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Abstract

The tragic fires at the Grenfell Tower (London, UK) in 2017 and the building in the Campanar neighbourhood (Valencia, Spain) in 2024, among other fires, occurring in existing high-rise residential buildings with combustible façades, have prompted a review on regulations and statutory procedures, as well as the development of new risk assessment methods, research reports, and expert studies in order to enhance fire safety in such buildings. Within this context, this article is aimed at providing a compilation, in the form of a preliminary state-of-the-art review, of various fire safety measures that can be adopted in these types of buildings, and to contrast the main measures identified with the requirements set out in Spanish national regulations.

Keywords: fire safety; high-rise buildings; combustible façades; existing buildings; residential; energy refurbishment

1. Introduction

Fire safety is one of the basic requirements set out in building codes. The major goal is to minimise the risk of harm to persons, but also to protect buildings, their contents, and the environment around from the destructive effects of fire, as outlined by the International Fire Safety Standards (henceforth, IFSS) [1].

Approximately 34% of fires worldwide throughout 2023 occurred in buildings and 25% in residential buildings, which caused 86% of all fire-related deaths that year [2].

Over time, building fires, and in particular those produced in residential buildings, have been catalysts for significant enhancements in safety standards, equipment and procedures [3]. Nevertheless, there is considerable room for improvement, especially in existing high-rise residential buildings using combustible materials on façades. It has been noted that the frequency of fires on façades in high-rise buildings has increased seven times in the last three decades, with 59 façade fires identified from 1990 to 2018 [4], and the trend is that this type of fires is becoming more and more recurrent [5].

In many cases this increase is due to the use of new materials and construction types for lightweight façades and curtain walls, and also to energy refurbishment of existing buildings, which has led to the incorporation of combustible materials in façades [6,7]. The tragic fires at Grenfell Tower in London in June 2017 and at the Campanar building in Valencia in February 2024 are two recent examples within this scenario.



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Furthermore, the risk to persons in this type of high-rise building is increased by the large number of occupants, the inherent limitations of exit and access with greater distances to travel for reaching a safe place, and the physical aspect of buildings [3], which, due to height, may favour the 'chimney effect'. Compared to other buildings, fire performance in high-rise buildings has the following particular features: rapid spread of fire and smoke, limited rescue and firefighting capacity from the outside, extended evacuation time, longer fire duration, and limited water supply. Also, the existence of non-residential uses increases challenges of fire protection [3].

Owing to the 'chimney effect', fire and smoke may spread very quickly through interior stairways, lifts shafts and pipes if protective measures are not adequate [3]. Furthermore, if an interior fire causes the window glass to break (or if the windows are open) and the fire spreads outside, it will be difficult to control, especially if exterior cladding systems are combustible, as these will significantly contribute to a rapid fire spread. This fact intensifies the difficulties for firefighters to carry out exterior firefighting and rescue operations. On the other hand, water supply can be limited if supplementary pumps, which are necessary in a high-rise building to put upward the supply pressure to upper floors, are out of order [3].

In these buildings, the time available for occupants to escape to a safe place, Available Safe Egress Time (ASET), is crucial [8]. The expected exit time should be compared with the speed of fire propagation across the façade system, although quantifying this parameter is a very complex task [9]. Within the performance-based design (PBD) framework, this analysis is defined by comparing the ASET with the Required Safe Egress Time (RSET). In high-rise buildings with combustible façades, evacuation modelling becomes critical, as accelerated vertical spread can simultaneously compromise the ASET across multiple levels relative to the RSET [9,10].

Furthermore, since these are existing residential buildings, there could be significant gaps within fire safety regulatory systems at the time buildings were constructed [11].

On the other hand, fire safety regulations can vary considerably according to different countries in both requirements and scope. For example, the definition of high-rise buildings, which dictates compliance with stricter conditions, differs in regulations of the UK, Germany and France, with heights equal to or greater than 18 m, 22 m, or 28 m, respectively [12]. Furthermore, toxicity of smoke has not been sufficiently regulated yet; this is a critical legal gap, since inhalation of smoke and toxic gases appears to be the main cause of 70% to 80% of deaths from fires in buildings [13,14].

For all these reasons, there is currently great concern among construction professionals and fire protection experts worldwide, who are calling for a review and update of national regulations and, in particular, the implementation of unified procedures related to external fire spread in high-rise buildings. It is also necessary to improve safety throughout the entire building process: from the design and refurbishment by professionals to the use and maintenance of the building itself by occupants and various agents involved [15–18].

Extensive scientific literature exists regarding fire safety in newly constructed high-rise buildings, but that relating to fires in existing high-rise buildings with combustible façades is relatively scarce [19].

Thus, the purpose of this article is to provide a compilation of potential fire risk mitigation measures developed by international experts for existing high-rise residential buildings with combustible façades. This compilation is based on a holistic approach, without being limited solely to risk reduction in façades.

Also, as a result of the analysis of the measures, a review of certain conditions established by Spanish fire protection regulations, specifically the Basic Fire Safety Document (DB SI) of the Technical Building Code (CTE) is proposed (hereafter cited as CTE DB SI) [20].

Such requirements would apply to both newly constructed buildings and intervention in existing buildings.

On the other hand, measures for skyscrapers, exceeding 128 m in height according to the International Building Code (henceforth, IBC) [21], are not regarded, nor those specific to buildings with structures made of combustible materials such as wood [22].

2. Materials and Methods

As already stated, the aim of this article is to enrich the knowledge of fire safety improvement measures for existing high-rise residential buildings with combustible façades (identified as ‘COFIGHT measures,’ referring to Combustible Façades in High-Rise Residential Buildings: Holistic Treatment), in addition to cross-referencing the main measures compiled against the requirements of Spanish regulations.

To this end, a preliminary study is conducted on the main COFIGHT measures proposed in various information sources. Methodology used is summarised in Figure 1 and explained below.

