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Fire performance of light timber frame construction in Europe: a review on fire protection measures and fire safety design

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ABSTRACT

Timber construction is becoming increasingly relevant for the climate and energy transition of the building sector. Notably, modern multilayered light frame elements are attractive due to their versatility and ease of prefabrication, and they are now used in a wide range of building heights and occupancies. However, wood and wood-based products are combustible, and verifying the fire resistance of timber frame elements and certification of innovative eco-materials require appropriate design and fire testing. This work contextualises the relevance of European timber structures towards the green transition. It further discusses the fire performance and fire safety design of light timber frame systems, emphasising passive fire protection measures. The paper also briefly addresses new developments in Eurocode 5 related to fire resistance verification of light timber frame elements. Additionally, as increasingly complex and innovative assemblies arise in construction practice, developing advanced models, such as finite element and comprehensive multiscale models, is required for performance-based fire engineering and product development. These models simulate the thermal and structural behaviour of timber at elevated temperatures, providing practical tools for assessing fire resistance. Therefore, an instructive background on comprehensive models for modelling the fire behaviour of timber is presented. This work is intended to be a one-stop reference for understanding the relevance of timber elements in Europe and the fire protection and fire safety design strategies for light timber frame construction within the framework of European guidelines.

1. Introduction

The design of energy and resource-efficient buildings and the adoption of sustainable and circular construction practices are essential to reduce the environmental impact of the building stock, which, according to the European Commission [1], is responsible for 40 % of energy consumption and one-third of greenhouse gas emissions related to energy in the European Union (EU). In this context, the strengthening of the legal and technical framework to meet building performance requirements, coupled with the urge to curb climate change, is leading to increasing interest in timber construction, mainly because sustainably harvested wood is a renewable resource with low embodied energy and low carbon impact compared to energy-intensive materials such as steel, plastics, and concrete [2,3]. Wood is also known for its outstanding strength-weight ratio, visual properties, durability, and flexibility of use, making timber-based products suitable for a wide range of construction applications [4,5]. Well-designed timber elements provide

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improved thermal insulation behaviour in new and renovated buildings, thus reducing energy needs for heating and cooling [6–9]. In addition, recent studies have highlighted the opportunities to improve circularity in modern timber construction through the recycling and reusing of wood products [10–13].

Timber construction has advanced considerably in recent years. The necessity to reduce the carbon footprint of the construction sector, along with advances in the development of highly engineered wood-based products, allowed timber solutions to become a viable alternative in low-rise and multi-storey constructions for various purposes. In the EU, the number of timber buildings, forest areas and growing stocks has expanded, although between 2010 and 2018, wood resources comprised, on average, only 2.4 % of the market for building materials [14]. Hopefully, the wood construction market will expand significantly until 2030, driven mainly by the

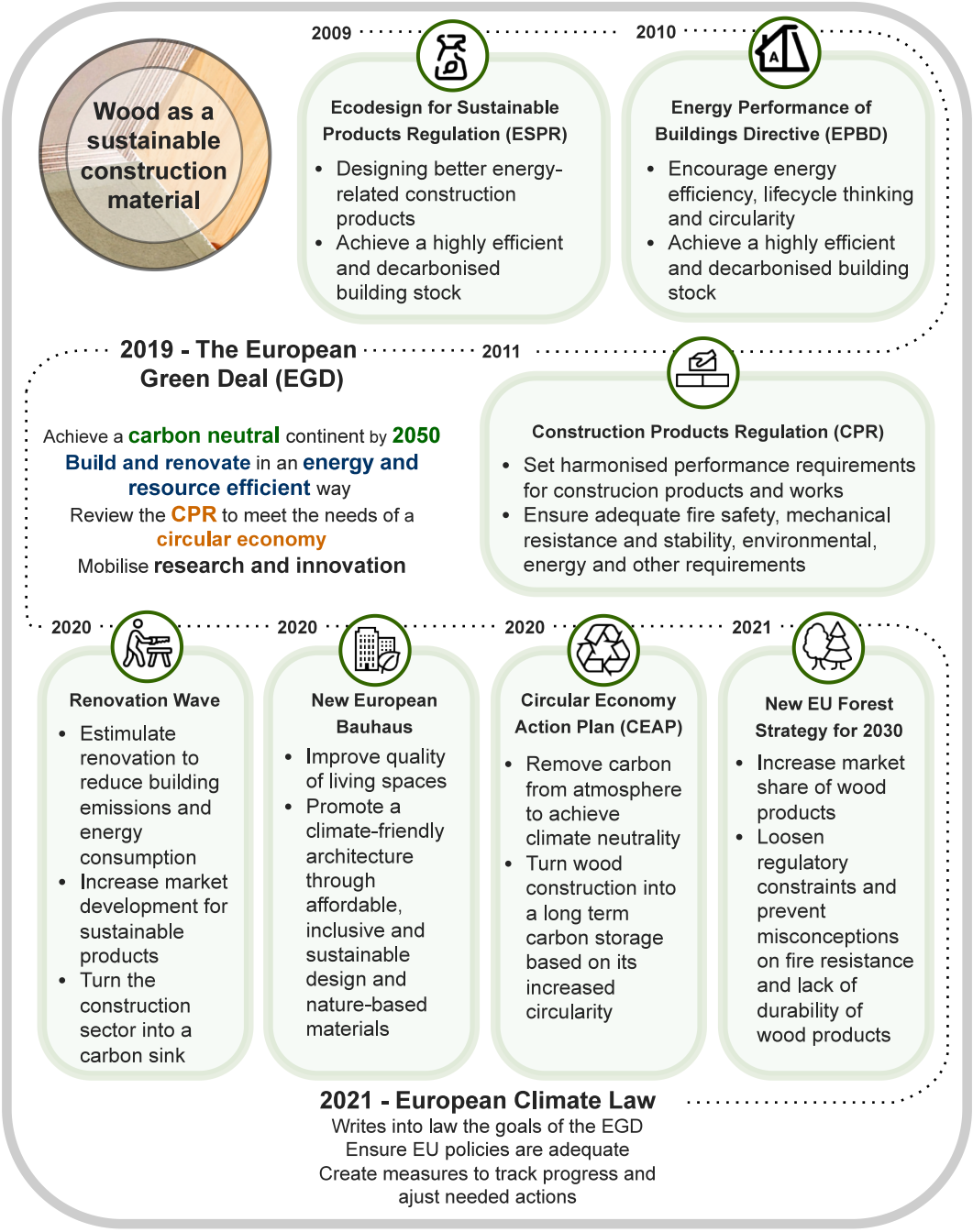

Fig. 1. Objectives of initiatives implemented in the European Union to promote wood products as sustainable construction materials. All icons by Icons8 [21].

consumption of engineered wood, which has consistent and predictable technical properties, making it suitable for high-quality constructions [15]. However, concerns about fire resistance, acoustic performance, and lack of durability are the primary reasons that limit the potential of wood products to foster an innovative, efficient, and sustainable construction sector and improve circular economy rates [16,17], which are fundamental goals of the European Green Deal [1] agenda (henceforth EGD).

The EGD [1] was adopted in 2019 to tackle climate change and achieve a carbon-neutral continent by 2050 by promoting key measures towards a green transition, including strategies to build and renovate in an energy and resource-efficient way. As shown in Fig. 1, various actions are being implemented to decarbonise the construction sector and meet the EGD goals. These initiatives, such as the New EU Forest Strategy for 2030 [14] and the Renovation Wave Strategy [18], highlight the role of timber construction in leveraging decarbonisation and improving the energy efficiency of existing and new building stock. The Energy Performance of Buildings Directive is the most important political instrument of the EU to ensure the sustainability and efficiency of the built environment. Nevertheless, further efforts are required to evaluate how wood and wood-based products offset carbon emissions throughout the entire lifecycle of buildings, constituting an essential challenge for the European Commission and member states [19]. Also, the marketing of wood as a feasible alternative to non-renewable resources must respond to demanding performance requirements following the harmonised conditions of the Construction Products Regulation (CPR) [20], which was recently revised in 2022 to keep pace with the EGD targets and include the environmental and circular performance of construction products in the CE marking process.

Safety is a common aspect amongst the basic requirements in the CPR for construction works, for which essential product characteristics are laid down through harmonised technical specifications. Fire safety is vital because fires are responsible for several human and economic losses worldwide. The European Fire Safety Alliance [22] estimates that fires in European residential buildings cause over 5000 deaths annually and approximately ten times as many injuries. However, fire death rates have decreased in Europe and North America by more than 60 % between 1979 and 2007, as noted in the report conducted by the United States Fire Administration [23]. In England, fire-related deaths decreased between 1981 and 2016, partly linked to advances in fire protection measures

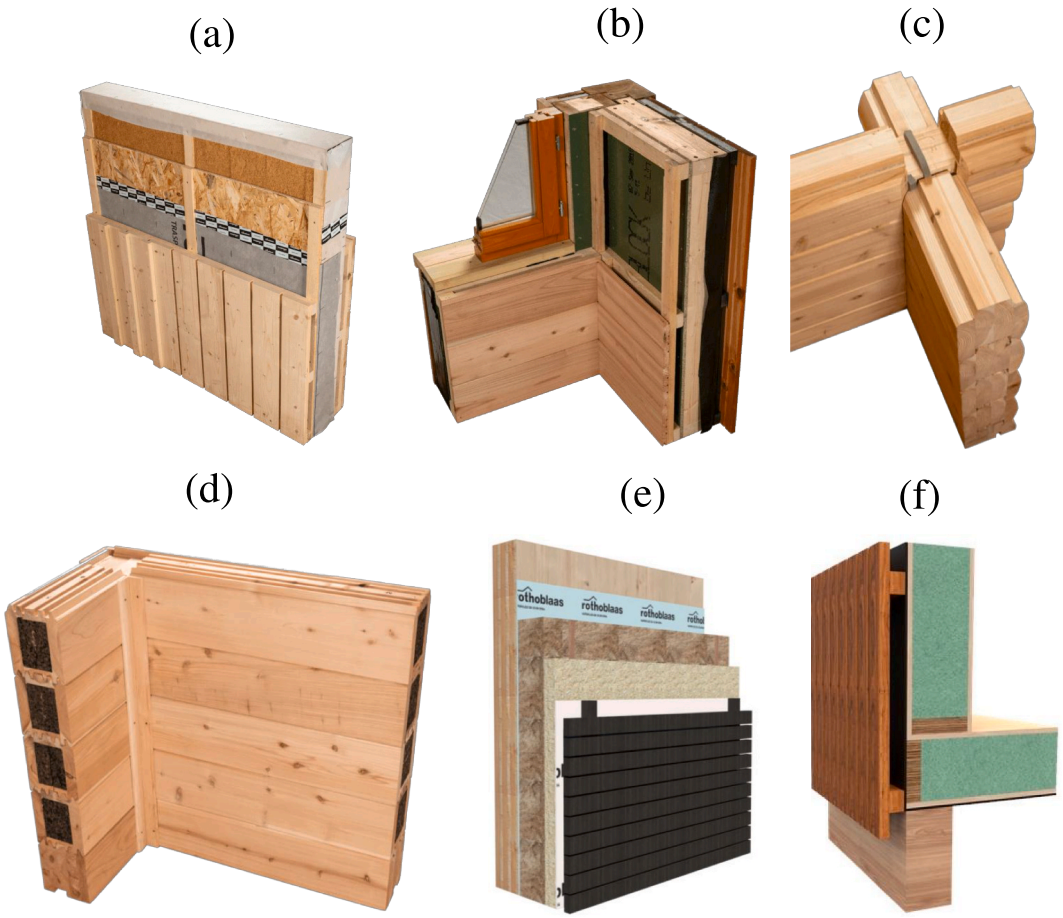

Fig. 2. Methods to assemble building elements in timber construction: (a) LTF wall with wood fibre cavity insulation; (b) Post-and-beam structure with a timber frame infill wall; (c) Wall junction with laminated logs; (d) Prefabricated timber system with cork core insulation; (e) CLT wall with double insulation; (f) Prefabricated structural insulated panels with foam insulation sandwiched between wood-based boards; Photos (a), (b), (c), (d) by Rusticasa [27]; Photos (e), (f) by New Edge [28].

