**Zone models**	**Computational fluid dynamics**
	Sensitivity to cavity fire spread	No[5] (prescriptive measures recommended)	No (prescriptive measures recommended)	No (prescriptive measures recommended)	No (prescriptive measures recommended)
	Glue (bond) line integrity failure of mass timber	No[6]	No	Possibly	No
	Lack of robustness against (re-) entering of external flaming & high external radiation	No (prescriptive measures recommended for details)	No (prescriptive measures recommended for details)	No (prescriptive measures recommended for details) External radiation can possibly be considered with zone modelling	No[7] (prescriptive measures recommended for details)
	Lack of, or malfunctioning of sprinkler systems	No	Yes	Yes	Yes
	Lack of compartmentation	No	No	No	No/Possibly[8]
	High percentages of fully exposed timber & configuration of combustible surfaces	Contribution of exposed wood to the fuel: No Interaction between exposed surfaces: No	Contribution of exposed wood to the fuel: Possibly Interaction between exposed surfaces: No	Contribution of exposed wood to the fuel: Yes Interaction between exposed surfaces: No	Contribution of exposed wood to the fuel: No[9] Interaction between exposed surfaces: No
	Insufficient gypsum board protection of protected surfaces	No	Yes	Yes	No

[5] Although fire resistance tests for cavity barriers exist, the focus of testing is on specific products, not on the robustness of the entire design which is identified as the main problem

[6] Although products that exhibit glue line integrity can be identified in furnace tests with exposure according to ISO 834 it is not possible to prevent glue line integrity failure in real fires just by using ISO 834 fire exposure to justify a building design.

[7] CFD is generally not used for post-flashover fires especially not in ventilation-controlled conditions. In such fires, the external exposure is more significant than in fuel-controlled fires.

[8] Parametric fires and zone models cannot be used to assess fire spread in large spaces. CFD is generally not used for post-flashover fires especially not in ventilation-controlled conditions, but it may be possible that it is useful for some fire scenarios

8.2.4 Knowledge gaps

As discussed in Section 8.1.3 this report indicates the relevance of the seven most relevant fire safety factors for buildings of specific consequence classes, number of floors, occupancy type, and timber construction type, using tables that are shown below. Based on a combination of gaps in prescriptive regulations and available design tools and concerns indicated by stakeholders, knowledge gaps were identified. The knowledge gaps are discussed and listed at the corresponding identified safety factors. Each identified knowledge gap is has its own identification using a combination of a number and letter. This identification is further used in the action plan

I- Sensitivity to cavity fire spread:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X		X	X	X	X	X		

Prescriptive regulations concerning the sensitivity to cavity fire spread:

- Most countries lack regulations that reduce sensitivity to cavity fire spread.
- Strict prescriptive rules for fire protection in cavities for some mass timber construction types in the USA and Canada

To increase the robustness[10] against cavity fire spread in especially constructions with many voids (typically timber frame assemblies) it does not suffice to solely aim to prevent fire spread into a cavity. It is also required to reduce the consequences in case the fire does spread to the cavity. Regarding this the following knowledge is identified to be lacking:

I-a) detailing requirements preventing cavity fire spread (as identified in 8.2.2)

I-b) knowledge of the involvement of combustible insulation

II- Glue (bond) line integrity failure of mass timber:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X		X	X	X	X		X	X

Prescriptive regulations concerning glue line integrity failure of mass timber:

- Lacking in most countries.
- Strict prescriptive rules in USA and Canada

Performance based tools to prevent glue line integrity failure are scarce and are not significantly validated against test results. However, it has been shown that (Janssen 2017; Brandon and Dagenais

[9] CFD is generally not used for post-flashover fires especially not in ventilation-controlled conditions. However, it may be useful for predictions in the pre-flashover phase.

[10] In this report robustness of fire protection system refers to its ability to limit fire spread even if the one or more fire barriers are compromised.

2018) this issue is avoidable through stricter product requirements for adhesives to continue to function fully under elevated temperatures.

Although proposed tests by Janssen (2017), Brandon and Dagenais (2018), Klippel et al (2018) all aim to distinguish mass timber members that do not exhibit glue line failure from members that do, it is known that there is a gradient of product performance. The binary approach where a product either fails or passes the requirements, limits the use of products with an intermediate performance (for example mass timber that only exhibits glue line integrity failure after relatively long fire exposure). The following knowledge gap was identified (also indicated by stakeholders from the adhesive industry in the GLIF research project led by RISE and ETH Zurich):

II-a) Knowledge for a performance based or prescriptive system that can use non-binary characteristics of glue lines of a mass timber product for safe implementation of that product

III- Lack of robustness against re-entering of external flaming & high external radiation:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X	X	X	X	X	X	X	X	X

Prescriptive regulations concerning the lack of robustness against (re-)entering of external flaming & high external radiation:

- Requirements may exist to avoid external flames to (re-)enter buildings, but robustness requirements are generally absent.
- Regarding external radiation to other buildings regulations differ, but regulations concerning this often have no dependence on the structural material.

As indicated in the analysis of Section 8.2.2, fire spread along the facade entering the building has a been critical in a significant share of the analysed high damage fires. In most of these cases, the external fire entered the building through the eave or through a roof detail. Therefore, a guidance document summarizing suitable solutions of such critical details is recommended. However, publicly available knowledge of robust solutions is limited.

For performance analysis of thermal radiation of exiting fire plumes to other buildings and potential identification of the risk of fire spread to a higher floor, methods to predict the flame height/size are required. As the height of the external flame can be influenced by the presence of exposed wood (Brandon and Östman, 2016), the required methods should account for such influence.

For the reasons mentioned above the following knowledge gaps were identified:

III-a) Substantial knowledge of detail alternatives providing robust systems to prevent external fires entering the building.

III-b) Validated methods for flame height predictions and prediction of radiation to neighbouring buildings that include the contribution of the structural fire load.

IV- Lack of (or malfunctioning of) sprinkler systems:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X		X	X	X	X	X	X	X

Prescriptive regulations concerning sprinkler protection:

- Regulations regarding sprinklers vary significantly in different countries.

For cases where sprinklers are present some regulations allow relaxing other requirements. EN 1991-1-2:2002, for example allows reducing the moveable fuel load and INSTA 950 suggests a reduced heat release rate of the fire for analyses. However, it is not known if the same reductions can be conservatively implemented if a part of the fuel contribution is provided by the structural material. In case the reductions provided in these standards are not suitable for structures with exposed timber, it is important to define alternative reductions to stimulate the implementation of sprinkler systems.

It is also not known if alternative active fire protection systems (such as detached sprinklers at an increased distance from an exposed timber ceiling, or water mist sprinklers) are suitable for implementation in buildings with exposed timber.

For these reasons, the following knowledge gaps were identified:

IV-a) Suitable relaxation of requirements as a compromise for implementation of sprinkler systems when not required. Hereby the implementation of sprinklers and the relaxation of requirements should lead to a reduction of the risks.

IV-b) Knowledge of the effectiveness of alternatively installed sprinklers or alternative sprinkler systems.

V- Size of compartments:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X	X	X	X		X		X	X

Prescriptive regulations concerning the allowed size of compartments:

- Regulations regarding maximum fire compartment size differ significantly.
- The UK allows in, many cases, fire compartments consisting of multiple floors.

Three fires of the analysis mentioned in 8.2.2 led to high damages because the fire ignited in very large compartments with significant combustible surfaces. In all three cases there is evidence of fast fire spread within the compartment. The fire spread within a compartment is dependent on the type and arrangement of combustibles (including exposed structural timber) in the compartment. For very large compartments, especially fire compartments involving multiple floors, an increased flame spread rate and increased extent of the flame spread can compromise safe evacuation and complexify firefighter intervention. Therefore, knowledge of the flame spread rate on exposed timber surfaces is needed. It is also proposed to study the suitability of existing traveling fire models as design fires for such compartments.

To improve conditions for safe evacuation, some buildings have smoke and heat extraction systems. To date there are no experiments known where such extraction systems were subjected to smoke or heat from a combination of moveable fuel and exposed mass timber surfaces.

For these reasons the identified knowledge gaps concerning the maximum size of fire compartments are:

V-a) Lack of knowledge of the flame spread on exposed timber surfaces in large compartments

V-b) Lack of knowledge of the suitability of existing traveling fire models.

V-c) Lack of experiments of smoke and heat exhaust systems with smoke and heat contributions of exposed mass timber.