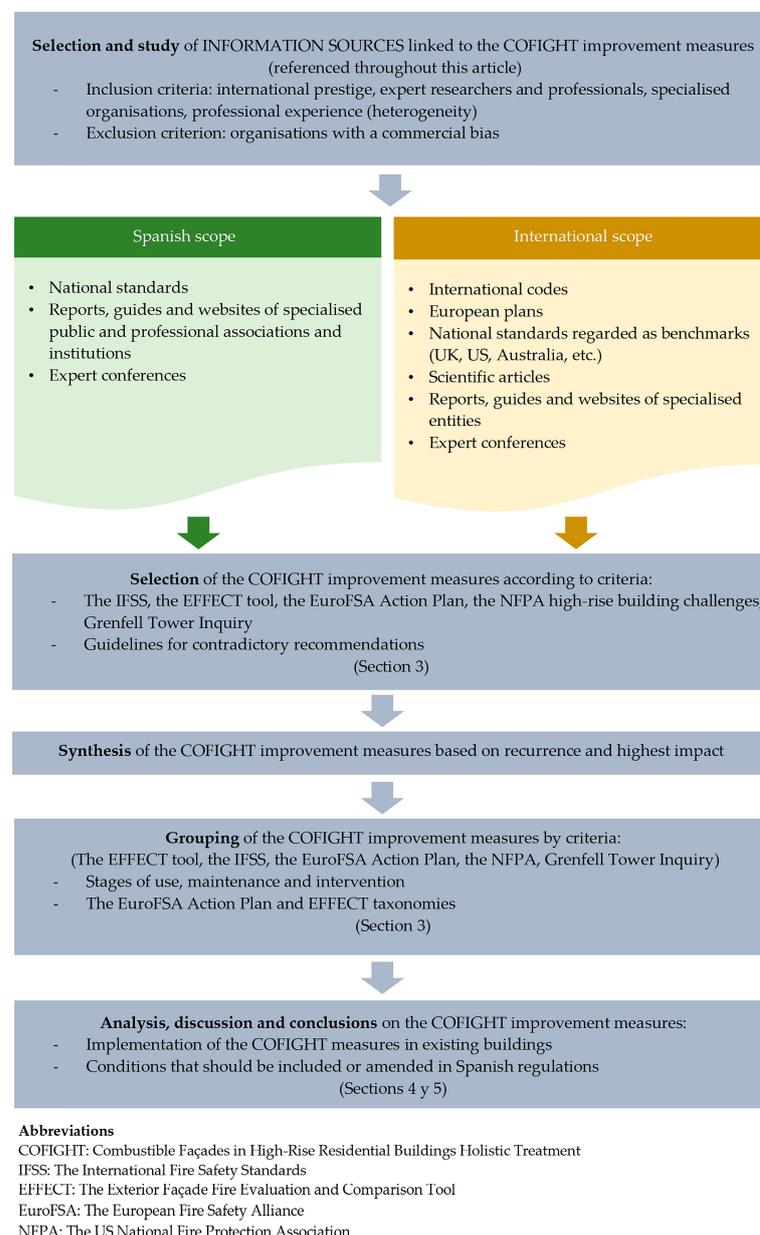


Figure 1. Methodology.

2.1. Study of Information Sources Related to the COFIGHT Measures

In order to obtain the COFIGHT measures, an exhaustive search of general and specific keywords was carried out on databases such as Google Scholar, web repositories of regulations from different countries, websites of associations and professional bodies of a public nature specialised in the subject, as well as online lectures by experts in this field.

Otherwise, to determine the key terms, the selection criteria set out in the following section are used as a guide, focusing the search on phases of use and intervention in existing buildings.

Some of the general keywords implemented for the search are 'fire safety,' 'existing high-rise buildings,' 'buildings with combustible façades,' 'fire protection systems,' 'fire service,' etc. In order to delve deeper into the various subjects collected, the general keywords have been combined with particular keywords, such as 'reaction to fire,' 'combustible interior cladding,' 'self-protection plan,' 'fire doors,' 'firefighters lift,' etc.

In this way, more than one hundred specialised sources of information, both national (Spain) and international, are analysed. The general criteria for source selection and inclusion are based on the international prestige of the sources within the fire safety field: expert researchers and practitioners (J. L. Torero, G. Rein, etc.), specialised organisations (NFPA, Fundación MAPFRE, etc.), and other professionals with proven expertise, such as Civil Protection and Fire Services. Furthermore, the heterogeneity of the sources (in terms of type and place of origin) is essential to ensure the realistic and practical nature of the COFIGHT measures. Commercial bias is established as an exclusion criterion, rendering organisations with such interests invalid as information sources.

These inclusion/exclusion criteria, together with the number of sources consulted, provide sufficient information to yield consistent results upon analysis.

The percentages of information sources analysed are shown below through graphs, according to the following features:

- source type: standard (S), article (A), report (R), guide (G), lecture (L), and website (W) (Figure 2);

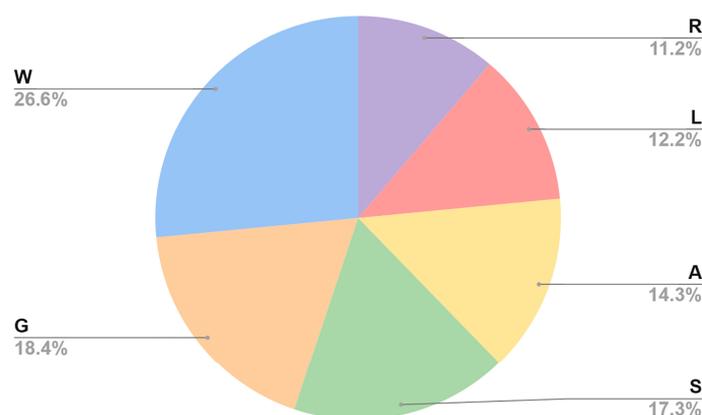
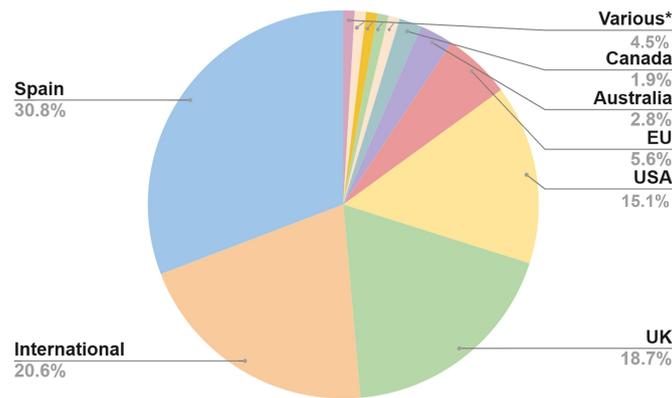


Figure 2. Percentages of information sources analysed according to source type.

- place of origin (Figure 3). The global representativeness of this review is ensured by sources from the International Building Council and the NFPA, as these organisations lead the resolution of fire safety challenges in high-rise buildings on an international level.



*Various: Belgium, Brazil, Croatia, France, New Zealand (0.9% per country)

Figure 3. Percentages of information sources analysed according to country of origin.