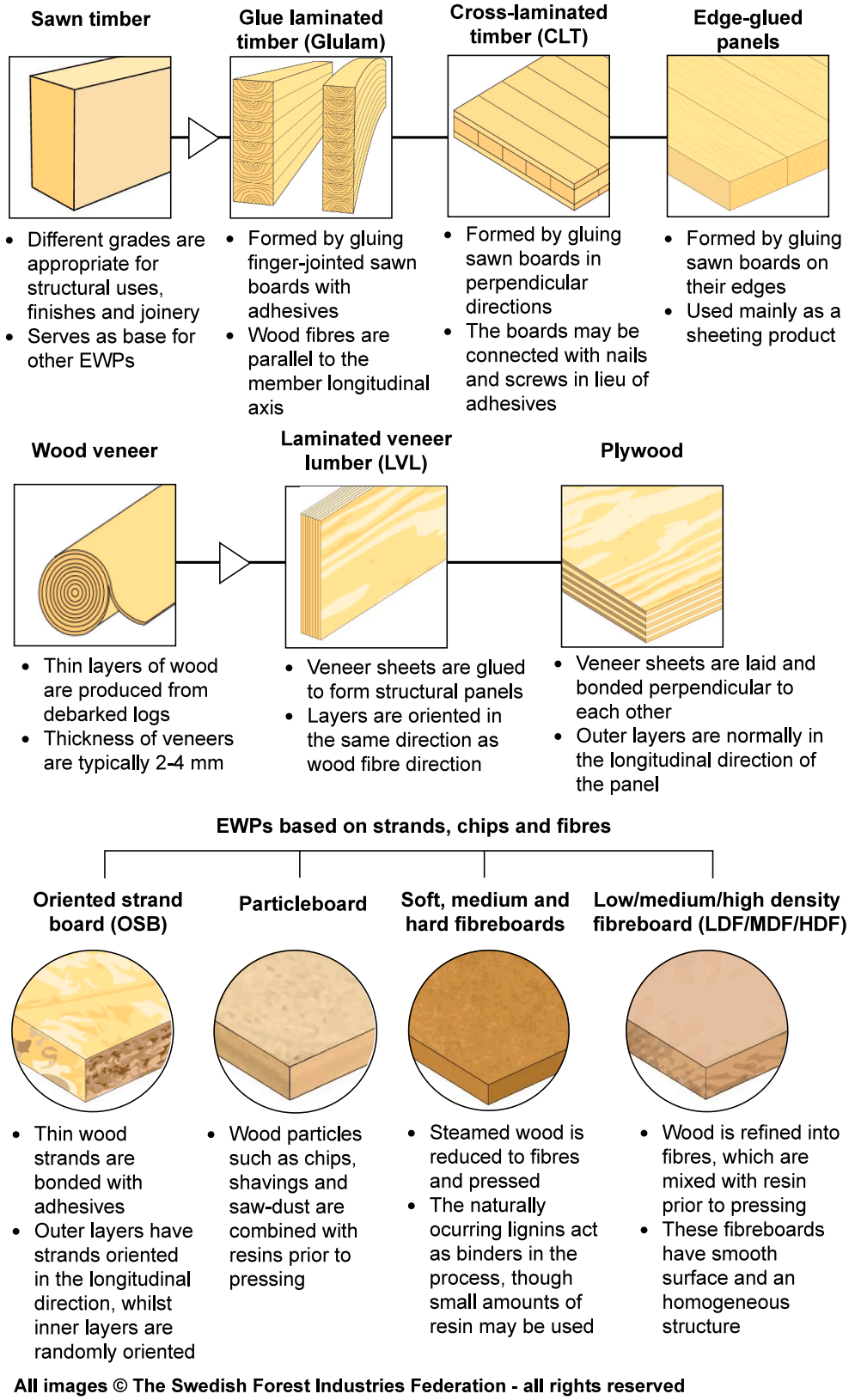

Fig. 3. Common wood products for construction purposes. All illustrations by Swedish Wood [35].

and a robust regulatory body [24]. According to the CPR, in the event of fire outbreaks, construction works must be designed and built to maintain structural integrity while limiting the generation and spread of fire and smoke between compartments and neighbouring constructions, hence providing tenable conditions for evacuation and rescue operations [20].

Fire is a significant action to consider in timber structures because burning wood can add to a building's fire load. However, the controlled charring of wood surfaces protects the inner layers from rapid thermal decomposition by reducing heat transmission. If appropriate fire safety measures are taken, well-designed timber buildings offer comparable fire performance to traditional structures built with carbon-intensive resources. To avoid early structural collapse of timber structures and limit fire spread during the relevant design time, or until burnout occurs, typical design practices involve increasing the dimensions of structural members above the required for regular temperature design and adopting active and passive fire protection strategies. In the context of passive fire protection, using protective coverings, membranes, protection systems, special coatings, and cavity insulation materials is a standard practice for building fire-resistant timber solutions. However, designing these structures for fire resistance is challenging due to the complex thermomechanical interactions that occur during fire exposure. As a result, designers often rely on prescriptive designs and simplified calculation rules in building codes to meet the demands of national regulations. In Europe, simplified methods for calculating the fire resistance of timber structures are covered by Eurocode 5 Part 1–2 [25], which is currently under revision [26]. Ultimately, fire tests are conducted to assess the fire resistance of timber designs and the fire behaviour of materials and protection systems. Fire testing is also required to verify product compliance for certification purposes. Nonetheless, simplified methods are limited, and fire testing is relatively expensive, justifying the development of advanced numerical models with different degrees of complexity to analyse the thermal and structural behaviour of timber structures under fire, thus supporting product development and allowing for a performance-based fire safety strategy.

Due to the relevance of light timber frame (LTF) structures, this work reviews the current state-of-the-art fire performance of this construction method in Europe. Traditional and innovative passive fire protection materials and practices in LTF construction are reviewed, and the requirements for fire reaction, fire resistance, and fire protection ability are discussed. New developments in the future version of Eurocode 5, henceforth designated FprEN 1995 1–2 [26], are also highlighted in relation to the fire resistance of LTF structures. An instructive background is provided regarding the thermomechanical behaviour of wood at elevated temperatures, serving as a basis for developing comprehensive multiscale models towards a performance-based approach. This has been encouraged in the fire science community to study the role of physicochemical processes in the fire behaviour of building materials and structures across scales.

2. Light timber frame construction

Timber construction methods are generally classified according to their gravity-resistant arrangement, as shown in Fig. 2. For example, in traditional LTF, small-sized sawn timber sections or prefabricated elements carry vertical loads, while structural sheathing provides in-plane resistance. In mass timber construction, cross laminated timber (CLT) panels are widely used as load-bearing elements for walls and floors. Post-and-beam or heavy timber structures consist of frames with large cross-sectional dimensions that support long spans and are generally infilled with panelised systems. Prefabricated load-bearing and non-load-bearing planar elements and volumetric modules are versatile, as they increase productivity by allowing components to be assembled off-site and further integrated into the construction process [27]. Hybrid buildings often combine different methods and materials to achieve technically challenging solutions [28]. Regardless of the construction method, in addition to being aesthetically pleasing and structurally safe, building elements are designed to provide adequate thermal and acoustic comfort, airtightness, and protection against weathering, moisture condensation, and fire. As shown in Fig. 2, modern timber construction techniques aim to combine materials with different properties and functions into multilayered structures to optimise the serviceability and fire performance of on-site and prefabricated elements, which are mainly comprised of a wide variety of wood products and building insulation materials.

LTF is the most frequent method for residential construction in North America, where it originated. It is also popular in Nordic and German-speaking countries to build low- and mid-rise buildings, and it is less used in Mediterranean regions [29]. Due to its ease of construction and lightweight nature, it is also the basic structural system of multilayered planar elements, such as walls, floors, and roofs, whether built on-site or prefabricated [17]. In modern low-to mid-rise LTF buildings, *platform framing* is the universal building method, where floor-to-ceiling height wall panels are erected upon the floor platform, allowing one storey to be assembled at a time [30,31]. This building method minimises fire spread because the wall frames are built with top and bottom rails, and rim boards enclose floor frames. Still, in the case of fire-rated assemblies, weak spots such as intersections, openings, cavities, penetrations and protrusions require special firestopping measures [32,33]. The structural frame may be composed of structural-grade sawn timber or engineered wood products. Unlike mass timber constructions, small-sized elements are used in LTF, thus requiring additional protection measures to withstand fire. This is achieved through the use of protection materials and systems, as well as proper detailing and execution. This section examines the multilayer structure of LTF assemblies, providing an overview of the types of wood products and insulation materials involved. Fire protection materials are addressed separately in Section 4.

2.1. Wood products

Wood products are generally distinguished into two main classes: sawn timber and engineered wood products (EWPs); see Fig. 3. Sawn timber is obtained through cutting or profiling of softwoods and hardwoods, while EWPs are manufactured from sawn timber boards, veneers, strands, chips, or fibres joined with adhesives or resins to form composite panels and systems [34]. EWPs may be composed of mechanically attached components (e.g., nailed laminated timber or NLT; tongue and groove floorboards) or

manufactured by bonding wood bits or elements with resins and adhesives under pressure, such as oriented strand board (OSB), medium density fibreboard (MDF), and CLT panels.

In Europe, the performance of construction products must be assessed in relation to the basic requirements defined in the CPR: mechanical resistance and stability, fire safety, hygiene, health and environment, safety and accessibility in use, noise protection, energy efficiency, and sustainable resource use [20]. For each requirement, the product performance is assessed against essential characteristics that vary depending on product type and end-use application. Harmonised standards specify these characteristics, conformity assessment procedures, and CE marking conditions within the European system. Table 1 provides examples of standard wood products, their main applications and the corresponding harmonised standards, noting that the list is not exhaustive and may evolve with industry developments.

In LTF buildings, load-bearing elements, such as wall studs and floor joists, are generally made from structural sawn timber spaced 450–600 mm apart. When higher performance is required, EWPs such as lightweight I-joists/I-studs and laminated veneer lumber (LVL) are used due to their improved dimensional stability and suitability for larger spans [32,34]. Strength-graded sawn timber sections typically range from 35 to 75 mm in width and 75–300 mm in depth [30,36], with tolerances defined in EN 336 [37], whereas I-joists/I-studs are 160–500 mm high, with flange widths of 45–90 mm and thicknesses of 39–45 mm. Due to their small cross-sections, structural LTF members are rarely exposed, requiring fire protection to prevent rapid charring and loss of load-bearing capacity [32]. Sawn timber can also be engineered into structural EWPs, including CLT and Glulam, where multiple layers are face-glued to achieve larger sections with improved structural, dimensional and fire performance. In contrast, non-structural EWPs made from sawn timber are used in cladding, panelling and flooring applications (see Table 1), and can also act as fire barriers. Adhesive fire performance in bonded EWPs is critical, since weak bonds may cause delamination, increase fire load and reduce assembly integrity [38]. Moreover, wood-based panels in LTF are widely used for cladding and panelling, or as structural sheathing to provide bracing and bending resistance. Combined with thin membranes, they improve airtightness, moisture control, and acoustic performance. Although these panels tend to char more quickly than solid timber, they still provide some fire protection when used as sacrificial layers [39] (see Section 4).

2.2. Insulation materials

Insulation materials contribute to energy savings, acoustic comfort, and building fire performance [40–43]. The most in-demand materials for building purposes are mineral wools (rock wool and glass wool), synthetic foams based on polystyrene and polyurethane polymers, and biobased insulation such as spray cellulose, wood fibres and cork [44–46]. These materials are available in different formats, including loose-fill forms, fibre blankets, rigid or flexible foams, and sprays [45]. Table 2 presents a non-exhaustive list of harmonised product standards related to common building insulation materials and their classification for fire safety design according to the simplified methods of FprEN 1995-1-2 [26].

The energy efficiency benefits of building insulation materials are intrinsically related to their low density and low thermal conductivity. This translates into low thermal inertia and reduced heat flow to and from building elements, so that energy is conserved indoors during the cold seasons and interior overheating is minimised in hot climates. For multilayer constructions, optimising thermal performance involves minimising the overall heat transfer coefficient of the solution, or U-value, which is a function of the thermal conductivity, thickness, and density of the element layers [45]. Humidity levels and the temperature to which timber elements are typically exposed will influence U-values, as the thermal conductivity of wood products and insulation materials tends to increase with temperature, density, and moisture content [47–50]. Insulation materials are commonly installed within wall cavities between timber studs, in roof spaces between rafters, and under floors between joists to minimise heat transfer and prevent thermal bridging. Furthermore, as discussed in Section 4, insulation is often essential in fire-rated LTF designs.