VI- High percentages of fully exposed timber & configuration of combustible surfaces:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
		X	X		X	X	X	X		X	X

Prescriptive regulations concerning the presence of exposed timber surfaces:

- Regulations regarding allowable surface areas of exposed timber differ significantly.
- Some countries, such as, Denmark, UK, Norway and Luxemburg require certain buildings to withstand burnout using a performance based approach.
- With only a few exceptions (such as the US building code), most countries do not specify specific allowed configurations of exposed mass timber surfaces.

In case performance-based design is required, the method used should include the contribution of the combustible structure to a fire as a fuel. As stated above, such method is generally required for, so named, burnout analysis. It is, however, no general agreement on how burnout is defined. In some countries clear definition of the performance based requirement is lacking.

The presence of exposed timber in a compartment can increase the likelihood of a flashover fire in a compartment in case effective sprinkler activation is lacking. A probabilistic approach would be needed to account for this in risk assessments.

Although some performance-based methods have been proposed to include the contribution of structural timber to the fire load in compartment fires, there is a need for simple methods. For design of steel structures against design fires a time equivalency method exists, which can be implemented to link the performance of steel exposed to a certain design fire to results of fire resistance tests. Such method, however does not exist for timber structures.

Recent studies have proposed the use of parametric design fires according to Eurocode 1 (EN 1991-1-2:2002) to make predictions where the contribution of exposed timber to a fire as a fuel is included. The parametric design fires from DIN EN 1991-1-2, NA (DIN 2010) are generally considered to have a more realistic decay phase. There is, however, bo method proposed for the parametric fires according to DIN.

A recent study (Brandon et al. 2020) showed the configuration of closely spaced exposed surfaces (with a high relative view factor) has an influence on the fire dynamics and may compromise the structures ability to fully decay. Knowledge of suitable distance limits and configurations where this effect is insignificant is limited.

For the reasons mentioned above, the following knowledge gaps were defined:

VI-a) Generally accepted and practicable definitions and criteria of, burnout or extinction are missing.

VI b) Quantification of increased likelihood of fully developed fire (unsprinklered case) is needed for complete risk analyses.

VI c) The development of potentially simple methods such as a time equivalency method for timber and a method using the parametric fires specified by DIN would improve the ease of design.

VI d) Increased knowledge is needed regarding view-factor limitations for closely spaced exposed timber surfaces in the bottom part of a compartment.

VII- Insufficient gypsum board protection on protected surfaces:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
		X	X		X	X	X	X	X	X	X

Prescriptive regulations concerning gypsum board protection:

Prescriptive regulations in some countries include requirements for the amount of fire protection or encapsulation of timber members. In some parts of Europe so named K-classes are used to indicate a protection time of 10 to 60 minutes in fire resistance test conditions. In the USA the required protection time for type IV-B and IV-A buildings (i.e. tall timber buildings) is two-thirds of the required fire resistance (which most often equates to 80 minutes). In most other countries such requirements do not exist

With respect to fire safety, gypsum boards can be used to increase the structural fire performance timber and/or to limit the contribution of the structural timber as a fuel to the fire.

Experimental studies have shown that gypsum board fall off (Su et al. 2018a) and significant charring behind gypsum board protection (Su et al. 2018b) have a negative impact on the fire dynamics and can compromise full decay. The only known method to gypsum board fall-off in non-standard design fires use a temperature based failure criterion for gypsum boards. However, validation against relevant experimental data is limited.   Methods to predict charring behind gypsum board have been proposed (e.g. Brandon et al. 2021). However, the inclusion of the heat energy produced by the charring wood requires additional knowledge, as part of the heat released becomes trapped beyond the gypsum board protection. In case the assemblies have combustible insulation behind the gypsum boards, knowledge of the combustion behaviour and the location of the heat release is needed for performance based design.

In most compartment fire tests, co, gypsum board protection was directly implemented on the CLT surface. However, in real applications often resilient channels are present to improve sound insulation. This may change the fire performance. of the gypsum board protection.-

Based on the information above the following gaps were formulated:

VII-a) Validation and improvement of predictive models for gypsum fall-off in non-standard design fires.

VII-b) Correct inclusion of heat energy of charring wood behind gypsum board protection.

VII-c) Knowledge to include the involvement of different types of combustible insulation in performance based analysis.

VII-d) Fire performance of gypsum board protection attached with resilient channels in non-standard design fires

8.2.5 Gap analysis concerning other aspects

VIII- Fire safety during construction:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
		X	X	X	X	X	X	X	X	X	X

A statistical study of fires in England showed that fires that occurred during the construction phase in timber framed structures have been statistically larger than similar fires in other building types. Methods of active and passive fire protection during the construction phase should be studied.

The following gaps are identified:

VIII-a) Methods of active fire protection and its effectiveness during the construction phase

VIII-b) Methods of passive fire protection and its effectiveness during the construction phase

IX- post-fire repair of damaged timber:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X	X	X	X	X	X	X	X	X

For increasingly large buildings it becomes financially important to be able to repair post-fire structural damages.

The number of studies of post-fire repair of timber is small and is limited to repairing charred mass timber. There are no research studies of repairing structural timber damaged by water from fire suppression.

Identified gaps of knowledge concern:

IX-a) Repair of flame and smoke damage

IX-b) Repair of water damage.

X- Extinguishing methods:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X	X	X	X	X	X	X	X	X

Only a few recent studies have focused on suitable extinguishing methods for timber structures. Specific challenges concern identifying, locating and extinguishing fires in cavities and well insulated locations.

Identified gaps of knowledge concern:

X-a) Extinguishing methods using small amounts of water

X b) Extinguishing methods for cavity fires and smouldering in well-insulated locations.

XI- fire damage statistics:

CC1	CC2	CC3	CC4	<4	<10	>10	R	O	TFA	MTP	PBC
	X	X	X	X	X	X	X	X	X	X	X

For insurance purposes, it is important to have an objective comparisons between potential fire damages in buildings with different types of timber constructions and fire damages in other types of construction. For that reason studies involving such comparison are needed.

The identified knowledge gap concerns:

XI a) comparative statistics of fire damages in timber buildings versus other buildings.

8.3 Action plan

Studies concerning the identified knowledge gaps are recommended to be performed in short-term (<2 years), medium term (<5 years) or long term (<10 years) based on their relevance in past real fires and based on the size of the study. Table 9 indicates the identified knowledge gaps and a shortened description of the knowledge gap, together with the term in which the study is recommended to be performed and a short description of a potential study

Table 9: Action Plan.

	1	2	3
1	**Knowledge gap**	**Term**	**Short description of potential study**
2	1a) cavity fire spread related detail requirements	Short term	Systematic fire experiments of cavity details aiming for a generally applicable guidance document with fire tested details.
3	1b) the involvement of combustible insulation in cavities	Long term	
4	2a) non-binary method to ensure glue line integrity of mass timber.	Medium term	Perform furnace tests according to 'GLIF' testing method and perform intermediate scale compartment testing to find and a correlation, for use in performance based design.
5	3a) robust systems to prevent external fires entering in the building	Medium term	Perform fire experiments of the most critical details, such as the eave and provide a guidance document with robust detail solutions.
6	3b) flame height predictions and prediction of radiation to neighbouring buildings	Short term	With data of the external façade exposure from recent tests at RISE, a method can be developed.
7	4a) relaxation of requirements as a compromise for	Medium term	Using a probabilistic approach to determine the risk of scenarios with or without sprinklers and varying fuel

	1	2	3
	implementation of sprinklers		loads. Relevant knowledge of sprinkler reliability is essential for such analysis.
8	4b) effectiveness of alternatively installed sprinklers/ alternative sprinkler types	Long term	Experimental study sprinklers are varied.
9	5a) flame spread on exposed timber surfaces in large compartments	Short term	Analysis of real fire and recent compartment fire tests to determine an approximate flame spread rate.
10	5b) suitability of existing traveling fire models	Short term	Analysis of real fire and recent compartment fire tests and comparisons to predictions by traveling fire models.
11	5c) smoke and heat exhaust systems	Long term	A combination of small scale experiments and CFD analysis to quantify the smoke production of exposed timber and to determine whether additional requirements are needed for exhaust systems
12	6a) definitions and criteria of, burnout or extinction	short term	Communication with building authorities to more specifically design performance based requirements.
13	6b) inclusion of increased probability of fully developed fires in risk analysis	long term	If sufficient data is available in the long run, determine the frequency of fire accidents and the frequency of flashover fires in buildings with exposed timber structures. A similar study should be performed of a reference group to identify the increase likelihood of flashover fires in compartments with exposed timber.
14	6c) Development of simple methods such as a time equivalency method	Medium Term	Use existing compartment fire test data and numerical analysis to determine the capacity loss in real fires and determine the time at which the same capacity loss is reach in standard fire resistance tests. Attempt to find a correlation between the times at which this damage occurs.
15	6d) View-factor limitations for closely spaced exposed timber surfaces	Medium Term	A series of room corner tests studying different configurations.
16	7a) improvement of predictive models for gypsum fall-off in non-standard design fires	Short term	Improve previous numerical models for gypsum board fall-off in compartment fires using recent test data. Attempt to simplify the method to tabulated data.
17	7b) correct inclusion of heat energy of charring wood behind gypsum board proptecction.	Short term	For numerical analyses: include the heat release rate from charring wood in at the timber surface behind the gypsum board & validate the model
18	7c) include the involvement of different types of combustible insulation in performance based analysis	Long term	
19	7d) gypsum board protection attached with resilient channels in non-standard design fires		perform a symmetrical compartment test with gypsum board protected surfaces that are, both, directly attached on mass timber member or are attached to resilient channels and compare the performance.