2.2. Selection and Grouping Criteria for the COFIGHT Measures

To evaluate certainties and mitigate the risk of bias in the information obtained regarding the COFIGHT measures, the data is filtered according to the following international criteria:

1. Consider the five common principles of the IFSS [1]:
 - prevention (PRE): understand cause and risk factors for protection against the outbreak of fire and limit its effects;
 - detection and communication (DET): detect the fire as soon as possible and quickly inform occupants and the Fire Service;
 - occupant Protection (OP): making it easier for occupants to avoid fire and escape its effects;
 - containment (CON): limiting fire and all its consequences to the smallest possible area (including structural integrity);
 - extinguishment (EXT): suppress fire and protect the surrounding environment; within this principle, early extinguishment (eEXT) measures are differentiated [23], whose objective is to intervene in the initial phase of the fire in order to prevent spread and minimise damage.
2. The fire safety measures repository from the Exterior Façade Fire Evaluation and Comparison Tool (EFFECT) by the US National Fire Protection Association (NFPA) was used as a reference. This tool proposes mitigation measures at the building use and intervention phases based on fire risk factors, according to the following aspects:
 - management, repair and periodic maintenance of existing fire safety measures;
 - types of fire safety measures: active or passive; active protection measures cover systems that detect and extinguish fire (sprinklers, alarms, etc.), while passive protection measures comprise those affecting elements that contain and slow the spread of fire and smoke (walls, doors, modification of façade systems, etc.) [24].
3. Be aligned with the following areas of interest, included in the European Fire Safety Action Plan (EuroFSA) [25]:
 - intensify fire safety for the growing vulnerable community (elderly or disabled people);
 - reduce evacuation time of persons in a fire;
 - increase awareness of persons' responsibilities regarding fire safety.
4. Contemplate some of the challenges of high-rise buildings identified by the NFPA [26]:
 - longer exit times and distances;

- evacuation strategies;
 - smoke movement;
 - fire control.
5. Take into account the knowledge gained from the investigation of the fire at the Grenfell Tower, as recorded in reports resulting from the public inquiry [16,17].

In the event of conflicting recommendations from different jurisdictions, the most restrictive one prevails; otherwise, the contradictions are explicitly stated to highlight areas for further research.

Given the large number of actions that can be implemented, these are summarised into 100 measures. This is a curated synthesis of the most recurrent and high-impact actions identified in the literature, aimed at providing a comprehensive yet practical framework for risk assessment. Some measures are also critically examined, with alternatives to improve their effectiveness.

Subsequently, the 100 collected measures are grouped according to the following criteria:

- The ‘occupancy’ and ‘intervention’ stages of the life cycle of existing high-rise residential buildings with combustible façades; furthermore, within the occupancy stage, a distinction is made between measures specific to use and those related to maintenance;
- The EuroFSA plan taxonomy and the categories of the EFFECT.

Each measure is identified with a sequential number.

2.3. Agents Responsible for the COFIGHT Measures

The measures are analysed bearing in mind agents responsible for carrying them out: occupants, owners or persons responsible for the building (or those to whom they delegate), construction professionals, such as technical and maintenance staff, Public Administration (henceforth, PA) and Civil Protection and Fire Services (henceforth, FS).

The development of measures aimed exclusively at building occupants, although fundamental for fire prevention, is not the focus of this article.

2.4. Comparison of COFIGHT Measures with CTE DB SI Regulations

With the objective of reducing the risk of exterior fire spread in high-rise residential buildings in Spain—both for existing buildings with combustible façades and new constructions—a qualitative gap analysis of the Spanish regulations (CTE DB SI) is conducted. In this analysis, the COFIGHT measures are contrasted with the requirements set forth in sections SI 1 to SI 5 of the CTE DB SI. Section SI 6 (‘Structural Fire Resistance’) is excluded, as its technical complexity would require additional research that exceeds the scope of this research. As a result, modifications to the CTE DB SI are proposed regarding the aspects detailed in Section 4.2.

3. Results

This section provides a general compilation of potential risk mitigation measures in case of fire for occupants of high-rise residential buildings (generally those over 18 m high), in which there is also the aggravating factor that façades include combustible materials (COFIGHT measures). Figure 4 summarises the measures grouped by phases (building use and intervention) and by categories (management, training, maintenance, and building components).

The COFIGHT improvement measures are developed below based on one or more of the common principles of the IFSS described above. These principles are identified by acronyms at the end of each measure. A correspondence between the measures and the IFSS principles is established by identifying shared objectives.

Phase	Category	Number of measures	General description of measures
Use phase: use measures	Management	12	Verification of façades, evacuation routes and maintenance of the FPS, control of external ignition sources, self-protection plans, coordination with the FS, appointment of a responsible person
	Occupant Training	3	Occupant training in prevention, evacuation drills, awareness campaigns
Use phase: maintenance measures	Structural elements and installations	9	Periodic inspection of fire doors, firefighters lifts, electrical and gas installations, and FPS
Intervention	Training for professionals	7	Improvement of technical training for professionals, creation of databases (product and material testing, reports on serious fires, academic papers), new degree
	Evacuation Routes	22	Improvement of doors (opening/closing systems, direction of opening, vision panels and natural light entry, fire resistance), circulation areas (width, distance to a protected stairway, exit to another fire compartment or a refuge area, smoke dampers, ventilation), replacement of combustible interior linings, stairways (compartmentalised, protected, with lobby, smoke protection, width), firefighters lifts, signalling and emergency lighting
	Compartmentation	4	Adapt the fire resistance of compartmentation elements between dwellings and any other fire sector, firestopping of service penetrations, continuity of compartmentation in hidden spaces
	Façades	14	Removal of electrical points and kitchen smoke extraction grilles on façades, partial replacement of combustible cladding and insulation (at the building base, balconies, canopies, etc.), installation of fire barriers (around openings, between floors, in air cavities of façades, etc.), replacement of certain laminated glass parapets, fire resistance adaptation of horizontal strips between windows and fire sectors (or provision of protruding elements), verification of openings for the FS access, comprehensive replacement of combustible cladding with class A2-s1, d0 rated materials, replacement of glass and frames in openings with fire-resistant ones
	Structure	1	Reinforcement of structural fire resistance, considering potential exposure to electric vehicle fires
	Electricity and gas installations	6	Adaptation of installations to current safety regulations, upgrade of installations lacking differential protection elements, grounding connection, standby power source for the FPS, installation of gas detectors in flats, sealing of gas pipelines crossing fire sectors
	Detection and alarm installations	6	Installation of fire detection and alarm systems in all dwellings, common areas, car park areas, evacuation routes (with light signals in protected stairways to indicate if they are smoke-free), manual pushbuttons, building-wide alarm, installation allowing the FS to send evacuation signals (to the whole or part of the building), two-way telephone service for FS use in lifts, lobbies and each exit stairway floor level, increase redundancy of power and alarm systems
	Early Extinguishment	6	Installation of extinguishers, automatic fire suppression systems (interior sprinklers in dwellings, additional row for glass façades; external sprinklers on balconies, direct discharge on façade, inside the façade cavity), increase system redundancy, signalling
	Other FPS	10	Installation of fire hose reels, hydrants, dry risers (with façade inlets if there are sprinklers in the façade air cavity), pipes filled with water in buildings over 50m high, multi-level pumps, water storage tanks, smoke control systems in parking levels and basements, information box and FS panel, fire control center

Abbreviations

FPS: The building's Fire Protection Systems

FS: Civil Protection and Fire Services

Figure 4. Summary of the COFIGHT measures.