3. Fire safety requirements

One primary objective in fire safety engineering is to contain fire development within the origin room to minimise hazards to

Table 1
Applications of wood products for construction purposes and their related European product standards.

Product standard	Type of wood product	Main applications
EN 14081-1	Strength-graded structural timber with rectangular cross-section	Light timber frames, formwork, and source material for various EWPs
EN 14080	Glued laminated timber (Glulam)	Bar-shaped structural elements (beams, columns), long-span structures
EN 14374	Structural laminated veneer lumber (LVL)	Bar-shaped structural elements, I-joists/I-studs, light timber frames
EN 16351	Cross laminated timber (CLT)	Load-bearing and non-load-bearing planar elements (walls, floors and roofs)
EN 13986	Wood-based panels (e.g., edge-glued solid wood panel, OSB, MDF)	Structural bracing, cladding, panelling, and components of prefabricated elements
EN 14915	Solid wood panelling and cladding (e.g., tongue and groove profiles)	Exterior cladding and interior panelling in ceilings and walls
EN 14342	Wood flooring and parquet (e.g., solid wood floorboards, wood veneer floor coverings)	Flooring applications

Table 2
Fire protection level of building insulation products and their related European product standards.

Product standard	Type of insulation product	Protection level according to FprEN 1995-1-2 [26]
EN 13162	Mineral wool products (e.g., rock wool)	PL1 ($\rho \geq 20$ kg/m^3) PL2 ($\rho \geq 14$ kg/m^3)
EN 13163	Expanded polystyrene	PL3
EN 13164	Extruded polystyrene	PL3
EN 13165	Rigid polyurethane foam	PL3
EN 13168	Wood wool	–
EN 13170	Cork insulation boards	–
EN 13171	Wood fibre products	PL2 ($\rho \geq 50$ kg/m^3)
EN 14064-1	In-situ formed loose-fill mineral wool	–
EN 15101-1	In-situ formed loose-fill cellulose	PL2 ($\rho \geq 35$ kg/m^3)

*ρ is the density in kg/m^3; PL: protection level.

adjacent structures and other building areas, providing safety for occupants and rescue teams and preventing property damage. This strategy, known as compartmentation, involves controlling the spread of fire throughout the building by selecting appropriate building materials based on their combustibility characteristics and providing fire-resistant elements to define the boundaries of fire compartments. The typical time-temperature curve of a complete compartment fire is illustrated in Fig. 4, where four stages are distinguished. In the incipient phase, localised heating and preheating of the available fuel occur, and depending on the fuel type and distribution, ignition conditions may be reached. This initiates the growth stage, characterised by flaming combustion and flame spread to adjacent fuel within the compartment. Flashover is a rapid transitional event in which most directly exposed combustible surfaces ignite due to intense thermal radiation feedback and flame spread, marking the onset of the fully developed stage [51]. In the absence of active suppression, the fire eventually enters the decay stage as the heat release rate decreases because the fire becomes fuel-limited or ventilation-limited [52]. The burnout marks the end of the burning process, occurring when the limiting conditions, such as fuel availability, critical mass loss rate and oxygen concentration, are no longer sufficient to sustain combustion [53].

Designing for fire safety primarily involves adopting both active and passive measures. The first requires human intervention or the operation of automatic devices that enable the control of pre-flashover fires. Passive strategies rely on carefully selecting materials and systems to mitigate risks and consequences in both pre- and post-flashover stages. They often involve seeking compliance with the fire performance characteristics of construction materials and building elements, specifically fire reaction and fire resistance, which can be verified through testing and calculation procedures. In Europe, the fire performance of building materials and systems is declared based on a system of nominal ratings, as explained in the following sections. This classification is important because national building codes regulate the fire reaction properties of coverings and the fire resistance capabilities of building elements, aiming to achieve fire compartmentation, particularly at the boundaries of evacuation routes and high-risk compartments. An informative overview of

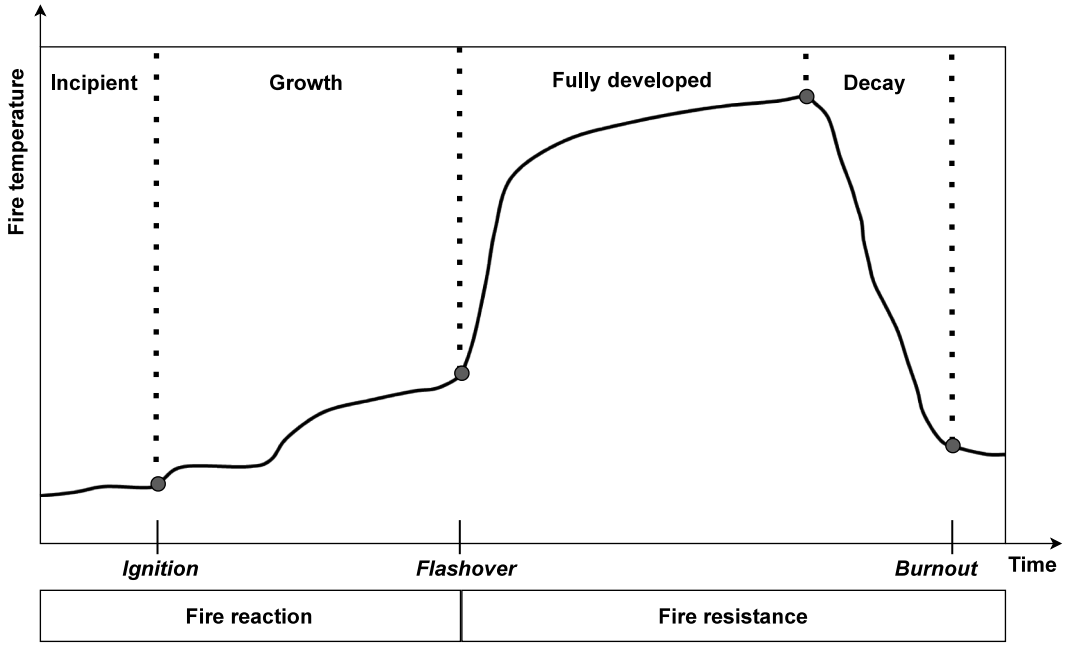

Fig. 4. Time-temperature diagram of a complete compartment fire showing the influence of different fire stages on the fire reaction and fire resistance characteristics of construction products and building elements.

worldwide fire resistance requirements, with a special emphasis on differences between building codes regarding the amount of exposed timber (both outside and inside), active protection systems and building typologies, is presented in Östman [54].

3.1. Fire reaction

Fire reaction relates to the thermal decomposition effects of materials exposed to heat sources. This primarily affects the burning rate, heat release, smoke production, and spread of flames in combustible building materials during the incipient and growth stages of a fire, as shown in Fig. 4. After ignition, the resulting flaming combustion and heat release from burning objects can trigger the ignition of nearby combustible fuels, initiating a fire-spread process that may lead to flashover as heat builds up. The intensity of fire growth and flashover time depends on the type, configuration, amount of burning items, and air entrainment rate [55]. In the case of timber buildings, managing exposed timber areas is necessary to control the fuel load and fire spread [56,57].

EN 13501-1 [58] classifies construction products and building elements according to their fire reaction from non-combustible (A1, A2) to easily combustible (F); see Table 3. Compliance with a specific class requires satisfying the criteria based on standard tests to determine parameters such as ignitability, mass loss rate, heat release, smoke production, and flame propagation. Wood products with density >300 kg/m^3 and thickness > 9–18 mm generally achieve class D, while fire-treated wood products fall into class B [59]. Non-combustible materials, such as rock wool with a limited binder content and glass wool, are commonly rated as A1 or A2. Reducing the combustibility of wood products is possible by incorporating fire-retardant compounds during manufacturing or through impregnation treatments and applying protective coatings after manufacture [60]. The composition of typical fire-retardant products is commonly based on halogen, phosphorus, nitrogen, boron, and inorganic compounds such as silicates and aluminium hydroxide [61,62]. However, the durability of fire-retardant compounds and protective coatings is particularly sensitive to weathering agents, and the fire performance of treated wood products can be reduced over time, especially in outdoor environments [60,63]. This issue has led to the development of EN 16755 [64], which addresses the classification of the durability of reaction to fire of wood products in both interior and exterior applications.

The reaction to fire characteristics of combustible solids are particularly relevant in performance-based fire safety engineering, where there is a need to establish material fire properties, such as ignition thresholds, pyrolysis properties, flame spread, heat release, smoke production, and mass loss rates. Tests at multiple scales, including microscale analyses and cone calorimeter studies, are helpful to determine such properties. This is not further discussed here as the fire reaction behaviour has little effect on post-flashover fire protection and fire resistance of building elements [54]. Still, useful references provide a substantial amount of data regarding the reaction to fire behaviour of wood and wood-based products [59,68,69], methods to improve it [61,70,71], durability considerations [72,73], and progress on fire-retardant bio-based solutions [74–77].

3.2. Fire resistance

As seen in Fig. 4, the start of a fully developed fire describes the moment it evolves from a localised phenomenon to an all-engulfing stage. During a fully developed fire and the subsequent decay phase, the provision of compartmentation depends essentially on the fire resistance function of the building elements, which refers to their ability to remain stable (load-bearing function) and prevent the passage of flames, smoke, hot gases, and heat to adjacent spaces (fire separating function) throughout the relevant fire design time [78,79]. The duration and temperature of the fully developed phase are influenced by the availability of fuel and ventilation conditions [78]. Once the fuel has been mostly consumed, temperatures decline, leading to burnout, provided the compartmentation strategy functions effectively. However, in timber structures, complete extinguishment requires firefighting intervention because the wood may continue to smoulder slowly after the decay phase, which impacts the fire resistance of structural timber members [79]. As seen in Section 4, delaying the charring of timber structures through fire protection measures in post-flashover stages is essential to avoid additional fuel loads that could increase fire severity and cause critical timber elements and connections to collapse.

Table 3
Fire reaction classes of construction products. Adapted from Refs. [59,65].

Class[a]	Contribution to fire	Smoke release[b]	Flaming droplets/ particles[c]	Typical construction products
A1	No contribution to fire	–	–	Products of natural stone, concrete, ceramic, and steel [65]
A2	No significant contribution to fire	s1, s2, or s3	d0, d1 or d2	Mineral wool, gypsum boards (thin paper) [59]
B	Very limited contribution to fire	s1, s2, or s3	d0, d1 or d2	Fire-retardant particleboard, cement-bonded particleboard [66] Fire-retardant birch, spruce panel [67] Gypsum plasterboards (thick paper) [59]
C	Limited contribution to fire	s1, s2, or s3	d0, d1 or d2	Fire-retardant spruce panel with surface treatment [67]
D	Contribution to fire	s1, s2, or s3	d0, d1 or d2	MDF, particleboard, plywood, OSB [66] Solid pinewood, spruce [67]
E	Significant contribution to fire	–	- or d2	Low-density fibreboard [67] Plastic-based insulation products [65]
F	Products that do not fulfil class E	–	–	

[a]Excluding floorings. A special notation is adopted for flooring applications by adding the subscript 'fl', e.g., A1$_{fl}$; [b] 's' = smoke; [c] 'd' = droplets.

The fire resistance classification of construction products and building elements based on data from fire tests is specified in EN 13051-2 [80]. Load-bearing elements, including walls, floors, beams, and columns, as well as non-load-bearing elements such as partitions, façades, and fire doors, are covered by this standard. Fire resistance is determined by exposing a representative specimen to a prescribed nominal fire and evaluating its behaviour against the performance characteristics shown in Table 4.

The fire resistance rating refers to the time, in completed minutes, that the element satisfies one or more performance characteristics according to the appropriate assessment criteria. The classification periods are 10, 15, 20, 30, 45, 60, 90, 120, 180, 240, or 360 min of standard fire exposure; however, specific timeframes apply to different categories of building products and systems. Additional requirements may apply depending on the type of building element and the regulations specified in national standards. For example, fire doors may be required to demonstrate self-closing ability (C) and the capacity to reduce or eliminate smoke passage (S), and a firewall (e.g., compartmentation between buildings) should withstand an impact mechanical action (M) after fulfilling the R, E and I requirements [80].