	1	2	3
20	8a) Methods of active fire protection and its effectiveness during the construction phase	Long term	Experimental case studies and development of a guidance document.
21	8b) Methods of passive fire protection and its effectiveness during the construction phase	Long term	Experimental case studies and development of a guidance document.
22	9a) Repair of flame and smoke damage	Medium term	Perform and report experimental case studies.
23	9b) Repair of water damage	Medium term	Perform and report experimental case studies.
24	10a) Extinguishing methods using small amounts of water		Experimental case studies and development of a guidance document for fire fighters.
25	10b) Extinguishing methods for cavity fires and smouldering in well insulated locations.		Experimental case studies and development of a guidance document for fire fighters.
26	11a) comparative statistics of fire damages in timber buildings versus other buildings.	Short, medium and long term	A large database of buildings of timber construction can be made. A reference group with non-timber buildings of the same description and same building years should also be made. The fire accidents and description of the damage per address can be requested from a national database. Requesting fire accident data again after a few years increases the statistical data for the analysis.

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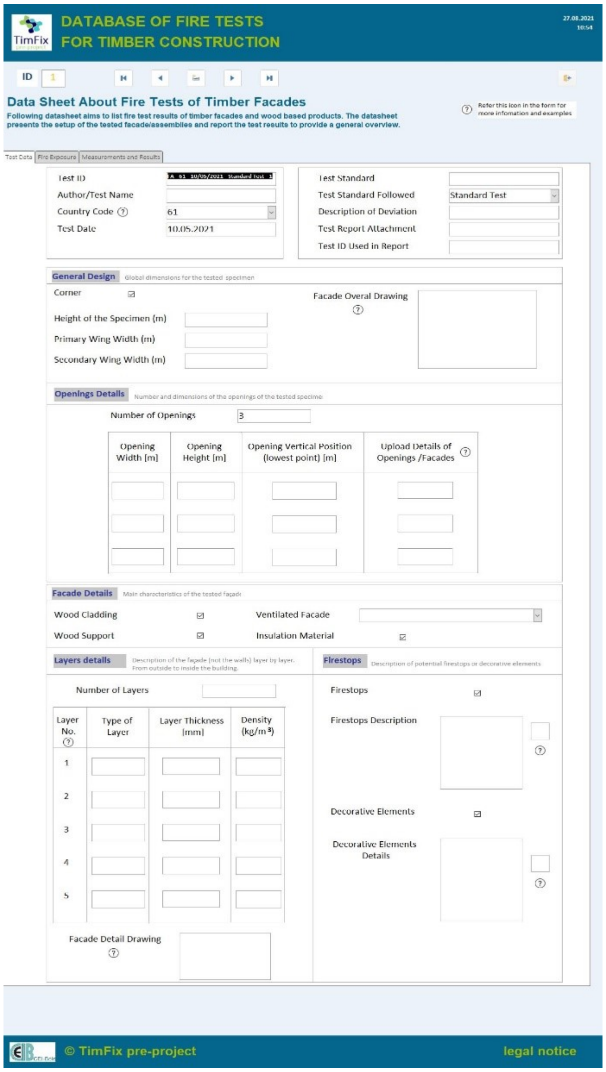
10 Annex D – Database

10.1 Appearance of the database

Test Data



Fire Exposure

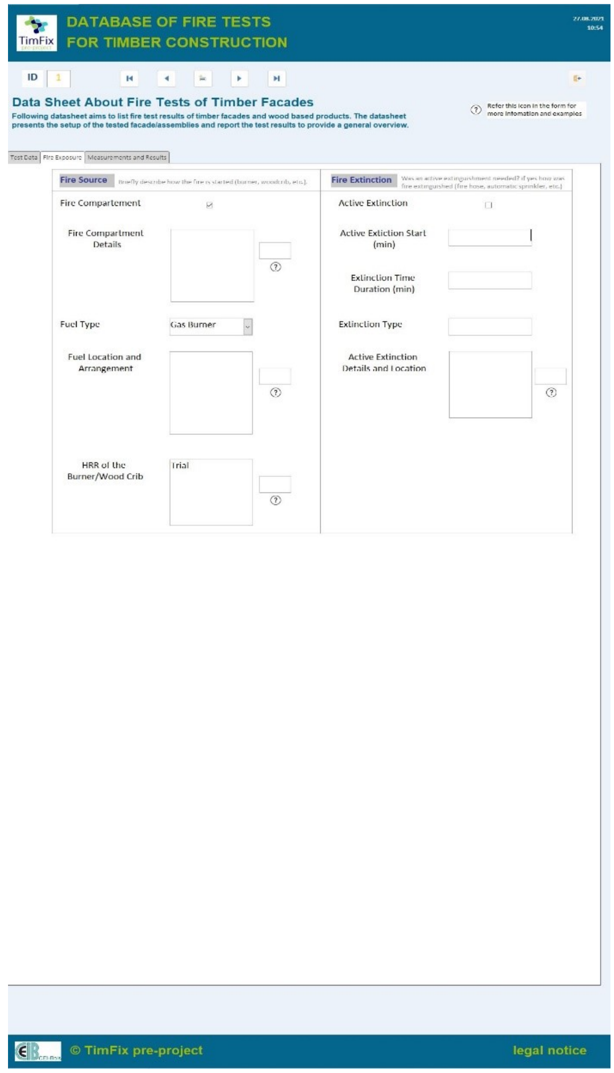


Figure 71: input mask/template in MS Access for the test data of facades (part 1)