3.1. Building Use Phase: Use Measures

This section covers the COFIGHT improvement measures related to building management procedures and occupant training in order to ensure a proper use of the building.

3.1.1. Management Procedures

Verification of the type of façade

1. Commission a competent construction building professional to verify the type of façade. Check whether the ‘substantial’ materials (those that are an important part of a heterogeneous product of the façade according to the UNE-EN 13501-1 standard [27]) are combustible or not, and, where applicable, whether they are protected or not by a layer with an EI 30 fire-resistance rating [20,28]; or a K₂ 30 fire protection capability [28]. In the event of complex façade systems or those with continuous exterior cladding, the involvement of fire safety experts is required to identify façade system safety (PRE) [29].

Procedures to avoid external ignition sources

2. Develop management procedures to prevent occupation of balconies near combustible façades, or at least prohibit barbecues, shisha pipes, and other ignition hazards, as well as to suppress fire load near the building base next to the façade (cars, garbage containers, etc.). This should be monitored on a daily basis or even more frequently (PRE) [22].

Verification of evacuation routes condition

3. Check that evacuation routes (corridors, stairways, etc.) are free of obstacles (OP) [30,31].
4. Check that fire doors are not blocked by items such as wedges or other objects not intended for proper functioning in the event of a fire (PRE, OP, CON) [20,31,32].
5. Check that the opening and closing systems of fire doors have not been altered with bolts or padlocks, as these prevent evacuation or access by the FS in case of fire (OP, EXT) [31].

Verification of Fire Protection Systems maintenance

6. Check that up-to-date maintenance certificates are available for the building’s Fire Protection Systems (henceforth, FPS) (PRE, EXT) [30].

Self-protection plan

7. Commission a professional expert in building fire safety to develop a self-protection plan for high-rise residential buildings that may include combustible materials on façades. When developing the evacuation strategy, these specific features, the building’s use, the presence of vulnerable persons, etc., must be considered (PRE, OP, CON) [33,34].

The self-protection plan shall consider:

- the provision of personal evacuation plans for all residents whose ability to evacuate may be compromised (such as persons with reduced mobility or cognition) [16]; the person responsible for the residential building should collect sufficient data about vulnerable residents (OP) [17];
- the study of the evacuation strategy and, if required, the update of the alarm system (OP, DET) [9,35];
- the provision of fire safety instructions (including evacuation instructions) in a manner that ensures they are understood by the building occupants, taking into account the nature of the building and occupants’ knowledge of it (OP) [16].

8. Provide the building's occupants with the self-protection plan and personal evacuation plans for disabled persons, including any updates that may be required. For the plans to be effective, there should be cooperation and exchange of information among the professionals who draft plans, building owners and occupants, and the FS (PRE, OP) [36,37].
9. Submit a copy of the self-protection plan to the FS, in electronic and paper format (OP) [16].

FS-related actions

10. Provide the FS with the following building information (in electronic and paper format):
 - updated floor plans for each floor identifying the location of key fire safety systems, as well as lifts intended for use by the FS (OP);
 - design of façades and details of the construction materials, as well as any material changes made (CON) [16,38,39].
11. In the event of façade systems made of combustible products, the FS, together with the PA, should review protocols for action (OP) [16].

Appointment of a responsible person

12. In buildings with dwellings located more than 18 m high, designate a person or organisation responsible for fire matters in a manner regulated by the PA (this role is required in the UK). Their main functions should be registering the building as a 'Higher-Risk Building', ensuring management of safety risks, channelling occupants' concerns, and exchanging building safety information with the FS (PRE) [32].

3.1.2. Occupant Training

Training building occupants in fire prevention, evacuation, and handling FPS is essential. The following are measures related to this aspect.

1. Provide training to occupants on:
 - precautions to be taken within dwellings to minimise the risk of fire regarding the use of electrical installations, gas installations, heating, cooking, and household appliances [40], rechargeable lithium batteries, etc. (PRE) [41];
 - how to avoid renovation work that compromises fire safety features of compartmentation [1] (e.g., removal of fire-resistant wall coverings, replacement of fire doors with non-fire doors, modification of installation layouts without maintaining the required fire resistance at the points in which they cross compartmentation [20], etc.), and the need to perform proper maintenance related to fire containment (CON);
 - the fire alarm sound recognition (OP) [32,42];
 - the use of manual FPS, such as fire extinguishers and fire hose reel (eEXT) [43].
2. Conduct safety drills, considering evacuation of disabled persons or those who may require assistance (elderly people and small children) (OP) [16,43–45].
3. Run awareness campaigns on maintenance and promote mandatory inspection campaigns, including penalties, in a way regulated by the PA (EXT) [17].

3.2. Building Use Phase: Maintenance Measures

This section covers the COFIGHT improvement measures related to maintenance (conservation and supervision) of evacuation routes and firefighters lifts, as well as FPS and electrical and gas installations, as the malfunctioning of these facilities is among the common causes of fire in residential buildings [2,46]. Maintenance operations must be

carried out by professionals under the control/initiative of occupants, owners or persons responsible for the building.

3.2.1. Maintenance of Evacuation Routes and Firefighters Lifts

Fire doors

1. Perform checks at intervals of no less than three/six months to ensure all fire doors are equipped with effective automatic devices, are in good working order, and comply with applicable regulations. (OP, CON) [16,47,48].

Firefighters lifts

2. Conduct monthly inspections of all lifts designed for use by the FS and report the results to the local FS. Testing shall include the mechanism that allows the FS to take control. Implement appropriate maintenance and verification plans (OP) [16,49].