The thermal exposure condition in fire resistance tests will vary depending on the type and function of the building element. The standard fire exposure from ISO 834-1 [81] shown in Fig. 5 represents the fully-developed stage of a ventilation-controlled compartment fire and is the most widely accepted thermal exposure to determine the fire rating of load-bearing and non-load-bearing elements with or without a fire separating function tested according to EN 1363-1 [82]. Other nominal fire exposures are shown in Fig. 5, where their common feature is the exclusion of a decay stage.

In prescriptive building codes, minimum fire resistance requirements for the load-bearing and non-load-bearing structure are usually 30, 60, 90, 120 or 180 min of standard fire exposure (fire design time) for different occupancies [54]. However, as seen in Fig. 4, standard fire curves fail to represent the thermal conditions of real compartment fires, particularly during the decay stage and when combustible exposed surfaces are involved, where the additional fuel could significantly alter fire severity [79]. In a performance-based pathway, more realistic fire models can be implemented in fire safety design using parametric curves, localised fires, travelling fires and comprehensive natural fire models, considering the compartment and fuel characteristics explicitly in a way that the definition of the appropriate design fire is compatible with the fire scenario identified in the fire safety strategy [83,84]. However, parametric fires such as those specified in EN 1991-1-2 [85] can only be used in compartments of combustible frames if the timber surfaces do not contribute to the fire dynamics, that is, if timber surfaces are fully encapsulated throughout fire exposure [83]. If the compartment is designed to withstand burnout, iterative, realistic fire scenarios reflecting, for example, the contribution of exposed timber surfaces, available fuel load, and ventilation conditions, as well as compartment openings and size, and the failure of protection systems, may be necessary to demonstrate compliance.

There has been active research on compartment fire dynamics at multiple scales involving exposed timber surfaces, especially in mass timber structures, with emphasis on determining the effects of the amount and arrangement of exposed timber, fire protection and lamellae failure, ventilation conditions and the limiting variables of the transition between stages in a compartment fire [86–89]. Data regarding the validation of natural fire models and fire dynamics in compartments involving LTF structures with exposed or non-exposed wood and wood-based materials is also documented in literature [90–94]. Full-scale tests on LTF compartments have shown that uninsulated assemblies with combustible linings can experience secondary flashover and pose a higher risk of external fire spread [90,91]. Insulated assemblies with gypsum plasterboard exhibit fire temperatures that differ significantly from standard fire curves [92,93]. Additionally, timber studs were observed to char at an average rate of 1.2 mm/min before gypsum failure [93], which exceeds the design assumptions for a standard fire [25,26]. Existing studies primarily address simple layer configurations, whereas modern LTF assemblies incorporate multiple layers, where additional fire loads and material failure, such as heat-induced delamination, char fall-off and protection fall-off, can significantly influence fire growth and burnout conditions. Current predictive methods cannot reliably account for these phenomena [83], underscoring the need for additional full-scale experiments to develop and validate design models for fire growth in multilayered compartments with varied geometries and ventilation conditions. Currently, Annexe A in FprEN 1995-1-2 [26] provides general guidance on the design of timber structures exposed to physically based design fires, including parametric, where it is possible to consider the influence of exposed timber on the fire load and duration iteratively [95]. Validations and comparative studies are expected to be conducted for LTF compartments. More details on this subject can be found in Wade et al.'s [83] and Brandon et al.'s [96] informative review of compartment fire models with varying levels of complexity.

4. Fire protection

Applied fire protection in timber elements reduces the impact of exposed combustible surfaces on the fire load and delays or minimises the charring of critical members, thereby preventing fire spread and further structural damage. EN 13501-2 [80] describes

Table 4
Definition of fire resistance performance characteristics of building elements exposed to standard fires according to EN 13501-2 [80].

Performance characteristics	Definition
R – Load-bearing capacity	The ability of a building element to withstand fire exposure while resisting the applied load without collapsing.
E – Integrity	The ability of a building element with a separating function to contain a fire when exposed on one side, without developing openings such as cracks and gaps that allow smoke, flames, and hot gases to pass through the assembly, and that may cause ignition of the unexposed side of the element or nearby surfaces. Failure of the load-bearing capacity is also considered a failure of integrity.
I – Insulation	The ability of building elements exposed to fire on one side to limit the increase in average and maximum temperatures on the unexposed side to 140 °C and 180 °C, respectively, above the initial mean temperature, to avoid ignition of nearby surfaces.

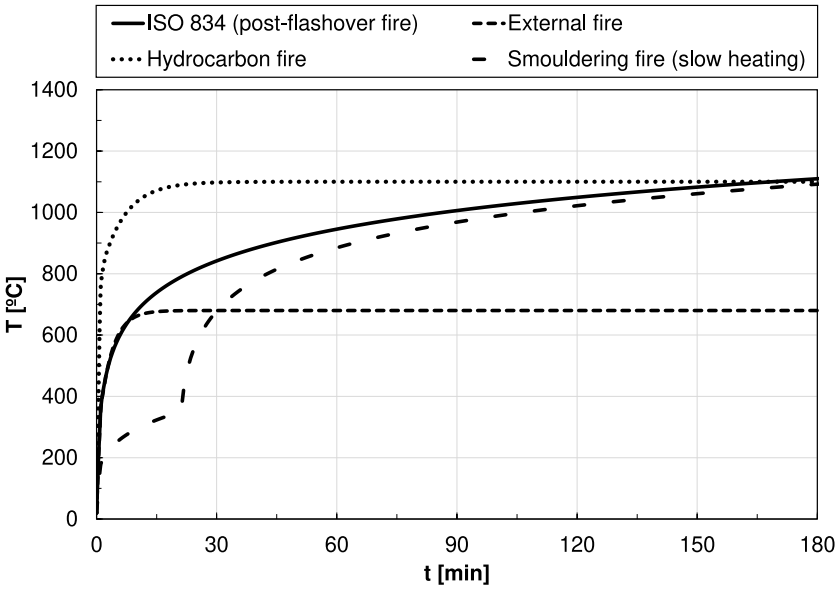

Fig. 5. Nominal fires to determine the fire resistance classification of building elements.

two classes of fire protection products: horizontal and vertical membranes without independent fire resistance, and fire-protective coatings, boards, renderings, and claddings. The contribution of these products to the fire resistance of timber elements may be assessed through experimental tests according to the appropriate parts of the EN 13381 series, where it is possible to determine the time required for the protected element to begin to char at a temperature of around 300 °C, its charring rate, and the time when the protection material or system loses its protective function (failure time). This information becomes accessible for further calculations regarding the separating and load-bearing functions of timber structures, and it is essential to investigate the feedback between the thermal decomposition and failure of exposed materials and the changes in fire dynamics. In alternative to EN 13381, the new generation FprEN 1995 1–2 [26], in its annexes C, F and G, presents significant improvements from the previous version [25] by informing alternative procedures to determine the charring onset time, the charring rate and the failure time of component layers in standard fire. It also provides experimental and analytical guidelines to extend the Separating Function Method (SFM) to other assembly configurations, as seen in Mäger et al. [97].

4.1. Fire protection through encapsulation and partial encapsulation

The term ‘encapsulation’ is used to describe the application of sufficient layers of protective materials to avoid ignition and the onset of charring during the designated fire design time or until burnout occurs, thus preserving the structural stability and reducing the contribution of timber surfaces to the fire load [79]. A system of European K classes was introduced to determine the fire protection ability (encapsulation rating) of coverings in standard fire tests according to EN 14135 [98] and classified to EN 13501-2 [80]. According to EN 13501-2 [80], coverings are the outermost layers of vertical structures (e.g., walls) or the lowermost layers of horizontal structures (e.g., floors, ceilings). They protect any underlying structure from elevated temperatures and typically have the most influence on the fire resistance rating of the assembly in terms of insulation capacity [99]. Fig. 6 exemplifies the application of fire protection coverings in LTF structures.

As described in Table 5, the type of substrate behind the covering determines the K_1 10 or K_2 10/30/60 classification. This

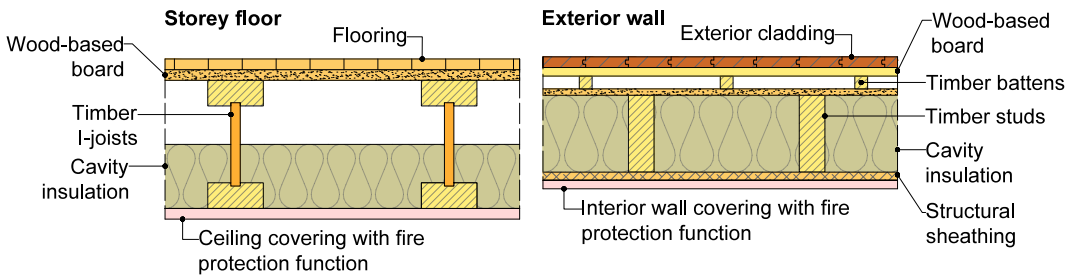

Fig. 6. Cross-sectional details of floor (left) and wall (right) light timber frame assemblies with fire protection applied as ceiling or wall coverings. Thin membranes and barriers are omitted for clarity.

classification is relevant because, in addition to the usual fire reaction requirements for coverings in buildings (see subsection 3.1), some European countries (e.g. Germany, Denmark and Sweden) also place limits on their K classification [39].

Fig. 7 illustrates the performance criteria to determine the encapsulation rating of coverings installed horizontally, which is the most unfavourable situation in a fire. The main criterion is the temperature rise behind the protection layer and on the substrate after 10, 30, and 60 min of fire exposure. Additionally, no fall-off of the protection material or its parts is allowed, and the acceptable degree of damage depends on the designation K_1 or K_2. The temperature criteria are closely related to the basic protection time of layers in timber assemblies [97,100] and the charring onset time of the protected member, as seen in the simplified methods of both the previous and new generations of Eurocode 5 Part 1–2 [25,26]. However, the limit for the maximum temperature increase on the substrate (270 °C) is lower than the 300 °C charring threshold for timber structures. This is because, during the fire test, the thermal wave continues to propagate before the final observation of the test specimen [101].

Table 6 presents the encapsulation times for various exposed materials and substrates, as determined through experimental tests conducted in furnaces. Low-combustible and incombustible covering materials (e.g., gypsum and cementitious boards) are the most widely used materials for encapsulation. Additionally, wood-based panels offer fire protection for building elements due to the slow charring rate of wood. They can be used as ceiling and wall coverings and as 'sacrifice' fire protection layers [102,103]. As shown in Table 6, the encapsulation time of wood-based boards increases with their thickness. Most wood products, with densities ranging from 450 to 800 kg/m[c] and thicknesses of 9–30 mm, offer fire protection capabilities of 10–30 min. However, if wood products are allowed to remain visible in a building as a covering material or will be exposed in a fire event, considerations about the increase in the fire load density are necessary if the building is designed to withstand burnout, as is usually required for tall and high-risk buildings [79]. Therefore, the type, quantity and arrangement of exposed combustible surfaces must be carefully planned, and their effects on fire severity and duration should be quantified [83]. Nevertheless, wood products are still a better alternative to common synthetic polymers, which can ignite quickly and are more susceptible to rapid flame spread and toxic smoke release [59,69].