Measurements and Results

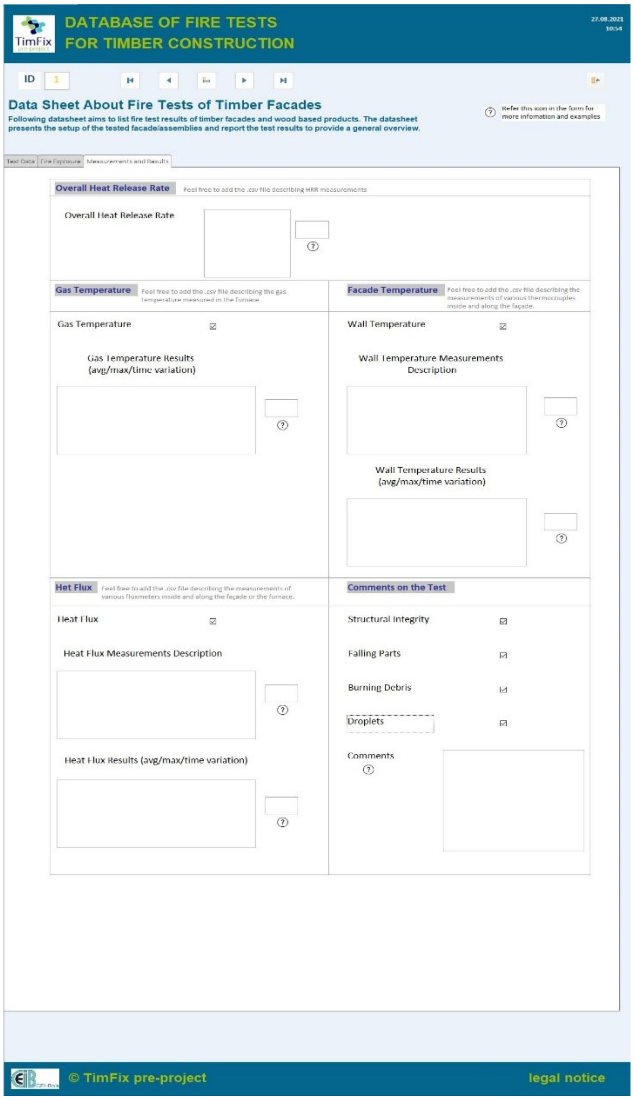
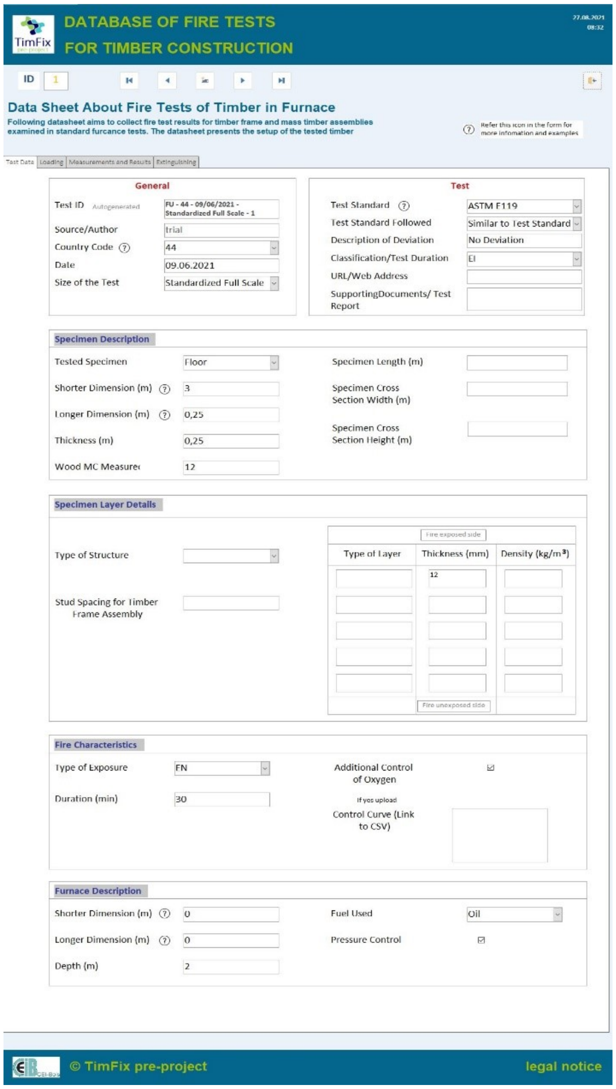


Figure 72: input mask/template in MS Access for the test data of facades (part 2)

Test Data



Loading

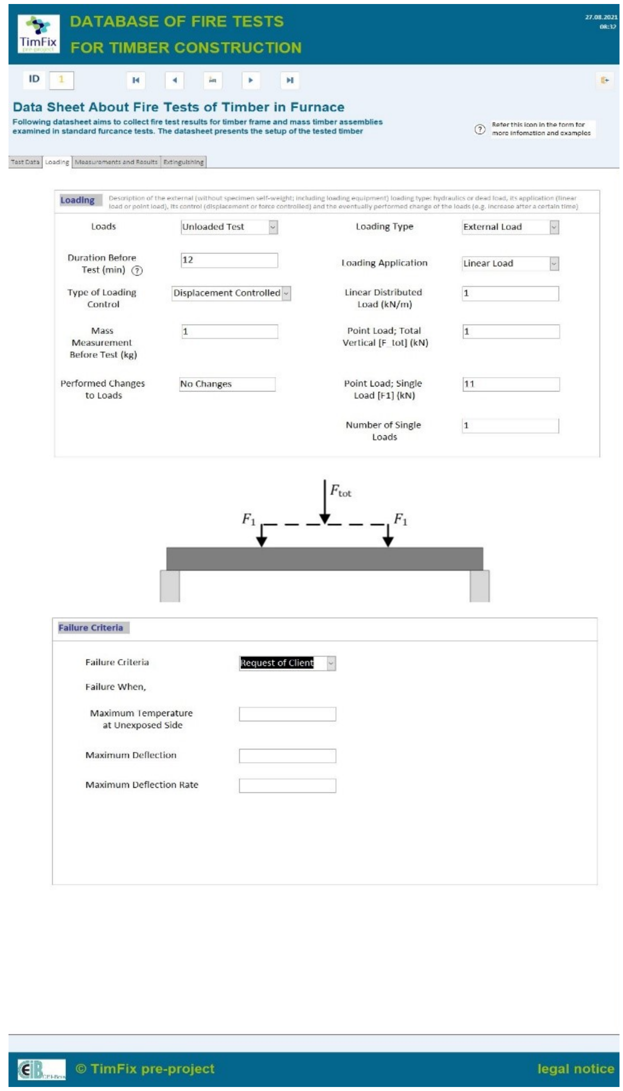
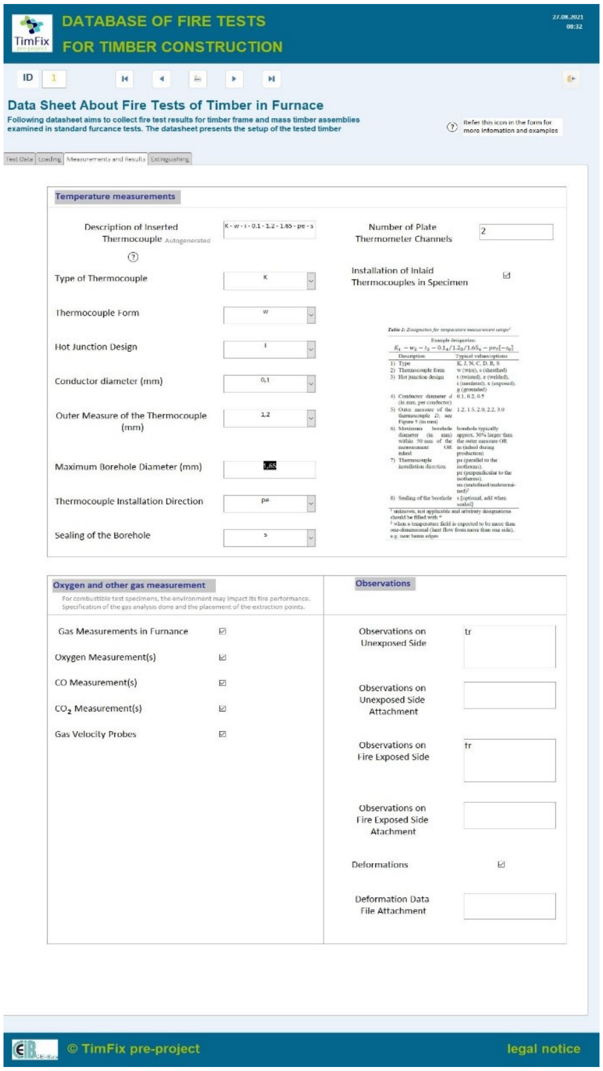


Figure 73: input mask/template in MS Access for the test data of furnace tests (part 1)