3.2.2. Maintenance of the Electrical Installation

1. If necessary, review and update of the residential distribution board by an authorised installer. [50] Electrical installation and appliance inspection (PRE) [51,52].
2. In light of the increasing electrification of residential buildings due to the energy transition [53], the PA should regulate the frequency to carry out the supervision of the electrical installation in dwellings or in the building by accredited electricians. The sources consulted recommend the following frequencies:
 - periodically, every 10 years;
 - when occupancy of dwellings changes;
 - in the case of major works: renovations, installation of new equipment such as heat pumps, photovoltaic panels, batteries or electric vehicle charging points, power supply upgrade, etc. (PRE) [54,55].

All of which may involve having to modify installation (as specified in Section 3.3.6).

3. Maintenance of emergency lighting installation in accordance with current legislation carried out by qualified staff. During the inspection of emergency lighting devices (monthly/annual), both correct operation and autonomy time shall be checked. Promote the use of emergency lighting luminaires equipped with an automatic verification system, as they facilitate maintenance (OP) [56,57].

3.2.3. Maintenance of Gas Installation

1. Periodic inspection of the gas installation by accredited staff [58], for example, yearly (PRE).
2. Control or manage ignition sources: gas pipes for barbecues (PRE) [59].
3. Check accessibility of gas pipeline isolation valves at least once every three years, so that the gas supply can be cut off quickly in case of emergency (PRE) [17].

3.2.4. Maintenance of the FPS

1. Maintenance of the FPS: fire extinguishers, equipped fire hydrants (EFHs), fire detection and alarm systems, automatic fire suppression systems, etc., according to current legislation, including the specified frequency and qualification of the companies contracted (DET, eEXT, EXT) [20,32,60,61]. The following are some relevant maintenance operations:
 - commencement of a testing and maintenance regime in accordance with regulations for any passive or active system that has been neglected during the building's lifespan (EXT) [22,62];

- fire detection and alarm system: inspection and, where necessary, repair/replacement of the faulty system and implementation of a testing and maintenance regime in accordance with regulations, to minimise false alarms (DET) [22,63];
- fire pump (for fire water supply): reinspection and, where applicable, repair of a defective pump (EXT) [20];
- sprinkler system: start of a testing/maintenance regime in accordance with regulations [22]. A basic but key aspect is to ensure that the sprinkler opening valve is not closed due to a failure of the installation management (eEXT) [35];
- inspection of the proper location of signs (eEXT, EXT) [1].

3.3. Building Intervention Phase

This section outlines the COFIGHT measures during the building intervention phase. Firstly, it details training measures for professionals, which should be promoted by the PA. Secondly, it provides measures related to the renovation or modification of building elements and installations, to be carried out by qualified professionals at the initiative of the persons responsible for the building and its occupants. These measures are derived from the documentary analysis, and as mentioned in Section 2 (Methodology) both recommendations and conditions based on mandatory requirements are included (identified with an asterisk), according to the Spanish CTE for new buildings. However, their implementation in a specific building shall be subject to a fire safety study conducted by a fire safety expert and compliance with current regulations.

3.3.1. Training for Professionals

This section compiles recommendations primarily aimed at national authorities to promote improved training and impartiality for professionals involved in building fire safety, so that problems detected in the design and construction of certain existing buildings are not repeated and emerging incidents can be avoided in future interventions.

Training and professional competencies

1. Undertake a national fire safety education and training effort for fire protection engineers, structural engineers, architects, and code writers; in particular, improve training of architects in the selection of materials (PRE) [3,17,29].
2. The national building regulator should sponsor the development of a library containing data on product and material testing, reports on serious fires, and academic papers, to provide with an ongoing resource for drafters of renovation projects for particularly complex and high-risk buildings [17,19]. Some references are The University of Queensland's Cladding Materials Library [17,64] and the KRESNIK Database of commercial façade tests in Poland (PRE) [19].
3. Provide with more university training in performance-based building design and basic fire safety knowledge, as opposed to prescriptive application of regulations; pay special attention to design-based training in addition to technology-based training; offer more training on risk assessment, as well as feeding back the knowledge acquired in engineering into the educational programme (PRE) [3,29].
4. Put technical project drafters and fire protection engineers in contact with the FS to exchange knowledge (PRE) [65,66].

New degree

5. Establish the profession of fire safety engineer and an independent body to regulate such profession, define the necessary membership criteria, maintain a register of members, and supervise their performance (PRE) [17,29].

6. In order to accelerate the creation of a professional fire protection engineering corps, it is recommended that the Government takes urgent measures to increase the number of places on high-quality master's degree courses accredited by a professional regulator (PRE) [17].

Powers regarding the monitoring of construction works

7. The Government should appoint an independent group to examine whether those with commercial interest in the building process can perform construction monitoring functions. The same group should examine whether all construction monitoring functions should be performed by a national authority (PRE) [17].

3.3.2. Modification of Evacuation Routes

This section covers passive safety measures for evacuation routes (corridors, stairways, etc.). In these buildings, 'protected stairways' are considered to be interior stairways that meet certain fire safety conditions as specified by regulations; they can be compartmented stairways and, in some cases, can also have a protected lobby. Active measures are also incorporated, such as those relating to smoke control systems and emergency lighting.

Doors

1. * On doors located on evacuation routes, and in particular on those intended as building exits that require a key to open, incorporate an easy-to-operate opening device that can be activated without a key and without having to operate more than one mechanism from the side approached by occupants escaping (handle, push button, horizontal push or slide bar) (OP) [3,20,32].
2. On evacuation routes, if the expected occupancy in the building is high, for example, more than 60 occupants, arrange for doors to be opened in the direction of evacuation (OP) [32].
3. Incorporate vision panels and natural light inlets in doors that divide corridors into evacuation routes, in doors leading to stairways, and in those that open in both directions. Vision panels allow fire risks to be assessed and enable users to check whether there are persons on the other side to avoid collisions. They also help to prevent occupants from keeping doors open to allow natural light into windowless spaces (OP, CON) [32,65].
4. Replace doors of dwellings with fire-resistant doors, with a self-closing device (a device that closes a door when it is open at any angle, against the door frame) (OP, CON) [32].
5. * Replace the doors of the special risk premises located on ground floor near the evacuation stairway, with fire-resistant door, to minimise the risk of smoke invading the stairway (CON) [20,32,67].
6. If the building has a detection and alarm system, fire doors that are normally open should be equipped with an automatic closing system using a retention device that keeps them open and closes them automatically when the detection system alerts there is a fire (OP, CON) [32,34,68,69].
7. * Install certified fire doors on evacuation routes (CON) [20,32,70].