When complete encapsulation is not possible or undesired, partial encapsulation initially reduces flame spread and heat transfer; however, charring or ignition of the underlying structure may eventually occur, potentially contributing to an increase in the compartment fire load. If the protection material or system fails during a fire, the initially protected structure will be subjected to a higher heat flux, thus increasing charring rates [115]. These thermal dynamics will impact the fire resistance of the protected element and alter the conditions that lead to burnout. Comprehensive studies have been conducted to determine the failure time of gypsum plasterboards in full-scale standard fire tests [107,116], which form the basis of the recommendations in FprEN 1995 1–2 [26]. Compared to the previous generation, the new one offers much more flexibility and a wider range of protection materials where the time to charring (t_{ch}) and failure time ($t_{f,pr}$) are readily obtained using tabulated data or calculation formulas for standard fire exposure. It also provides valuable recommendations for conducting experimental tests to determine these variables for other fire protection materials and systems that fall outside its scope. Previous research [91,117,118] indicates that gypsum board failure is strongly influenced by the type of board and the type of fire exposure to which it is subjected. While multilayer encapsulation improves the fire resistance of timber elements, it does not ensure burnout protection under non-standard fires due to mechanisms such as fall-off and seam opening [119]. Detachment and cracking often occur earlier than expected in standard fire, with cooling phases amplifying damage. These failures are driven more by heating/cooling rates than peak temperature, challenging standard fire assumptions. Ramzi and Hajiloo [120] confirmed that fall-off times increase with additional layers and reduced channel spacing but decrease with cavity insulation, and emphasised the need to study fastener type, spacing, loading, and joint details. Since current standards (e.g., EN 13381 series and FprEN 1995 1–2 [26]) focus on standard fires, further research should address how gypsum board types and similar fire protection materials, installation quality, loading, and detailing affect failure mechanisms under non-standard scenarios.

Similarly, limited experimental data are available concerning the protection failure time of wood products [111,113], and it is usually assumed that it coincides with the onset of charring on the substrate for elements oriented vertically or horizontally [25,26]. Proft et al. [121] reported that for a 22 mm particleboard panel in standard fire, the protection failure time ($t_{f,pr}$) was nearly twice the charring onset time (t_{ch}). Kolaitis et al. [111] found that $t_{f,pr}$ and t_{ch} were similar for MDF under natural fire. However, for particleboard, the difference was at least 7 min. Both studies used unloaded specimens. Since the failure conditions for wood-based coverings are poorly documented, further research should examine the effects of loading, detailing, and installation practices. Moreover, although treatments such as impregnation and thermal/chemical modification reduce flammability, their impact on charring and fire protection at the fire scale remains unclear, as existing studies focus on small-scale tests [71,122–125]. Nonetheless, the EN 13381 series and FprEN 1995-1-2 [26] provide a sound basis for extending investigations into the fire protection behaviour of conventional and innovative wood and wood-based products and systems.

Table 5
The system of European K classes to evaluate the fire protection ability of coverings and the performance criteria according to EN 14135 [98].

Classification	Substrate behind the covering	Rating encapsulation time [minutes]	Classification criteria
K_1 10/30/60	Standard chipboard or substrate with density <300 kg/m^3 or other specific substrate	10	• No collapse of the covering or parts of it • No damage on specified surfaces[a] (charred, burnt, melted or shrunk material)
K_2 10/30/60	Standard chipboard or other specific substrate	10	• The mean and maximum temperature increase on specified surfaces[a] are limited to 250 °C and 270 °C above the initial temperature, respectively
K_2 30		30	
K_2 60		60	

[a] The surfaces on which the classification criteria apply depend on whether there is a cavity behind the covering; see Fig. 7.

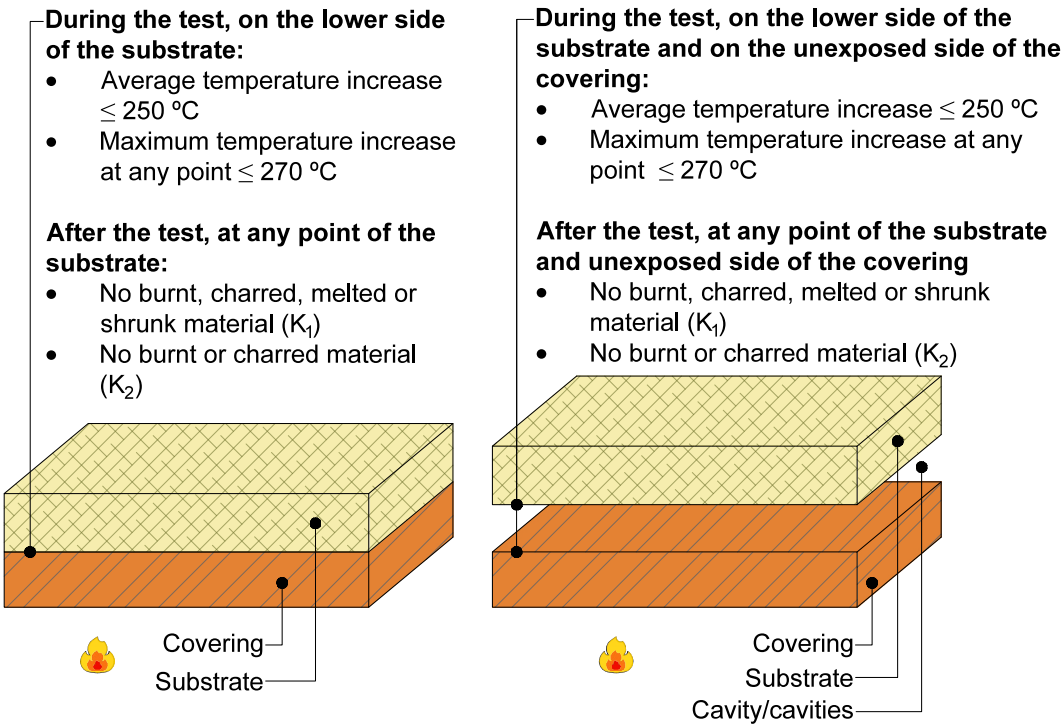

Fig. 7. Classification criteria to determine the protection ability of coverings exposed to standard fire on one side in horizontal orientation, in assemblies without (drawing on the left) and with (drawing on the right) cavities.

4.2. Cavity insulation and protective coatings

Insulation materials play an essential role in the fire performance of timber construction as they minimise the spread of fire inside cavities. As seen in Table 6, they significantly delay the onset of charring in timber members. The primary example is flexible batt-type insulation such as rock wool, which can retain its integrity at high temperatures and reduce heat transfer through insulated assemblies. However, the insulation must remain in place throughout fire exposure or most of it; thus, adequate fitting, e.g., timber battens, resilient channels, glueing and tight fitting, is recommended. On the contrary, the low thermal inertia of the cavity insulation increases the build-up of heat behind the preceding layers, resulting in an early fall of these layers [100]. This effect is now considered in the simplified methods of FprEN 1995 1–2 [26] by reducing the protection time of the layer backed by different materials, including insulation. The role of cavity insulation on the fire resistance of timber assemblies is addressed in the same standard, which introduces a protection classification for typical building insulation materials, as presented in Table 2. This classification is a new approach compared to the current counterpart standard [25], and more insulation types other than glass fibre and rock wool are included. Additionally, a more comprehensive approach to determining the effective cross-section of cavity-insulated members for structural calculations is presented. Another significant change is the possibility of determining the protection level of various insulation materials through an experimental procedure (Annexe D [26,126]) in addition to the ratings shown in Table 2.

Experimental and numerical evidence on the fire performance of mineral wools and bio-based insulation materials, such as wood fibre boards and loose-fill cellulose in LTF assemblies, is well documented under standard fire exposure [127–130]. Simplified design methods in FprEN 1995 1–2 [26] already include these materials for LTF elements with rectangular and I-shaped cross sections. However, the influence of mechanical load and load-induced deformations on cavity insulation stability and its ability to remain in place during fire exposure has not been thoroughly investigated, which may be particularly relevant for bio-based insulations [129]. As a broader range of lignocellulosic cavity insulation materials emerges for sustainable timber building systems [131], including cork [132,133] and sawdust or straw composites [134–136], fire-scale experimental and numerical data would be valuable for developing product-specific material models and extending simplified design approaches.

Fire-retardant coatings and impregnation treatments are also intended to minimise fire hazards in the early stages of fire development, with a minor impact on the fire resistance of building elements during fully developed fires. As an exception, intumescent surface coatings protect the underlying virgin material by expanding into an insulating layer when exposed to elevated temperatures, thus delaying the onset of charring and improving the fire resistance of protected members [61]; see Table 6. The main disadvantage of this type of protection is that it is customarily non-transparent coatings [103]. Earlier, White [137] demonstrated that intumescent coatings significantly increased the fire resistance of a timber frame wall mounted in a small vertical furnace. Lucherini et al. [138] showed that when exposed to a constant heat flux of 50 kW/m^2, the charring of timber was delayed by up to 40 min when coated with commercially available intumescent paints. Johnson et al. [139] got contrasting results when comparing three intumescent coatings

Table 6
Encapsulation times of wall and ceiling fire protection coverings applied on different substrates.

Protection material	Number of layers	Thickness [mm]	Density [kg/m^3]	Substrate behind the covering	Encapsulation time [minutes]	Ref.
Type X gypsum plasterboard	3	12.7	–	CLT	80	[104]
	2	5.9	–	CLT	61	[104]
	3	15.9	–	CLT	100	[104]
	1/2	12.7–15.9	–	Plywood	21-25/57-68	[105]
Type F gypsum plasterboard/ gypsum fibreboard	1/2	10-18 or 2x12.5-2x18	–	Particleboard	10-30-60	[106]
Gypsum fibreboard	1	15	1186–1504	Solid timber	30–32	[107]
Gypsum-concrete	1	25–39	–	Plywood	28–52	[105]
Cement board	1/2	12.7	–	Plywood	16/42	[105]
	2	12.7	–	CLT	36	[108]
	1	10–30	–	Glulam	15–60	[109]
Particleboard	1	30	650	–	38[a]	[110]
	1	10–25	580–680	Particleboard	10–30[b]	[39]
	1	12-25 (min.)	600 (min.)	–	10–30[c]	[106]
	2	16		Plywood	44[d]	[111]
Plywood	1	28	420–670	–	26–33[a]	[110]
	1	9–24	470–530	Particleboard	10–30[b]	[39]
	1	12-24 (min.)	450 (min.)	–	10–30[c]	[106]
OSB	1	10–30	590–600	Particleboard	10–30[b]	[39]
	1	10-30 (min.)	600 (min.)	–	10–30[c]	[106]
MDF	1	30	770	–	36[a]	[112]
	2	16	–	Plywood	45[d]	[111]
	1	6	840	Rock wool	5[d]	[113]
	1	10	840	OSB	17[d]	[113]
	1	10	840	Solid wood	12[d]	[113]
	1	16	752	Rock wool	41[d]	[113]
Hardboard	1	9	770	Particleboard	10[b]	[39]
Solid wood panel	1	13–52	440–490	Particleboard	10–60[b]	[39]
	1	13-25-52 (min.)	450 (min.)	Particleboard	10-30-60[c]	[106]
	1	20	667	Rock wool	14[d]	[113]
Solid wood panel and cladding	1	15–27	450–460	Particleboard	10–60[b]	[39]
		15-27-2x27 (min.)	450 (min.)	–	10-30-60[c]	[106]
Intumescent coating	1	–	–	CLT	20–30[d]	[114]
	1	0.6–5		Glulam	11–78[d]	[109]
Rock wool	1	51–76	128	CLT	43–57[d]	[114]
	1	20–40	–	Glulam	35–74[d]	[109]
Glass fibre	1	50	–	Solid timber	30[d]	[109]

* Values without a superscript are shown based on the maximum temperature rise of 270 °C on the interface between the protection layer and the substrate.
*min. means minimum required thickness or density.
[a] Determined in furnace fire resistance tests where the maximum temperature criterion on the unexposed side was 200 °C. The specimens were vertically oriented with no back substrate.
[b] Rated in terms of K classes according to EN 14135 [98].
[c] Generically classified without further testing (CWFT) to EN 14135 [98].
[d] Based on the onset of charring at 300 °C.

applied in timber exposed to a constant heat flux (35–60 kW/m^2). They verified that one of the coatings did not expand, and the protected sample exhibited behaviour similar to that of the uncoated specimen. Xu et al. [140] analysed the fire behaviour of LTF floors protected with gypsum, cavity insulation and intumescent coating in a standard fire. A slight improvement in the fire resistance of the assembly, amounting to approximately 6 min, was verified compared to the control specimen. The high moisture content of timber could have contributed to the ineffectiveness of the intumescent coating. Small-scale studies have demonstrated the potential to enhance the fire performance and moisture resistance of intumescent coatings for timber surfaces [141,142], also revealing the importance of surface inclination on the effectiveness of intumescence [143]. Thus, intumescent coatings may prevent charring of the substrate, but in some cases have proven unreliable. Experimental evidence regarding the durability, compatibility, and effectiveness of intumescent coatings for timber structures subjected to fire scenarios is required.