Measurements



Extinguishing and Results

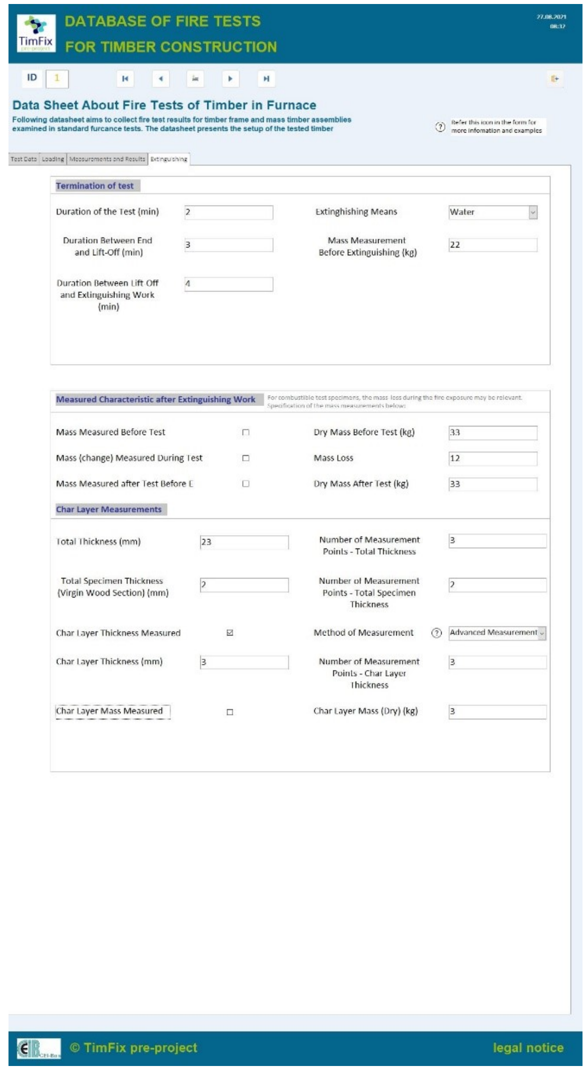
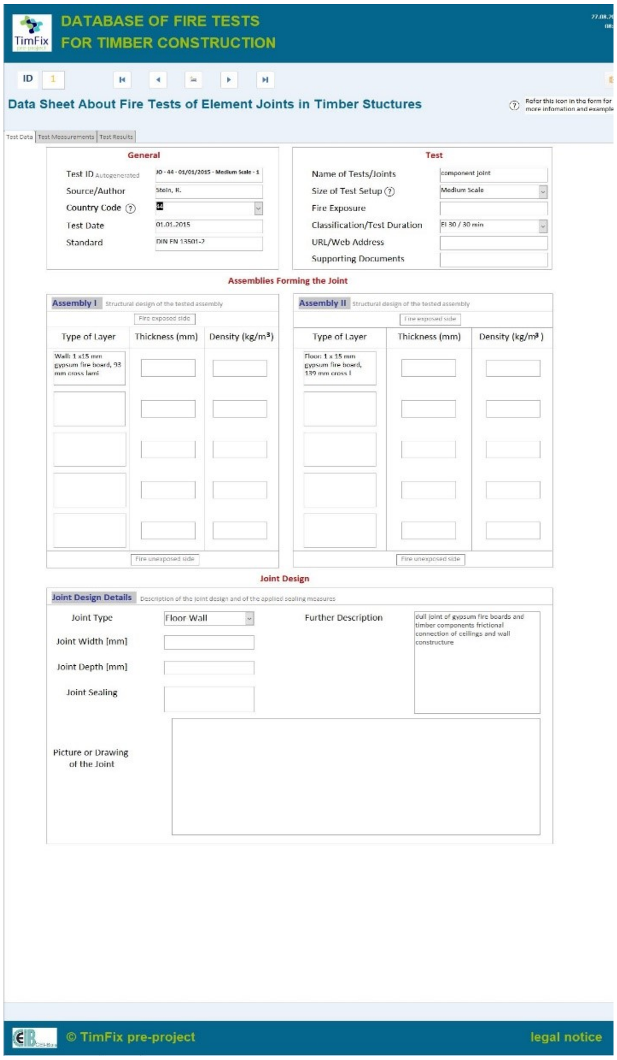


Figure 74: input mask/template in MS Access for the test data of furnace tests (part 2)

Test Data



Measurements

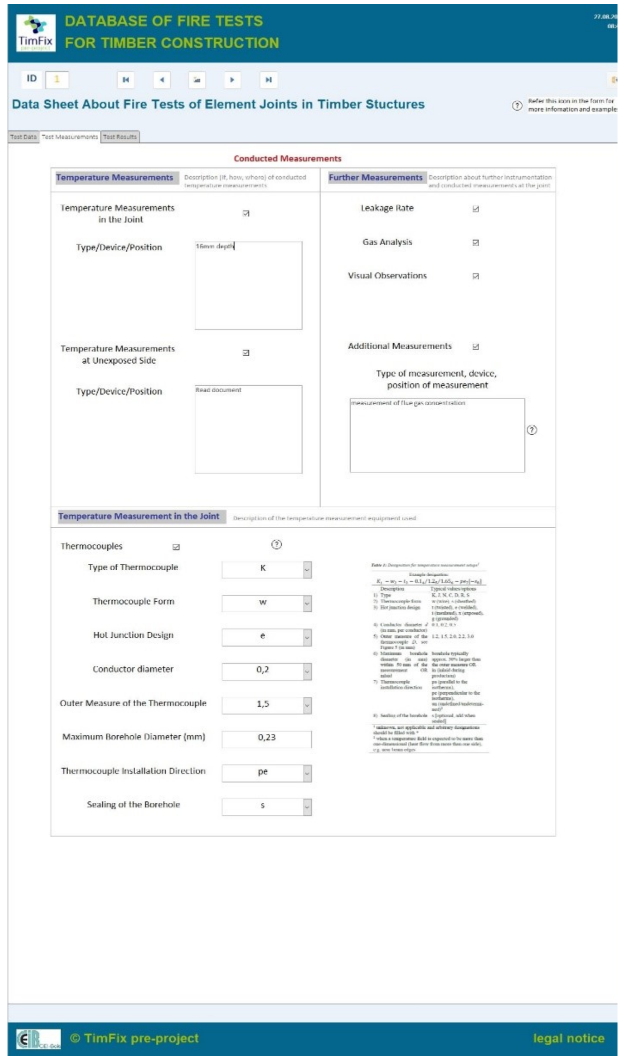


Figure 75: input mask/template in MS Access for the test data of joints (part 1)

Test Results

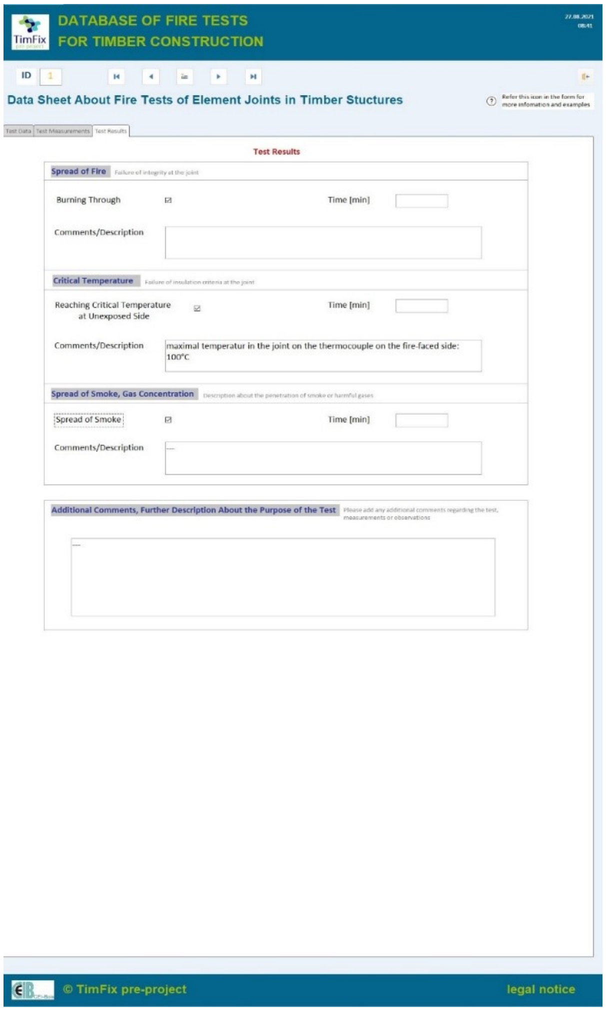


Figure 76: input mask/template in MS Access for the test data of joints (part)

10.2 Future web-based database - Database Design and Development

The main requirements of the database system, that is intended to be developed in TG 4.5, are identified as below.

- Document storage
- User roles and access rights
- Uploading & downloading function
- Approval process
- Email notification options
- Tagging and advanced search

- Simple handling and maintenance
- Server type, cost and time requirements

Three user scenarios are recognized to use the system such as uploader, viewer an approver. Each user scenario has different requirements within the system, which is needed to fulfil by the proposing solution. Figure 64 shows the workflow of the database system, how the each user scenario interact with the web based system.