Circulation areas

8. * Adjust the width of evacuation elements (doors, passages, corridors, ramps, stairs) to the number of occupants passing through them (OP) [20,32].
9. * Adapt the length of evacuation routes to a protected stairway, fire escape or other sector/compartment (OP) [20,32].
10. * On residential storeys, where feasible, provide with an accessible storey exit to another fire compartment or a refuge area. (OP) [20,71].

11. * Ventilate escape routes to keep them free of smoke: install smoke dampers and smoke ventilation systems (OP, CON) [35].

Interior linings

12. Reduce the fire load by replacing combustible lining materials (on walls, ceilings and floors) on evacuation routes with others which do not contribute to fire spread (A1) or have very limited combustibility (A2), and also very low smoke emission (s1) and no falling drops or flaming particles (d0) (PRE, CON) [12,72–74].

Stairways

13. * Install new protected stairways or protected stairways with a lobby, in accordance with current regulations regarding quantity and layout (OP, CON) [3,20,28,32].
14. * Compartmentalise existing stairways from common circulation areas and install a system to protect from smoke (CON) [72]. This can be achieved by ventilating stairways and lobbies (if they exist), or by pressurisation to prevent smoke from entering the stairways (OP, CON) [20,35].
15. In protected stairways or those protected by a lobby, have the existing ventilation system checked by fire safety experts to ensure that, in the event of a fire, smoke is prevented from entering the protected area for the necessary duration. If a pressurisation system is installed, it must have extra air flow capacity to prevent smoke from invading the stairway and reaching upper floors, taking into account realistic evacuation scenarios that include opening of doors, expected evacuation time, height of the building and potential smoke leaks inside the stairway (CON) [75–77]. Some research is critical concerning design and implementation of the pressurisation system for evacuation routes as generally proposed, and suggests studying the ventilation system based on the needs and risks of each building, through the PBD using CFD (Computational Fluid Dynamics) simulation [78,79], which involves the participation of fire safety engineers and other skilled professionals [29]. One solution adopted in the UK under the PBD has been, in many cases, to move away from pressurisation and opting for alternative solutions based on air exchange rates or ‘smoke clearance’; for instance, the system installed in the Beetham Tower in Manchester [78].
16. Adapt the width of the evacuation stairway to accommodate not only the occupants but also rescue personnel (OP, EXT) [3].

Firefighters lift

17. * Provide with an exclusive lift for firefighters with access from a protected enclosure (EXT) [3,20,32].

Signalling

18. Install signage for evacuation routes. Signs must be visible even in the event of a failure in the normal lighting supply (OP, EXT) [20,44,80].
19. Clearly mark the floor numbers on every landing within stairways and also in a prominent place in all corridors and lobbies of all high-rise buildings, so that they are visible to the FS under normal conditions as well as in low light or smoky conditions (OP, EXT) [16,32].
20. In the event of fire doors that should be fire doors but are not clearly marked or identified as such, confirm whether or not they are fire doors and provide with required signage (OP) [81].
21. Place the prohibition sign according to EN ISO 7010:2020 (pictogram P020) near the firefighters lift so that it is easily visible from all landings [82]. The text ‘Do not use the lift in case of fire’ may be added to the pictogram (OP) [83].

Emergency lighting

22. * Install emergency lighting (OP) [20,32,34,84,85].

3.3.3. Modification of Other Interior Compartmentation Elements

1. Adapt the fire resistance of compartmentation elements and between dwellings and any other area of the building (CON) [32].
2. * Adapt the fire resistance of compartmentation elements separating fire sectors (CON) [20,32].
3. * Keep fire resistance of fire compartmentation elements at points in which they are penetrated by installations such as cables, pipes, conduits, ventilation ducts, etc. (CON) [20,32,68].
4. * Provide with continuity of fire compartmentation in hidden spaces such as service risers, cavities, suspended ceilings, raised floors, etc. (CON) [20,32,68].

3.3.4. Modification of Façade System

This subsection covers measures to be taken on the façade system to reduce the risk of vertical external fire spread in the event of combustible cladding or insulation is present.

It must be clarified that, in general, cladding materials considered combustible, or which may contain combustible materials, include wood, plastic, polycarbonate, glass-reinforced polymers (GRP), high-pressure laminates (HPL), and, in the case of metal composite materials (MCM), for example, some aluminium composite panels (ACP). Foam-based materials are considered combustible insulation [20].

If, upon inspection of the cladding or insulation of façades, their composition cannot be identified with certainty, samples should be taken for testing [22,59]. The current issues regarding fire reaction testing are mentioned in Section 4.1.1.

Following this, firstly, partial intervention measures on the façade are presented, either by acting on the sources of ignition or by modifying part of the façade system, until a comprehensive solution for the latter is implemented. This article does not cover intervention on complex façades such as curtain walls [22,29].

1. Remove or de-energise photovoltaic panels and lighting systems on the façade or in the cavity (including associated low-voltage transformers), as well as power sockets, electrical wiring, lightning conductor wiring, electric motors for automated awnings, etc., in order to minimise the risk of ignition (PRE, CON) [22,59].
2. Take out kitchen smoke extraction grilles and also remove the combustible façade system above and in the vicinity of extraction grilles (PRE, CON) [22,59].
3. Replace combustible cladding and insulation of façades, including decorative elements made of combustible materials, in the vicinity of potential ignition sources, particularly near the building base (PRE, CON) [16,18,22].
4. Install fire barriers around openings, doors, windows, vents, ventilation grilles (CON) [59,86].
5. Interrupt combustible cladding and insulation of the façade system arranged continuously and vertically (connecting floors), by replacing it with strips of non-combustible materials [22]. The height of these strips is crucial to preventing fire from spreading further, as the flame can 'jump' over strips of non-combustible materials [87]. Thus, in large-scale tests conducted according to the BS 8414-1:2002 standard [88], such as those developed by the Faculty of Civil Engineering of the University of Zagreb, the failure of samples incorporating fire barriers has been observed [89]. The height of the non-combustible strips can be determined through performance-based design by evaluating the rate of combustible gas production of combustible material that heats up when reached by the 'jumping' flame (CON) [87].