A challenging aspect of fire safety in sustainable timber structures is the development of eco-friendly materials with fire-resistant and fire-retardant properties, which should be treated with special priority in research [144,145]. Over the last decade, ongoing research has been conducted on this matter. A comprehensive and helpful review of improvements regarding the fire-retardant characteristics of wood and wood-based materials, including bio-based alternatives, is presented in Albert and Liew [71]. Fu et al. [146] used nano-scale techniques to impregnate delignified balsa wood with colloidal clay. They exposed the samples to radiant heat flux in the cone calorimeter, verifying a reduction in total heat release and smoke production, as well as the formation of a more thermally and structurally stable char compared to the control samples, which revealed a new fire-retardant mechanism. This

mechanism works because the clay nanoparticles increase the char yield of cellulose by reducing oxygen diffusion. Impregnation treatments through mineralisation of CLT with struvite have been analysed by Guo et al. [147], showing that the treated samples exhibited a significantly slower temperature increase on their back when exposed to radiation in the cone calorimeter. However, their mechanical properties in the longitudinal direction remained unchanged or reduced when compared to the untreated samples. Densification treatments have been shown to improve wood's mechanical and fire-resisting properties. This technique enables the manufacture of adhesive-free EWPs [148]. Also, chemical modifications with standard and bio-based flame retardants can improve the fire properties of densified wood by forming a stable char [149–151]. The formation of a more stable char layer due to the addition of non-formaldehyde aluminophosphate in MDF and metal phytates in pine wood was also verified by Wu et al. [152] and Zhang et al. [153], respectively. The fire protection of clay plasters with organic fibres (hemp, straw, cattail) and lime plasters applied to timber surfaces was investigated by Liblik et al. [154,155]. They measured the time to start the charring of timber in furnace and cone calorimeter tests, revealing its dependence on the panel thickness. Similarly, Kallakas et al. [156] demonstrated that when used as covering for wood samples exposed in the cone calorimeter, hemp and clay boards offer comparable fire protection ability compared to gypsum plasterboard. The investigation of thermally stable surface coatings has lately received much attention in the fire protection of building materials. For example, Wang et al. [157] concluded that a bio-based transparent epoxy coating enhances the flammability and smoke suppression of wood-based samples due to the formation of a thermally stable char. Similarly, a solvent-free epoxy-based coating with flame-retardant properties and the ability to form a stable and dense char was developed recently by Wang et al. [158]. Montoya et al. [159] developed an eco-friendly intumescent coating obtained from the tannins of bark residues of pine wood. They applied the intumescent coating on wood substrates and revealed a significant reduction in the charring index. Aqlibous et al. [160] developed a water-based intumescent coating with bio-fillers applied on wood surfaces. Samples were exposed to irradiation of 30–50 kW/m^2, revealing excellent insulating capabilities. It was verified that the addition of bio-based fillers led to a lower heat release rate. Tang et al. [161] developed multifunctional graphene-based composite coatings with excellent heat-insulating performance. Kang et al. [162] formulated a bio-based intumescent and transparent coating that expands in a honeycomb-like layer after 180 °C. This layer slows oxygen diffusion and heat transmission to the protected material. These studies show that innovation in bio-based fire protection is an active and promising field of research. However, experimental evidence regarding their durability, compatibility, and

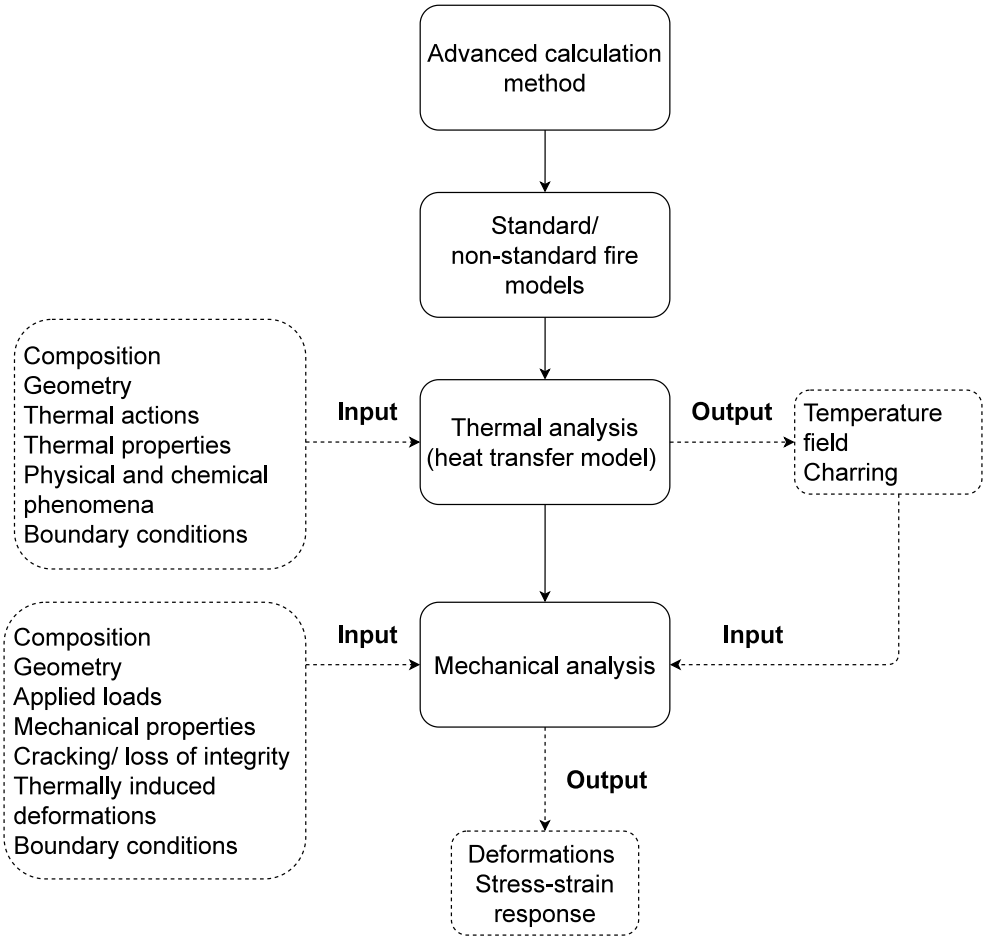

Fig. 8. Generic flowchart to assess the fire performance of building structures under fire using advanced models. Inspired by Buchanan et al. [117].

effectiveness under fire scenarios is required, as well as efforts concerning scaling up and standardisation. Some standardised bio-based products, such as wood-based, clay plaster and clay boards, have already been recognised by codes of practice, such as FprEN 1995-1-2 [26].

5. Advanced calculation models

Advanced calculation models are the most complex yet versatile design resources in fire engineering for assessing the fire performance of timber structures with any cross-section, and their validation with experimental results is essential. The main components of advanced calculation models are shown in Fig. 8.

The majority of advanced calculation procedures are based on the Finite Element Method (FEM), which involves solving governing differential equations incrementally and iteratively at any point within the domain to determine the temperature distribution and charring depth of members subjected to standard and non-standard fires. Finite-difference schemes have also been used successfully to model the structural and thermal behaviour of LTF in both standard and non-standard fires [163,164]. The temperature field serves as input to calculate deformations and the stress-strain response of structures under the applied loading conditions throughout the relevant fire design time. Approaches based on the FEM have been well-validated in the literature regarding the fire design of LTF. Hopkin et al. [127,128] established material models for timber and gypsum plasterboard in natural fire conditions through calibration routines. Frangi et al. [100,107,127] developed a series of finite element (FE) simulations to propose a simplified method for calculating the separating function of LTF wall and floor assemblies, in which the thermal properties of several materials were calibrated to standard fire exposure conditions. More recently, Piloto et al. [165,166] analysed the thermal and structural performance of gypsum-sheathed LTF walls in standard fire. They implemented an elastoplastic and orthotropic with damage constitutive model for timber compression in a FE model, describing the dependence of the fire resistance rating on the load level and validating the approach at both reduced and full scales. They also verified a reasonable agreement regarding the charring rate of the timber members with the new European Charring Model (ECM) proposed in FprEN 1995-1-2 [26].

In many advanced techniques, the complex thermostructural and thermochemical phenomena undergone by building materials at elevated temperatures are implicitly accounted for using effective temperature-dependent material properties because measuring fundamental properties is often difficult due to experimental limitations. In FprEN 1995-1-2 [26], thermal analyses are performed considering the thermal actions specified in EN 1991-1-2 [85]. Effective density values, specific heat and thermal conductivity are given for wood and typical wood-based, insulation and fire protection materials under the standard fire exposure of ISO 834-1 [81] for temperatures up to 1200 °C. The bilinear reduction of strength and stiffness of timber members under compression, tension, and shear is also provided as effective values up to 300 °C, assuming char has zero strength.

Recently, considerable efforts have been made to develop comprehensive theoretical models that predict the charring behaviour and heat release of wood and wood-based materials at elevated temperatures, including those in compartment fires. These models can incorporate more realistic material behaviour at the expense of simulating complex phenomena. For that reason, they often involve estimating several thermophysical parameters, increasing model complexity and uncertainty [167]. Their flexibility enables the establishment of more comprehensible feedback between fire dynamics and the thermal decomposition, heat, and mass transfer effects occurring in the materials. Some widely recognised computational resources with different degrees of complexity have been developed, including the Fire Dynamics Simulator (FDS) from the National Institute of Standards and Technology (NIST), which can deal with both fire dynamics and solid phase thermal decomposition and Gpyro [168] and ThermaKin [169] for condensed-phase modelling. The remaining part of this section is devoted to a basic comprehension of the thermomechanical behaviour of wood under fire, followed by a brief description of comprehensive models and their use in the fire safety engineering of timber structures. The objective of the following subsections is to be merely instructive rather than to provide exhaustive descriptions of the phenomena

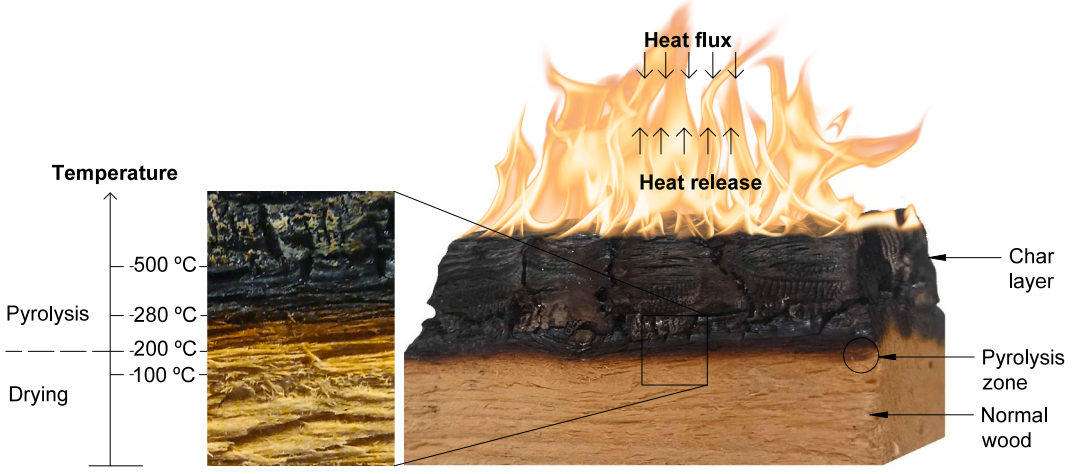

Fig. 9. Through-thickness decomposition zones during flaming combustion of a wood sample.

and the underlying mathematical formulation. This can be found in dedicated publications [168,170].

5.1. Thermomechanical behaviour of wood under fire

Wood is a natural polymer with a complex structure composed mainly of cellulose, hemicellulose, lignin, and smaller contents of extractives, inorganic compounds, and moisture. Wood-based materials are made primarily of wood particles combined with resins and additives [171]. Wood decomposition under external heat is characterised by water evaporation and multistep pyrolysis and oxidation reactions, where the primary product yields are a carbonaceous char residue or inorganic ash, and a mixture of volatiles. This process results in significant mass loss, heat release, and the production of smoke. At high external heat fluxes or in the presence of an ignition source, flaming ignition characterises the onset of fast combustion by reacting combustible gases with oxygen. Glowing ignition occurs at low external heat flux levels when the primary char oxidises at the surface. This can later develop into smouldering (slow combustion) or flaming combustion. Burnout may occur depending on the level of incident heat flux and the availability of fuel and oxygen, and wood may continue to smoulder afterwards if there is enough heat to sustain the combustion process [16,68].