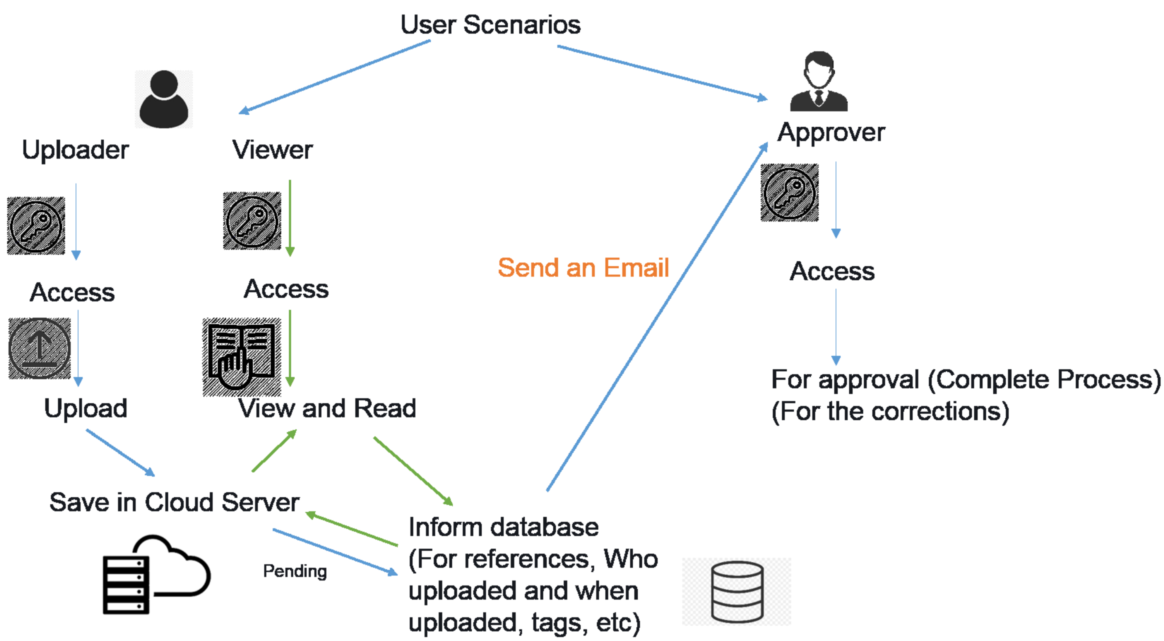


Figure 77: *Intended database system structure*

10.3 Front-end functionalities of users

10.3.1 Uploader

- Login Access
- Ability to download datasheet
- Upload filled Datasheet, Data CSV/excel file, research paper pdf
- When uploading accept general terms and conditions
- After uploading process is shown as pending until approver confirm it and approver should receive email (notification) about the upload
- Uploader can see the previous test documents uploaded by him/her

10.3.2 Viewer

- Login Access

- Ability to download documents
- Ability to search documents (using tags, keywords in name)
- When a user download a document an email (notification) should be sent to uploader (also to the approver if needed)

10.3.3 Approver

- Login Access
- Receive notification about new uploads
- Show the details about the uploads and ability to review them
- A way to contact/inform uploader if changes are needed to be done
- If everything correct approve the documents and it will permanently save in the server database. Uploader receive an email (notification) saying it is approved

Development of front-end with the interface can be done by ourselves or with a software development partner company. Before that, it is necessary to find out a solution to create the back-end to support the required functionalities. Some solutions have the ability to develop front-end and back-end of the solution together. For this currently looked into three services namely, Microsoft SharePoint by ETH, Amazon Web Services (AWS) and Google Cloud Platform (GCP).

10.3.4 Microsoft SharePoint by ETH

This is a centrally managed, SharePoint-based collaboration platform provided by ETH Zurich. SharePoint offers each user a personal profile space (My Site) for hosting personal documents, wikis, blogs and connecting with colleagues under the guidance of enterprise-wide governance.

The main reason to consider SharePoint as an initial solution for the Timfix database is that SharePoint allows developing front-end and back-end together within the system with a website. Figure 65 shows a demo website created with SharePoint and Figure 66 shows a document database in SharePoint.

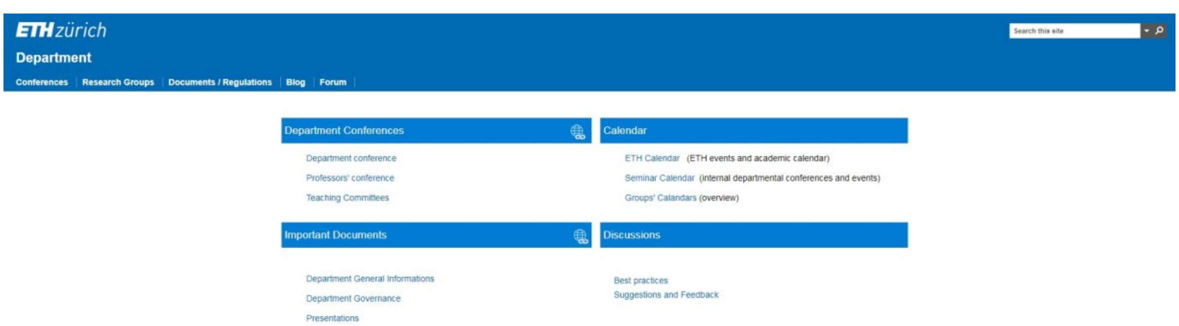


Figure 78: *SharePoint Demo Website*

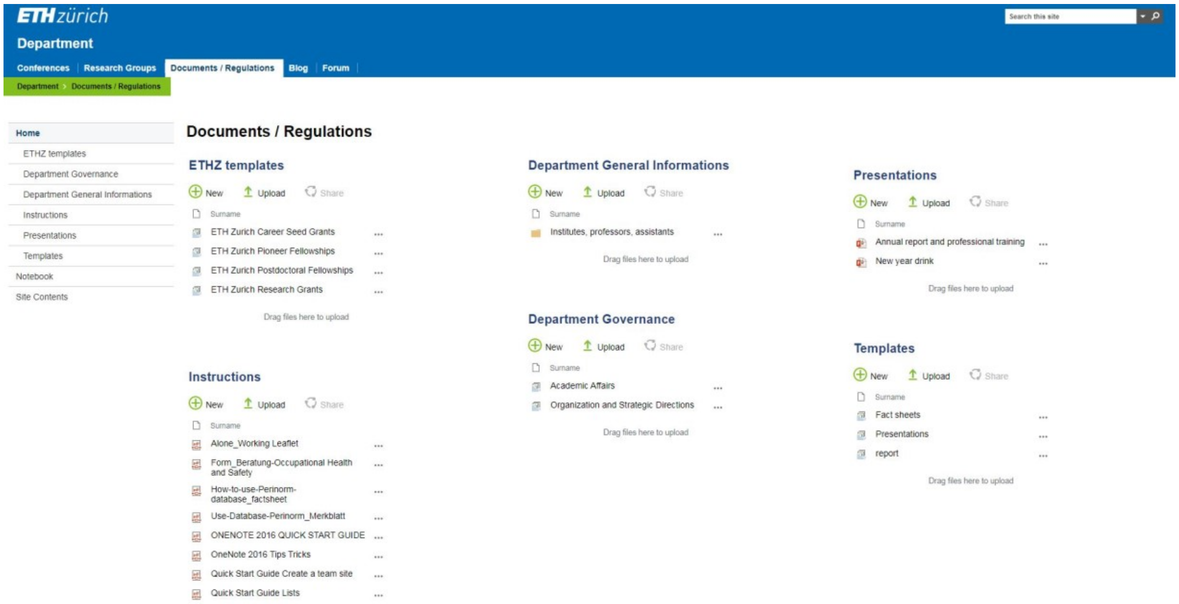


Figure 79: *SharePoint Document Database.*

SharePoint provides core functionalities as below.

- Collaboration sites
- Authentication and authorization
- Site collection and site management
- Provisioning and consuming content
- Search functionality within following areas: Content, Sites, People
- Backup and restore data

10.3.5 Cost estimation of SharePoint

The Table 1 shows the cost for the storage use in SharePoint site and need to pay annually.

Table 10: *Cost of SharePoint Site Collection is based on data volume*

Model	Volume	Price per year
S	< 2 GB	Free
M	< 10 GB	300 CHF
L	< 50 GB	1000 CHF

Setting up the database and the website can be developed by our own or can get the consultation from the ETH SharePoint team. Table 2 shows the hourly cost for the consulting service. From the discussions of the ETH SharePoint team, generally around 40 hours need for setting up a SharePoint workflow with the website. That is roughly 4000 CHF for a simple web solution. Since our database system has unique requirements, the setting up cost can be higher than this. Furthermore, with the drawbacks in SharePoint as discussed in the next section, it is recognized that SharePoint is not a viable solution considering our requirements and setting up cost.

Table 11: *Cost for consulting service in SharePoint*

Additional Services	**Hourly fee**
Content editing and authoring	CHF 110
Additional user teaching (coaching)	
Consulting (structure, navigation, workflow, solutions)	
Customizing, branding, and design	
Development of solutions, Web Parts, views, and workflows	
Specific migration work beyond automatic migration from previous SharePoint versions	

10.3.6 Disadvantages of SharePoint

- ETH SharePoint is still on-premise solution. They are in a transaction to a cloud-based solution. But still, it is not possible to use the cloud service
- Not possible to restrict access of all the documents and therefore it is a problem with the document security
- There is no clear solution for notifications and approver confirming process in SharePoint
- Database is not user-friendly
- The maximum size of file uploaded to a document library is 10 GB. During batch upload, this limit applies to the total size of files, or content
- URL naming is limited to https://sitename.sp.ethz.ch

10.4 Amazon Web Services (AWS)

Amazon web services provide more than 100 different services to develop applications with increased flexibility, scalability, security, and reliability. After a few meetings, our requirements were identified point by point and they suggested the AWS services which are suitable for our solution as shown in Figure 67 to develop the back-end of our database system.