6. * In the event of façades with ventilated cavities, in addition to the previous measure, horizontally interrupt the air cavities in continuity with the floor slabs on each floor [59], or every two floors [28] and, at least, in continuity with the floor slabs that separate fire sectors (CON) [20,59].
7. Replace combustible cladding and insulation on façade projections (balconies, canopies, etc.) with fire-resistant and non-combustible alternatives (PRE, CON) [22].
8. On balconies and terraces, replace the laminated glass parapet containing an intermediate layer of plastic film (e.g., polyvinyl butyral) with another non-combustible solution (e.g., laminated glass with an intumescent film). However, this measure is questioned due to its implications for balcony design (CON) [90,91].
9. * Adapt the fire resistance to a minimum of 60 min for the horizontal strip of the façade situated between the top of the windows on one floor and the sill of the windows on the floor above. Adapt, at least, fire resistance of the strip between windows in different fire sectors (CON) [20].
10. * Instead of the strip on the façade indicated in the previous measure, or in addition to it, horizontal protruding elements such as eaves, balconies or recesses, which are fire-resistant and non-combustible, may be installed above the windows so as to reduce the risk of fire spreading through the window openings between floors or, at least, between different fire compartments (CON) [20,92,93].

Below is a detailed description of how elements of the two previous measures are standardised by certain regulations in various countries:

- the minimum height established for the horizontal strip of the façade varies, for example, from 0.90 m (Australia, USA, UAE), to 1 m between fire sectors (Spain), and 1.20 m (Belgium), to 1.50 m (Singapore, for residential buildings over 24 m high); in Spain, if horizontal projections are provided, the minimum height of 1 m may be reduced by a dimension equal to that of the projection;
 - likewise, the minimum projection of horizontal protruding elements varies, for example, from 0.60 m (New Zealand, Belgium, Singapore), 0.76 m (USA) up to 1.10 m (Australia) [20,21,28,94];
 - some countries, such as the UK, do not regulate such dimensions [32,94].
11. * If the façade is modified, verify that openings allow access from the outside to the FS (EXT) [20].
 12. Replace all combustible cladding and insulation, including decorative elements made of combustible materials [22] with cladding and insulation with fire reaction class A2-s1, d0–A2-s2, d0, even on façades that are difficult to access (light wells, inner courtyards, narrow streets in old town centres, façades supporting external escape routes) [16,22,32,33,72,92]. In any case, pay attention to execution at critical points such as joints or seams (CON) [33].
 13. * In façades with a ventilated cavity, in addition to the previous measure, install cavity barriers. The width of the air cavity, ventilation and the scale of the fire are crucial parameters that may influence fire behaviour inside the cavity. Wind speed may also influence air flow in ventilated cavities. Further studies are required to identify how air flow within air cavities governs fire behaviour (CON) [20,95].
 14. As an additional measure to the two previous, so as to slow down fire spread, replace the glass and frames of openings with fire-resistant ones (CON) [32,96].

3.3.5. Fire Resistance of Structures

1. Intervene in the structure, bearing in mind that the objective of fire safety in existing high-rise buildings is to prevent fire spread and keep structural integrity until the available fuel load has been consumed, rather than merely preserving integrity for a

specified period of time to allow occupants to evacuate (survival of the full burnout) (CON) [3]. This approach is consistent with the advanced design methods of Eurocode 1 (EN 1991-1-2), which allows for the use of parametric fire curves based on the specific fuel load and building ventilation [97]. In the case of floors used for parking, the potential exposure to electric vehicle (EV) fires should be considered (CON) [98].

3.3.6. Electricity and Gas Installations

1. * Adaptation of existing installations to current safety regulations (PRE).

Electrical installation

2. Renovation of building's electrical installation in the event it is old and does not have differential protection elements for indirect contact (PRE) [40,99].
3. If the building does not have a grounding connection, proceed with its installation (PRE) [100,101].
4. * Provide with a sufficient backup source of electrical power to supply the fire protection equipment (EXT) [34].

Gas installation

5. Install detectors that warn of potential gas leaks in flats (DET) [40].
6. * In gas pipelines that cross fire sectors, seal the junctions with walls and floors delimiting the sector by using fire-resistant materials, to keep the integrity of sectors and reduce the risk of pipeline failure due to fire effects (PRE) [17,20,102].

3.3.7. Detection and Alarm Installations

1. Install fire detection and alarm systems in all dwellings. The fire alarm must sound simultaneously throughout the entire building, not just in the dwelling where the fire originates. (DET) [14,22,32,44,72,81]. In addition, install manual pushbuttons that allow the transmission of local alarms, general alarms, and verbal instructions (DET) [34,44,72].
2. * Install a fire detection and fire alarm system in common areas of floors used for residential housing and parking use (DET) [3,20,21].
3. Install fire detection and alarm systems on evacuation routes, with light signals indicating whether the protected stairways are smoke-free or not (DET) [75].
4. Equip all buildings with installations so that the FS can send an evacuation signal to the whole or part of the building by means of sirens or similar devices (DET) [16].
5. Increase redundancy of power and alarm systems to keep a high level of safety even in the event of partial failure of any of these systems [3], for example, by providing backup power systems (DET).
6. Install a two-way telephone service for FS use in all lifts cabins and lobbies, and also on each exit stairway floor level (OP, EXT) [34].

3.3.8. Early Fire Extinguishing Systems

Fire extinguishers

1. * Install fire extinguishers on each floor and in particular risk areas (utility rooms, storage rooms, etc.) (eEXT) [20,103].

Automatic fire suppression system

2. * Install an automatic interior sprinkler system to control an interior fire and reduce the likelihood of ignition of a combustible façade system due to such a fire (eEXT) [3,20–22,34,44,104]. Sprinklers must be installed in individual dwellings and in common areas (except in fire-sterile common areas) [32].

3. Incorporate an additional row of interior sprinklers in a glass façade to preserve the integrity of the glazing and insulation and reduce thermal radiation (eEXT) [104].
4. Install sprinklers on balconies [22,105] or direct discharge on the façade (eEXT) [73,106,107]. Incorporate sprinklers inside the façade cavity to inhibit spread of smoke and fire throughout the air cavity and prevent it from reaching the level above the floor height (eEXT) [108].

System redundancy

5. Increase redundancy of power and fire suppression systems to keep a high level of safety even in the case of a partial failure of one of these systems (eEXT) [3].

Signaling

6. * Install signage for manual fire protection installations (eEXT) [20,44,109].