Fig. 9 shows the different decomposition zones of a wood section during flaming combustion. Mass loss at temperatures up to 200 °C is due to drying and release of non-combustible gases. In oxygen-depleted conditions, thermal decomposition from 200 °C to around 500 °C occurs through primary pyrolysis reactions, where the main components of wood are converted to char and resinous products (tar) while releasing water vapour and flammable gases. The primary tar undergoes secondary pyrolysis reactions at higher temperatures to give a secondary char residue and additional combustible gases [172]. The diffusion of oxygen into the reacting wood initiates oxidative thermal decomposition, which causes the components to decompose at a lower temperature and typically increases the peak mass loss rates compared to inert pyrolysis [16].

Additional decomposition steps can occur in wood-based materials due to the thermal decomposition of resins and additives [173]. In the case of fire-treated products, many fire-retardant compounds work by increasing the char yield and diluting the concentration of combustible gases, thus delaying ignition onset and slowing further decomposition rates [62]. High incident heating fluxes and flaming combustion are expected on exposed surfaces during fires. In this case, the contribution of in-depth oxidative reactions to wood decomposition is reduced, as flaming prevents oxygen from diffusing into the reacting surface, and high heating rates tend to shift the decomposition process to a pyrolysis-driven state [16,174]. However, following flameout or when the wood is exposed to high airflow velocities and low external heat fluxes, typical of the decay stage in compartment fires, thermal-oxidative smouldering combustion may become the leading thermal conversion mechanism if no transition to flaming occurs [175,176].

Regarding the thermomechanical behaviour of wood at elevated temperatures, thermal softening of the hemicellulose and lignin is the primary mechanism of strength degradation at temperatures <200 °C. This is the primary reason simplified methods for load-bearing verification, such as the Effective Cross-Section Method (ECSM) in FprEN 1995-1-2 [26], defines a partially degraded zone of the member with zero-strength and stiffness (zero-strength layer), where its value for LTF elements depends mainly on whether the cavity is insulated, the type of insulation and the strength verification case (e.g., bending, buckling). For higher temperatures, the mass loss rate increases significantly due to the onset of primary and secondary thermal decomposition reactions, causing the cell structure to break down, shrink, and increase its porosity, resulting in a charred solid [177]. The thermomechanical properties of wood and wood-based materials tend to decrease with temperature [177,178], and it is widely accepted in fire engineering that from 300 °C and on, the char layer has nearly zero strength and stiffness. In the case of treated wood-based products, fire retardants may harm the mechanical behaviour under fire [179–182]. In addition to strength loss, cracking decreases the insulating performance of the char layer, as it allows for a more effortless transfer of heat and oxygen into the unaffected zone. This phenomenon has been linked to thermomechanical instabilities, in which the crack patterns can be predicted [183,184]. However, its effect on heat and mass transfer rates and the failure of materials under fire conditions remains a challenge in fire engineering [185,186].

5.2. Comprehensive models

Developing advanced strategies to simulate the coupling between thermal decomposition reactions with transport processes and strength degradation effects undergone by building materials under fire has been the primary objective of recent fire engineering studies [187–189]. Particular attention has been paid to establishing comprehensive approaches to study the role of physicochemical processes in the fire behaviour of wood and wood-based materials across various scales. The description of comprehensive thermal decomposition models consists of three main blocks [190,191].

- Development of a kinetic reaction model.
- Description of the thermophysical material properties.
- Definition of a heat and mass transport model considering the coupling between the condensed and gas phases.

Formulating a kinetic reaction model is crucial for estimating the reaction rate and kinetic parameters of each decomposition step from experimental data of microscale apparatuses [190]. Once the kinetic scheme is defined and the thermophysical properties of each species are derived, whether through experimental testing, analytical formulations, or optimisation techniques, implementing a heat and mass transfer analysis at upper-scale levels is possible. Mesoscale experiments include the cone calorimeter and the fire propagation apparatus (FPA), while macroscale experiments are primarily conducted through tests in a fire resistance furnace or fire compartments. In addition, the study of the coupling between the condensed and gaseous phases allows for the investigation of the mechanisms of ignition, flame spread, burnout, and smouldering in combustible products. This comprehensive technique has been

employed by Fredlund [192] and Craft et al. [193] to predict the fire resistance of LTF walls and floors in both standard and non-standard fires. However, further comprehensive studies could be developed to gain insight into the research directions previously highlighted in Sections 3 and 4.

5.2.1. Heat and mass transfer

A heat and mass transfer analysis is particularly relevant to determine the variables that affect the fire resistance of building structures (e.g., in-depth temperatures, char front). The complexity of the analysis is linked to the number of species considered in the reaction kinetic model and the account of different types of energy transport. The energy balance of the condensed solid phase in comprehensive heat and mass transport models often assumes the following expression in one dimension [168].

$$\frac{\partial(\overline{\rho}\overline{h})}{\partial t}+\dot{Q}_{s-g}^{'''}+\frac{\partial \dot{q}_{r}^{''}}{\partial z}=\frac{\partial}{\partial z}\left(\overline{k}\frac{\partial T}{\partial z}\right)+\sum_{k=1}^{K}\dot{\omega}_{di}^{'''}\Delta H_{k} \tag{1}$$

The left-hand side of Equation (1) represents the change in the total enthalpy of the solid and volatiles in the control volume, defined here as an averaged product of density $\overline{\rho}$ and enthalpy $\overline{h}$ of species. On the right-hand side, each term describes the heat conduction through the condensed phase, a function of the averaged solid thermal conductivity $\overline{k}$ and temperature T, the energy released or absorbed through the thermal decomposition reactions (source term), where $\dot{\omega}_{di}^{'''}$ is the volumetric decomposition rate of the *ith* solid through reaction k and ΔH_k is the respective heat of reaction, $\dot{Q}_{s-g}^{'''}$ is the convective heat exchange between the solid and volatiles, and $\dot{q}_r^{''}$ is the in-depth radiation absorption.

Variations of Equation (1) are found in the literature to describe energy conservation in the condensed phase. For example, the most straightforward approach involves a heat conduction analysis with a heat source term to account for the thermochemical reactions; therefore, it does not include mass transfer limitations. This approach has been found appropriate for predicting properties such as time to ignition or smouldering, heat release, mass loss rate, pyrolysis front position, and surface temperatures, for which residence time and mass flux of volatiles have little influence [175,194–198]. Ignition, smouldering and burnout criteria have also been proposed based on these simplified models for constant and transient radiant exposure conditions at the mesoscale [175,194,195]. Additionally, it has been verified that to model combustion properties of fibreboards, the effects of the vertical density profile and sample shrinkage are relevant to improve predictions of the time to ignition and mass loss rate [195,196], as well as the temperature profile up to the ignition point [195].

The use of simplified heat conduction models to predict local variables within wood and wood-based materials exposed to fire across multiple scales has been widely documented [185,187,188,199–202]. As presented earlier, these models do not consider the mass transfer of volatiles within the sample. Thi et al. [199], Zhang et al. [200] and Tran et al. [201] built finite element models to predict temperatures and charring of solid wood under uniform heat fluxes [199,201] and of LVL exposed in a fire resistance furnace [199,200], obtaining consistent results for the temperature evolution at different depths. Similar models were used to evaluate the behaviour of solid wood and particleboard when tested in a cone calorimeter [185,198], as well as under ISO 834 [185,187,188] and parametric fires [185]. For example, Rinta-Paavola et al. [185] obtained reasonable results for the charring depth of wood exposed to ISO 834 fire. They also verified the strong coupling between the furnace oxygen concentration and charring rate. However, the lack of mass transport phenomena and the difficulties in accounting for char cracking limit the achievement of better predictions of temperature profiles at large scales [185]. More detailed investigations have included the influence of convective heat transfer between the solid and volatiles to study combustion properties. This requires a mass transport analysis, thus improving predictions of surface and local variables inside the solid before and after ignition [203–210]. In this case, the third term on the right-hand side of Equation (1) becomes relevant. Nevertheless, this quantity is sometimes disregarded in specific models due to its relatively minor magnitude compared to other terms [168,211] can be significant at high heat fluxes with steep temperature gradients within the solid [211]. A frequent simplification of the convective heat transfer term, assuming thermal equilibrium between the solid and gaseous volatiles [168,176], is

$$\dot{Q}_{s-g}^{'''}=\frac{\partial\left(\dot{m}^{''}\overline{h}_{g}\right)}{\partial z} \tag{2}$$

The mass flux of gas volatiles appearing in Equation (2), $\dot{m}^{''}$, requires a mass transfer analysis, typically governed by Darcian flow and momentum conservation. In this approach, the models of Richter et al. [191,212–214] have been validated at multiple scales for different species of wood and for particleboard using the open-source code Gpyro, considering variations in grain orientation, moisture content, oxygen concentration, and fire exposure conditions. Another component of Equation (1) is the term that accounts for the in-depth radiative heat transfer. Its formulation is not given here as it differs significantly between comprehensive codes [167]. In-depth radiation absorption is addressed in works on the burning behaviour of wood and wood-based materials at the mesoscale [212,215–217]. Vermesi et al. [216] and Zhao et al. [215] concluded that in-depth radiation is significant to model cone calorimeter and FPA experiments, respectively. In contrast, in-depth radiation was negligible in predicting the surface mass loss rate of wood and fibreboard in bench-scale experiments [191,195,196]. Nevertheless, in-depth radiation absorption depends on the type of radiation source [211] and more studies are needed to investigate its effect on larger scales.

One common aspect between simplified and detailed heat and mass transport models is volume shrinkage, which is accounted for in most comprehensive models in the literature [191,195,196,213,216,218]. Indeed, shrinkage influences the predictions of the mass loss rate of fibreboard since it decreases the heat penetration depth and char thickness [196]. Still, its significance in the in-depth

temperatures of wood and wood-based materials is not widely discussed. Strategies to model sample shrinkage include the implementation of moving boundaries [203,218], using transient cell sizes [196], introducing shrinkage factors [218] or assuming that it is a function of the local extent of thermal decomposition [204,206].

In comprehensive models, heat and mass transfer properties must be specified for each species involved in the reaction scheme. Accurate determination of thermophysical properties for fire analysis is challenging due to experimental limitations and structural changes (e.g., cracking, delamination) during thermal decomposition, and it currently represents one of the main shortcomings of available comprehensive models. In detailed heat and mass transfer models, discrepancies between numerical and experimental in-depth temperatures are mainly due to uncertainties in material properties [191,209]. Thermophysical properties are typically specified as temperature-dependent quantities, as weighted functions of the conversion degree over time, or both. Inverse optimisation methods can also be implemented to obtain effective properties [196,198,217]. Mixture rules based on each species' mass or volume fraction and the known properties of the intermediate components have helped obtain the apparent values of density, porosity, specific heat, thermal conductivity and permeability of the solid material during thermal decomposition [185,186].

Cracking significantly affects the heat and mass transfer dynamics in charring solids. Recent efforts have proposed comprehensive thermomechanical models based on fracture mechanics principles to predict the crack patterns and their dependence on the external heat flux [184,186]. Šulc et al. [219] studied the effects of char cracking on the fire resistance of timber panels using an FE model where the elements are deactivated based on a temperature criterion. A time-dependent moving boundary initialises the condition as the effective depth varies. The models of Nguyen, Pence and Wichman [220,221] represent an explicit consideration of char cracking on the mass flux enhancement of volatiles, which is proportional to the increase in the available area for pyrolysis. Models of such complexity may be difficult to incorporate into engineering simulations, but they can help determine effective thermophysical properties for the char layer [186]. In LTF structures, the failure of the protection layers or substructure is possibly linked to a thermomechanical failure due to moisture and pyrolysis-induced deformations [222]. Still, this interaction has not yet been comprehensively explored in the literature, with current approaches relying on a temperature criterion (typically 300 °C for wood products) or failure times observed in experimental tests [112,223]. However, experimental evidence suggests that material failure in timber assemblies under fire conditions is not directly correlated to an isothermal temperature criterion, but rather to heating or cooling rates [222,224].