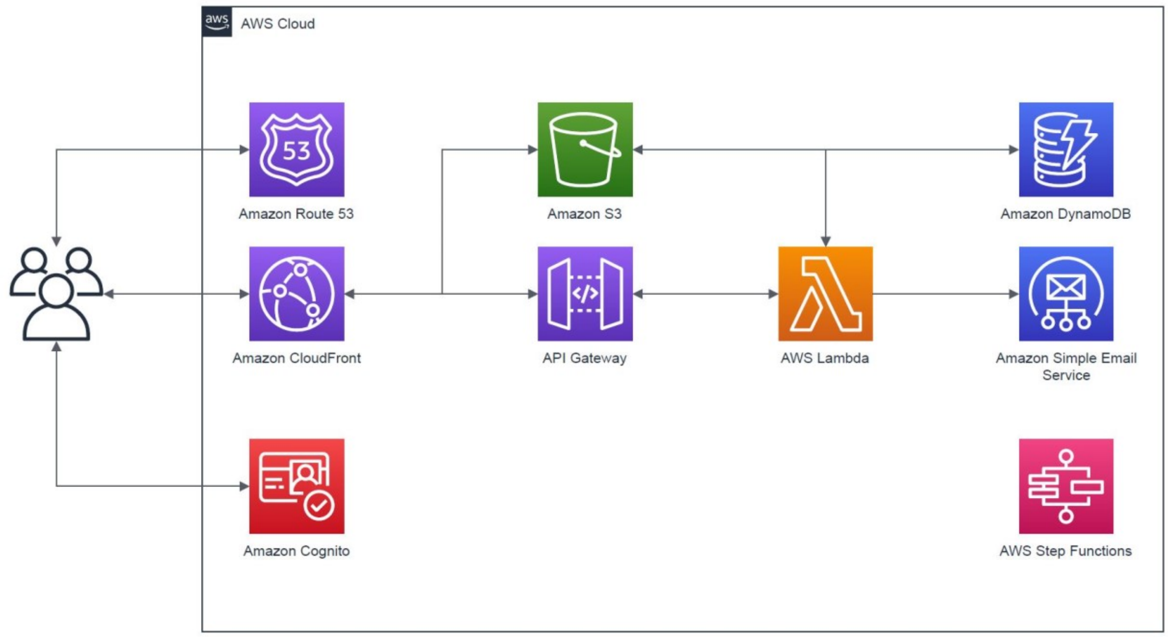


Figure 80: *AWS Services to use in TimFix Database*

Next, the main AWS services suitable for our system have briefly explained and more information can be found through the link provided under each service category.

SES - *https://aws.amazon.com/ses/*
Amazon Simple Email Service (SES) is a cost-effective, flexible, and scalable email service that enables developers to send mail from within any application. Amazon SES's flexible IP deployment and email authentication options help drive higher deliverability and protect sender reputation, while sending analytics measure the impact of each email.
Lambda - *https://aws.amazon.com/lambda/*

AWS Lambda is a serverless compute service that runs our code in response to events and automatically manages the underlying compute resources. AWS Lambda can automatically run code in response to multiple events, such as HTTP requests via Amazon API Gateway, modifications to objects in Amazon S3 buckets, table updates in Amazon DynamoDB, and state transitions in AWS Step Functions.

DynamoDB - *https://aws.amazon.com/dynamodb/*

Amazon DynamoDB is a NoSQL database that supports key-value and document data models, and enables developers to build modern, serverless applications that can start small and scale globally to support petabytes of data and tens of millions of read and write requests per second. DynamoDB is designed to run high-performance, internet-scale applications that would overburden traditional relational databases.

S3 - *https://aws.amazon.com/s3/?nc2=h_ql_prod_fs_s3*

Amazon Simple Storage Service (Amazon S3) is an object storage service that offers industry-leading scalability, data availability, security, and performance. This means customers of all sizes and industries can use it to store and protect any amount of data for a range of use cases, such as websites, mobile applications, backup and restore, archive, enterprise applications, IoT devices, and big data analytics.

Cognito - *https://aws.amazon.com/cognito/*

With Amazon Cognito, users can sign-in through social identity providers such as Google, Facebook, and Amazon, and through enterprise identity providers such as Microsoft Active Directory using SAML. Amazon Cognito provides a built-in and customizable UI for user sign-up and sign-in. It is possible to use Android, iOS, and JavaScript SDKs for Amazon Cognito to add user sign-up and sign-in pages to solutions.

AWS Step Functions - *https://aws.amazon.com/step-functions/*

AWS Step Functions is a serverless function orchestrator that makes it easy to sequence AWS Lambda functions and multiple AWS services into business-critical applications. Through its visual interface, we can create and run a series of checkpointed and event-driven workflows that maintain the application state. The output of one step acts as an input to the next. Each step in our application executes in order, as defined by our system logic.

Amazon CloudFront - *https://aws.amazon.com/cloudfront/?nc=sn&loc=1*

Amazon CloudFront is a fast content delivery network (CDN) service that securely delivers data, videos, applications, and APIs to customers globally with low latency, high transfer speeds, all within a developer-friendly environment. CloudFront is integrated with AWS – both physical locations that are directly connected to the AWS global infrastructure, as well as other AWS services.

In addition, each service has more than one feature and it is possible to select the most suitable category for our system within one service. As an example, Amazon S3 has different storage classes: S3 Standard, S3 Intelligent-Tiering, S3 Standard-Infrequent Access (S3 Standard-IA), S3 One Zone-Infrequent Access (S3 One Zone-IA), Amazon S3 Glacier (S3 Glacier), Amazon S3 Glacier Deep Archive (S3 Glacier Deep Archive), and S3 Outposts. From those, Amazon S3 One Zone-Infrequent Access (S3 One Zone-IA) can be considered as the most suitable storage class considering less frequent data access but gives rapid access when needed and saves data in on zone.

The front-end software solution can be developed by our own or can use AWS partner for the development with AWS services mentioned. Some of the suggested partners are listed below.

- *dbi services*
- *Amanox*
- *Copebit*
- *Innovation Process Technology AG*

10.5 Costs of AWS

The cost for different services are mainly based on the usage and therefore it is not a fixed number. Initial cost estimation was requested from AWS for its service with the following usage assumptions at the setting up.

10.5.1.1 Amazon S3 costs Assumptions

•10 GB/month stored in S3

10.5.1.2 Price calculations: 10 GB-month x 0.0245 USD/GB-month = 0.25 USD/month

1.1.1.1 Data transfer OUT costs Assumptions

• 100 GB are transferred every month out of AWS

Price calculations: the first GB of data transfer OUT every month is free of cost. The rest is billed at 0.09 USB per GB.

• 1 GB/month x 0 USD per GB = 0.00 USD

• 99 GB x 0.09 USD per GB = 8.91 USD/month

10.5.1.3 AWS Lambda costs

Unit conversions

• Amount of memory allocated: 256 MB x 0.0009765625 GB in a MB = 0.25 GB

Assumptions

• 3 million requests issued to the application API every month

• 256 MB of memory allocated to the Lambda function

• 300 ms average run time

Pricing calculations

• RoundUp (250) = 300 Duration rounded to nearest 100ms

• 3,000,000 requests x 300 ms x 0.001 ms to sec conversion factor = 900,000.00 total compute (seconds)

• 0.25 GB x 900,000.00 seconds = 225,000.00 total compute (GB-s)

• 225,000.00 GB-s - 400000 free tier GB-s = -175,000.00 GB-s

• Max (-175000.00 GB-s, 0) = 0.00 total billable GB-s

• 3,000,000 requests - 1000000 free tier requests = 2,000,000 monthly billable requests

• Max (2000000 monthly billable requests, 0) = 2,000,000.00 total monthly billable requests

• 2,000,000.00 total monthly billable requests x 0.0000002 USD = 0.40 USD (monthly request charges)

10.5.1.4 API Gateway costs assumptions

• 3 million requests to the application API

Price calculations

• 34 KB per request / 512 KB request increment = 0.06640625 request(s)

• RoundUp (0.06640625) = 1 billable request(s)

• 3 requests per month x 1,000,000 unit multiplier x 1 billable request(s) = 3,000,000 total billable request(s)

• Tiered price for: 3000000 requests

• 3000000 requests x 0.0000012000 USD = 3.60 USD

• Total tier cost = 3.60 USD (HTTP API requests)

• HTTP API request cost (monthly): 3.60 USD

10.5.1.5 DynamoDB costs

Assumptions

• 1 GB total data stored

• Average item size: 4 KB

• 3 million reads per month

• 1 million writes per month

• On-demand capacity

Price calculations

• 3 million 4kB reads * 0.305 USD/million reads = 0.915

• 1 million 1kB writes * 1.525 USD/million writes * 4 1/kB = 6.10

• Total cost: 7.02 USD/month

Note: Depending on the volume of data read and/or written to the database, using the Provisioned Capacity model within the free-tier limits can result in zero to low-cost (<10 USD) operation.

10.5.1.6 Amazon Simple Email Service (Amazon SES) assumptions

• 20 e-mails a day

• 20 e-mails/day * 30 days/month = 600 e-mails/month

Price calculations

• At this rate, usage would fall within the limits of the Amazon SES free tier.

10.5.1.7 AWS Step Functions assumptions

• 1000 approval flows started per month.

• An average of 5 state transitions per flow are needed

• 5 transitions/flow-month * 1000 flows = 5000 transitions/month

Price calculations

• The first 4000 state transitions fall within the AWS Step Functions free tier

• The remaining 1000 transitions are billed at 0.025 USD every 1000 transitions.

• Total cost: 0.025 USD/month

10.5.1.8 AWS Cognito

• Up to 50,000 monthly active users (MAU), there is no charge for using Amazon Cognito

• For each additional MAU, there is a cost of 0.0055 USD/MAU

• A MAU is a user that, within a calendar month, executes at least an identity operation, e.g.: sign-up, sign-in, token refresh, or password change

10.5.1.9 Amazon Route 53

• Supposing a single domain registered in Amazon Route 53, the cost would be 0.50 USD/month

10.5.1.10 Total Cost for AWS services

Total monthly cost of required services (no taxes included): 0.25 USD/month (S3) + 8.91 USD/month (Data transfer OUT) + 0.40 USD/month (Lambda) + 3.60 USD/month (API Gateway) + 7.02 USD/month (DynamoDB) + 0.025 USD/month (Step Functions) + 0.50 USD/month (Route 53) = 20.71 USD/month.

Cost for the front-end development with partners yet to be discussed with their opinions.

10.6 Google Cloud Platform (GCP)

Discussions are still going on with Google to finalize exactly which services we need to integrate in our system according to our requirements. One solution is to use Google GSuite (*https://edu.google.com/products/gsuite-for-education/?modal_active=compare-editions*) with integrating some extra services which are not available in GSuite.

Google provide "Google site" (*https://sites.google.com/new)* to create website if we develop front-end of the application by ourselves. This link provide a sample website created with Google site *https://www.sitebuilderreport.com/google-sites-examples.*

10.6.1 Cost of GCP

The cost of the Google services can be calculate using price calculator according to our requirement in usage (*https://cloud.google.com/products/calculator)*. Since still the services are finalizing it is not possible to estimate the cost.

Development of the front-end is also similar to AWS. We can develop by our own or hire a Google partner. Cost for the front-end development with partners yet to be discussed with their opinions. Rough cost is 1520 CHF for day and total 17 days with total of 25000 CHF from "Wabion" a Google partner.

10.6.2 Proposal of Wabino AG

Wabion is a leading Google Cloud Premier Partner and is enabling customers to use the GCP. Wabion expertise focuses exclusively on Google Cloud use cases and Wabion supports many companies, such as AXA, Coop Genossenschaft, and Tamedia. They have proposed following solution for TimFix database on Google Cloud Platform.

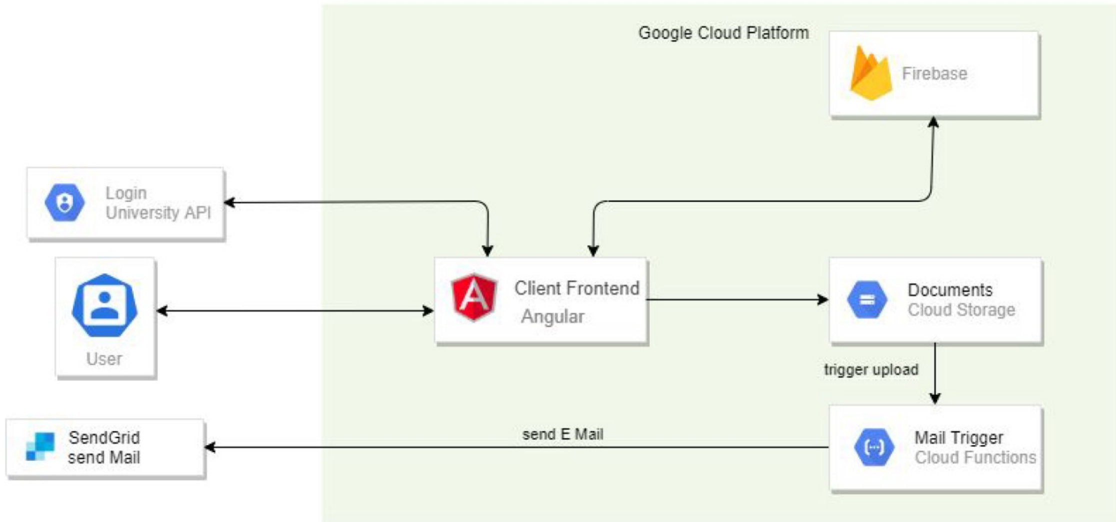


Figure 81: Architecture proposed by Wabion for TimFix database on GCP

The following components providing the following functionalities will be developed

Backend setup

- Setup and implementation of backend (Cloud Platform, Cloud Firestore, Cloud Function).

Frontend view and logic for file upload process

- Build and implementation of frontend (Webapp) with Angular Framework. They are building three different Views for the Roles Uploader, Viewer, and Approver with a simple frontend design. Upload and Viewer Views will be accessible to all logged in users. Approver View will only be accessible for a predefined group of users (2-3 predefined users).
- Inside the Webapp, they will implement the processing logic for the upload process.
- The Webapp will contain a simple search mechanism based on document tags provided by the Uploader.

Mailing Functionality

- Wabion recommend to build the Mail Functionality with the Send Grid API. But there is a second approach to implement the mail functionality with a fixed Gmail Account, which we should provide them. The Gmail approach would take 2 PD more to implement than the Send Grid Approach. With the Gmail approach, there is additionally a risk that other mail providers could make the mails from the Gmail account as spam if the mail provider receives too many emails from that mail account.

Login Integration

- All users can register to the platform (simple username based on mail address and password). The Login provides for all university user accounts (mails) access to the Web app. For mail addresses not registered as universities domain, a process to approve users is implemented (Approver View) Simple password forgotten, password reset logic is implemented.
- The Login process will not include Single Sign-On (SSO) login methods.

Security Rules

- Only valid Users inside the Webapp will have access to the Documents. With the Security Rules, system can restrict access to the documents who are not effectively logged in. Other general GCP security topics (like VPC) are out of scope.

10.6.2.1 Wabion Services

Wabion offers the following expert services. The estimated number of person-days [PD] to be worked by Wabion is shown in brackets to the right.

- Setup and implementation Backend [2 PD]
- Implementation Frontend View and Logic For Uploader [4 PD]
- Implementation Mail Functionality (SendGrid API assumed) [2 PD]
- Implementation Login Integration [4 PD]
- Implementation Firebase security rules [1 PD]
- Testing and deployment [2 PD]
- Project management (15% of Total) [2 PD]

10.6.2.2 GCP Usage Estimate

The cost of the Google services can be calculate using price calculator according to our requirement in usage (https://cloud.google.com/products/calculator).

Estimation: The total GCP Usage is around 2 USD per month for 400 Document uploads per month.

Since still the services are finalizing price indication may be subject to important changes depending on the effective consumption, Google price's change, etc.

10.6.2.3 Development Cost

The following hourly rates apply for services according to time expenditure:

- Software developer, Google Cloud Specialist CHF 185/h
- Members of the Management, Senior Project Managers CHF 200/h

Expenses for work carried out in Switzerland are included in these hourly rates, but not VAT. This will be charged in addition.

To determine a cost ceiling an average of 8 working hours per day is assumed. A daily rate of CHF 1’520 is used for calculating the cost ceiling. Thus, the following cost ceiling for the 17 PD listed in Chapter 8.7.1.1 may not be exceeded without written approval by the client:

Cost ceiling for services offered with this proposal is thus CHF 25’840 excluding VAT