Comprehensive models with varying degrees of complexity have been proposed in the literature, ranging from simple heat conduction analysis to complex heat and mass transfer models. Simple heat conduction models help predict the ignition time and in-depth temperatures at early fire exposure. Convective transport and in-depth radiation within the porous structure of wood and wood-based materials can improve predictions of the mass loss rate and the temperature profile of samples exposed in bench-scale apparatuses.

Table 7
Multiple-reaction models to describe the thermal decomposition of wood and wood-based materials.

Reaction models	
1 - One-step and multiple-step (homogeneous)	
[199] - Wood Wood → (k) Gas; (k) Char	[185,209,225] - Wood Wood – k → Char + Volatiles Char - - k - → CO_2 or Ash + CO_2
2- Multiple-step (heterogeneous)	
[195,196,198,203] – Wood/MDF H — k → Char + Volatiles C — k → Char + Volatiles L — k → Char + Volatiles R — k → Char + Volatiles	[176,185,208] - Wood E — k → Char + Volatiles H — k → Char + Volatiles C — k → Char + Volatiles L — k → Char + Volatiles Char - - - k - - → CO_2 or Ash + Volatiles
3- Multiple-step with intermediate components (heterogeneous)	
[191,213,214] - Wood H — k → (k ↑) L — k → Char + Volatiles Char - - k - → Ash + Volatiles Volatiles ↑ (k) C — k → Intermediate component — k → Char + Volatiles (k ↓) Pyrolysis — — — Thermo-oxidation	

Key: H = hemicellulose; C = cellulose; L = lignin; E = extractives; R = resin; MDF = medium density fibreboard; k = rate constant.

Still, further investigations are necessary to verify whether in-depth radiation is significant at larger scales, as its effects depend on the radiation source. Temperature predictions and charring depths of timber structures subjected to standard and non-standard fires have been studied using simplified heat conduction models, which offer consistent results for charring depth but show poor agreement for in-depth temperatures. This discrepancy is primarily due to the lack of mass transport phenomena, difficulties in accounting for material failure and uncertainty in thermophysical properties. Thus, since prediction of in-depth temperatures is particularly relevant for fire resistance purposes, significant efforts are required to establish thermomechanical formulations as well as reliable thermophysical properties of materials commonly encountered in fires, which must be supported by sufficient experimental evidence.

5.2.2. Reaction kinetics

In comprehensive models, an engineering kinetic scheme must be established to represent the global thermal decomposition reactions of the fuel. The reaction rate, $d\omega/dt$ of each reaction is commonly described in Arrhenius form as

$$\frac{d\omega}{dt} = f(\omega)^n \cdot A \cdot \exp\left(\frac{E_a}{RT}\right) \cdot Y_{O_2}^{n_{O_2}} \tag{3}$$

Where ω is the degree of conversion of the reacting component, t [s] is the time, T [K] is the absolute temperature, $f(\omega)^n$ is the term that characterises the reaction model, which depends on the appropriate reaction scheme and order n, A [s^{-1}] is the pre-exponential factor, E_a [kJ.mol^{-1}] is the activation energy, R [kJ.mol^{-1}. K^{-1}] is the universal gas constant ($R = 8.314$ kJ mol^{-1}. K^{-1}), and $Y_{O_2}^{n_{O_2}}$ is the oxygen mass fraction of oxidation order n_{O_2}. For pyrolysis and water evaporation, $n_{O_2} = 0$. Microscale tests such as thermogravimetric analyses (TGA) are necessary to determine the kinetic scheme and kinetic parameters of thermochemical reactions on a local level, typically using a model-fitting optimisation approach. For fire engineering purposes, most kinetic models of thermal decomposition assume that dry wood is a single homogeneous component (homogeneous), or a multicomponent material composed mainly of cellulose, hemicellulose, and lignin (heterogeneous); see Table 7. When exposed to a heat source, the component(s) of the solid material decompose through single, parallel, or consecutive reactions into gas, tar, and char species, and, in some cases, into the so-called intermediate products. Additional reactions are necessary to account for the oxidation of the virgin solid or char, leading to the formation of volatiles, char, and ash species.

As shown in Table 7, a one-step single-reaction model is the most straightforward mechanism to represent the primary thermal conversion of dry wood through a single Arrhenius-type reaction. The species involved are the dry solid, char, and volatiles. This simple scheme has been used to study the spontaneous ignition of different wood species at constant and variable heat fluxes [204–207]. The influence of in-depth radiation on the pyrolysis of MDF [215], the thermomechanical behaviour of particleboard panels in ISO-fire [187], the thermal response of LVL in a furnace [200] and the combustion properties of structural wood [198] have also been evaluated using a single reaction kinetic model. As observed by Zhai et al. [207] and Rinta-Paavola and Hostikka [198], the single-reaction scheme cannot capture the phenomenon of char oxidation, which has a substantial impact on the decomposition process during smouldering combustion and is critical to the fire safety of timber structures, especially during the decay stage of a fire. Thus, to gain a further understanding of secondary pyrolysis and thermo-oxidation decomposition mechanisms, most of the literature on fire science has proposed multiple-reaction models with varied degrees of complexity in which the thermal conversion of dry wood (homogeneous) or its pseudo-constituents (heterogeneous) proceeds through parallel or consecutive Arrhenius reactions, each with its own set of kinetic parameters. Reactions occur in a single step, simultaneously, or consecutively in multiple steps. Examples of multiple-reaction kinetic schemes are shown in Table 7.

Non-isothermal thermogravimetric analyses provide information about the complexity of reaction mechanisms by evaluating how the residual mass m/m_0 of milligram samples changes as the temperature increases linearly. Fig. 10 presents the thermogravimetric (TG, m/m_0) and derivative thermogravimetric (DTG, $d(m/m_0)/dt$) curves, which illustrate the thermal decomposition behaviour of pinewood at the microscale. The decomposition predominantly follows a single-step mechanism under inert conditions, such as

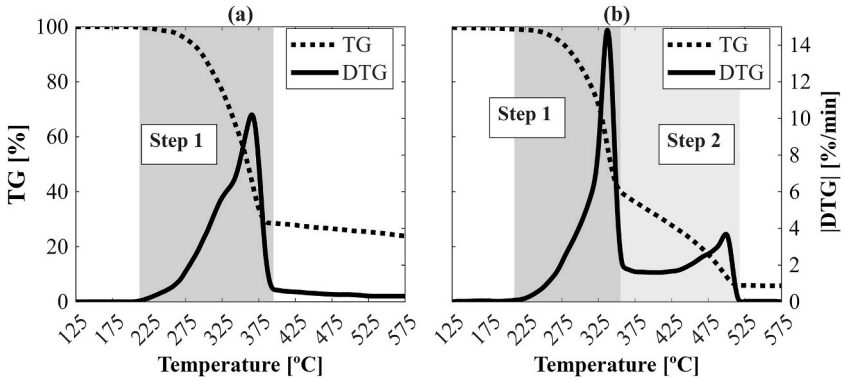

Fig. 10. TG and DTG curves of dry pinewood measured at a constant heating rate of 10 °C/min under (a) nitrogen atmosphere [226] and (b) air atmosphere [227].

heating in a nitrogen atmosphere (Fig. 10a). However, when exposed to an oxidative environment (Fig. 10b), an additional decomposition step occurs due to char oxidation.

Wood is considered a homogeneous component in a one-step [199] and multi-step [185,197,209,218,225] reaction schemes of primary and secondary thermal decomposition. Some models of this type also include the char oxidation reaction to model surface glowing ignition [197,209], flaming ignition [209], charring [185] and oxidation-driven thermal expansion [225] of wood at the mesoscale and macroscales. The second category, shown in Table 7, includes several studies that used a kinetic scheme of parallel reactions with or without oxidation stages to describe the thermal decomposition of the heterogeneous solid [176,185,188,195,196,198,203,208]. The introduction of a char oxidation stage in parallel kinetic schemes has been favoured to improve predictions concerning the autoignition [208], charring [185] and the smouldering and burnout [176,185] behaviours of wood, especially regarding the validation of large-scale models [185]. The last category of reaction models includes the models of Richter et al. [6,10,43], which comprise a detailed heterogeneous scheme for wood derived from an extensive literature review. The model features pyrolysis and thermo-oxidation of cellulose and hemicellulose, the pyrolysis of lignin, and char oxidation, and it has been used to validate experiments across scales [214]. The reaction of water evaporation (drying) is not shown in Table 7, as it is usually modelled separately. It is essential to describe this phenomenon in wood and wood-based materials, as the rate of temperature increases through the cross-section of an element in the early stages of fire exposure, as well as the charring rate and size of the zero-strength layer, depends on the moisture content of those materials [185,214]. Due to its simplicity, a kinetic approach using an Arrhenius formulation is often preferred to model drying [185,187,191,199,214,218].

Choosing an appropriate reaction model primarily relies on balancing complexity and the capacity to reasonably reproduce the thermochemical interactions during the thermal decomposition of wood and wood-based materials under fire. Simple schemes with one or multiple reactions lacking or including fuel or char oxidation have been verified to be sufficient to study ignition, char front progress, and in-depth temperatures in the early stages of fire exposure at the mesoscale [175,204,215,216]. The complexity of the kinetic model tends to increase with scale. It often requires a minimum of two reactions to describe the thermal decomposition of wood fuels submitted to common design fires, regardless of whether the homogeneous or heterogeneous approach is considered [185,214,228]. The role of char oxidation has been much debated, and it is clear that oxygen diffusion plays an essential role in the transition between the various decomposition steps of wood fuels under fire across scales, namely pyrolysis, ignition, flaming and smouldering combustion, and burnout [209,213].

6. Conclusion

This review has highlighted the increasing relevance of light timber frame (LTF) construction in Europe, driven by the need for sustainable and energy-efficient building practices. This analysis reveals that LTF systems, although versatile and conducive to prefabrication, pose unique challenges regarding fire performance and safety. The review has identified key passive fire protection measures, such as encapsulation and fire-resistant insulation materials, which are critical to enhancing the fire resistance of LTF structures. Advanced numerical models have been discussed as essential tools for predicting and assessing the fire performance of timber structures. This article also provided an instructive background regarding the fire behaviour of LTF structures, from standard methods in the European context to comprehensive numerical models. The following main takeaways and future research are proposed.

- Exploring eco-friendly fire-retardant treatments and coatings that align with the principles of sustainable construction will be critical in advancing the fire safety of sustainable timber buildings. However, gaps remain in understanding the long-term durability and reliability of innovative fire protection materials under fire conditions. Wood-based panels also have fire protection capabilities. Still, limited experimental data on their fire protection characteristics, such as failure and encapsulation times in standard and non-standard fires, are available.
- More investigations are necessary to understand the interaction of combustible and non-combustible lining failure with the development of fire temperatures in multilayer LTF compartments with different geometries and ventilation conditions. This should help validate current and future proposals of physically based fire models.
- Using comprehensive multiscale approaches enhances understanding of the thermal and mechanical behaviours of wood and wood-based materials under fire conditions. These models are essential for integrating detailed thermophysical properties and complex interactions at multiple scales, from the microstructural behaviour of wood to the global response of timber assemblies in fire scenarios. However, multiscale models have not yet been used extensively to predict the fire resistance of LTF structures. Additionally, efforts are necessary to establish reliable model parameters supported by experimental evidence.
- Cracking phenomena in timber significantly affect its heat-insulating properties by allowing more effortless transfer of heat and oxygen into the material, which can accelerate the thermal decomposition process. Explicit consideration of this phenomenon in comprehensive models is limited and complex; however, it can help establish effective properties for engineering calculations. The layer failure in timber assemblies (e.g. delamination, protection fall-off) is linked to dehydration and pyrolysis-induced deformations, leading to thermomechanical instabilities. Understanding such thermomechanical interactions could help to derive more reliable failure criteria, which is especially relevant in multilayer LTF structures, as their fire resistance is heavily dependent on fire protection performance.

CRediT authorship contribution statement

Matheus Alves: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Luís Mesquita:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Paulo Piloto:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Nuno Lopes:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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