3.3.9. Other FPS (FS Intervention)

Hose reels, fire hydrants, dry risers, fire pumps

1. * Install hose reels (EXT) [20]. The 25 mm hose reels could be used by building occupants trained in their use, requiring at least two people for operation. The 45 mm hose reels are for exclusive use by firefighters or qualified staff (eEXT) [110]. In the event of untrained occupants, it is preferable they evacuate the building rather than try to extinguish the fire by using hoses [111].
2. * Install exterior fire hydrants (EXT) [20,32].
3. * Install a dry riser for water supply for firefighting in the building's floors, supplied by connections to no fewer than two main water pipes located on different streets (EXT) [3,20,21,32,34]. Homogenise the arrangement of dry risers in buildings, so that the FS can easily find them (EXT) [65]. Further details of this measure are:
 - facilitate FS access to dry riser outlets with ample passage inside the building (EXT) [65];
 - outside the building, next to the police number, display a sign indicating the existence or non-existence of a dry riser for the information of the FS (EXT) [65].
4. In the event that sprinklers are installed within the cavities of façades with combustible cladding, provide with an independent dry riser for exclusive use of the FS, as an additional measure for supplying the sprinkler system, with inlets on the façade and a network of horizontal piping (EXT) [112].
5. In the case of buildings over 50 m high, include pipes filled with water supplied by pumps from tanks located in the building, so that the FS can connect hoses (EXT) [32].
6. * Provide with multi-level pumps (multistage pumps) and water storage tanks (EXT) [3,20,53].

Smoke control system

7. * Install a fire smoke control system in parking floors and basements with natural or mechanical ventilation and smoke detectors (OP, CON) [20,32].

Information box and FS panel

Measures that could be regulated by the PA to require implementation:

8. Following the building inspection, provide with an up-to-date information box containing the FPS, including a copy of the plans for each floor and information on each firefighters lift (EXT) [16,65].
9. Equip the building with an FS panel, as a nerve centre for monitoring and managing the building's fire safety systems (EXT) [65,72].

Fire Control Centre

10. In certain high-rise buildings, provide with a room for the FS emergency operations, which shall approve its location, design, contents and access (OP, EXT) [21,34].

3.4. Summary of the Common Principles of the IFSS Based on the Measures Compiled

The COFIGHT measures outlined above cover all the common principles of the IFSS (referenced by their acronyms at the end of each measure) and affect various components of the building that can be identified through the taxonomy. To summarise, Figure 5 shows the relationship between these components and each principle, as well as the life cycle phase at which the measures are applied, based on the analysis of the collected measures.

BUILDING COMPONENTS		COMMON PRINCIPLES OF THE IFSS					
		PRE	DET	OP	CON	eEXT	EXT
In general		●△▣		●	●	●	●
Spaces	Interior spaces	●					
	Evacuation routes	●		●△▣	●△▣		●
Construction elements	Façades	● ▣			▣	▣	▣
	Interior linings	▣			▣		
	Compartmentation				● ▣		
	Structure				▣		
Installations	Electricity	●△▣					
	Gas	●△	▣				
	Firefighters Lifts			△▣			
	Emergency lighting			△▣			
FPS	FPS in general	●	▣			△▣	●△▣
	Detection and communication system		●△▣	●			
	Automatic fire suppression system					△▣	
	Fire extinguishers					●△▣	
	EFHs, hydrants, dry risers, pumps						●△▣
	Smoke control system			△▣	△▣		
	FS panel						●
	Signalling			▣		△▣	△▣

Common principles of the IFSS:

PRE: Prevention. DET: Detection and communication. OP: Occupants protection. CON: Containment. eEXT: Early extinguishment. EXT: Extinguishment.

Life cycle phase:

- ● Use △ Maintenance
- ▣ INTERVENTION

Abbreviations

FPS: The building's Fire Protection Systems

EFHs: Equipped Fire Hydrants

FS: Civil Protection and Fire Services

Figure 5. Relationship of building components affected by the COFIGHT measures, with the IFSS principles and the life cycle phase.

3.5. Responsibility of the Agents Involved in Implementing the COFIGHT Measures

Figure 6 below sets out the various responsibilities of the agents involved in the process of implementing the COFIGHT improvement measures (collected in Section 2.3), according to the activities arising from the measures themselves and the phases in which they are carried out.

PHASES	ACTIVITIES	AGENTS					
		Occupants	Owners / Persons responsible for the building	Building / installations technical professional	Maintenance technical professional	Public Administration	Civil Protection and Fire Services
Use	Façade type verification	I	I	R		A	
	Develop procedures to prevent external ignition sources	I	I	R			C
	Verification of evacuation routes	R	R	C			C
	Verification of FPS maintenance	I	I		R	A	
	Self-protection plan	I	I	R		A	C
	Provide building information to the FS		R	C			I
	Review action protocols	I	I	I		A	R
	Appointment of a responsible person		I	I		R	
	Occupant training	I	I			R	C
Maintenance	Evacuation routes and firefighters lifts	I	I		R	A	
	Electrical and gas installations	I	I		R	A	
	FPS	I	I		R	A	
Intervention	Training for professionals			I	I	R	C
	Modification of evacuation routes	I	I	R		A	C
	Modification of other interior compartmentation elements	I	I	R		A	C
	Modification of façade system	I	I	R		A	C
	Fire resistance of structures	I	I	R		A	C
	Electricity and gas installations	I	I	R		A	
	Detection and alarm installations	I	I	R		A	C
	Early fire extinguishing systems	I	I	R		A	
	Other FPS (FS intervention)	I	I	R		A	C

Abbreviations

R: Responsible

A: Approver/Authority

C: Consulted

I: Informed

FPS: The building's Fire Protection Systems

FS: Civil Protection and Fire Services

Figure 6. Responsibility matrix for the stakeholders involved in the COFIGHT measures.

4. Discussion

Based on the analysis of the COFIGHT measures collected, a series of questions arise regarding the barriers and opportunities for their implementation.

4.1. Implementation of the COFIGHT Measures in Existing Buildings

4.1.1. How to Begin the Process of Improving Safety of Buildings at Risk of Having Combustible Façades?

At the initiative of the building owner or the PA, a fire safety expert with accredited training and experience should conduct a risk assessment of the building and, based on the

results, establish the most appropriate improvement measures, which may be additional to those required by regulation.

The risk assessment should cover both façade system and ignition sources (combustible cladding or insulation and vertical connections, extent of ignition sources, etc.), as well as fire protection installations, means of evacuation for building occupants, compartmentation and fire protection of the structure [24]. Some methods for assessing the risk of fire spread through the façade of existing buildings include the NFPA's EFFECT [22] and the Australian Practice Guide Façade/External Wall Fire Safety Design [59].

However, from the scientific literature studied, it is observed that it is very complex to determine the façade performance and assess the risk, with some of the procedures mentioned being questioned [9]. It is even considered that the currently testing methods established for evaluating vertical fire spread in façade systems do not reflect the construction reality [9], nor are they representative of all possible real-fire scenarios, and furthermore, these testing methods vary depending on the country that developed them [113].

4.1.2. What Should Be the Strategy for Implementing the COFIGHT Measures?

The robustness and performance of fire safety strategy is defined by a variety of protection conditions [9,108] and according to the common principles of the IFSS [2].

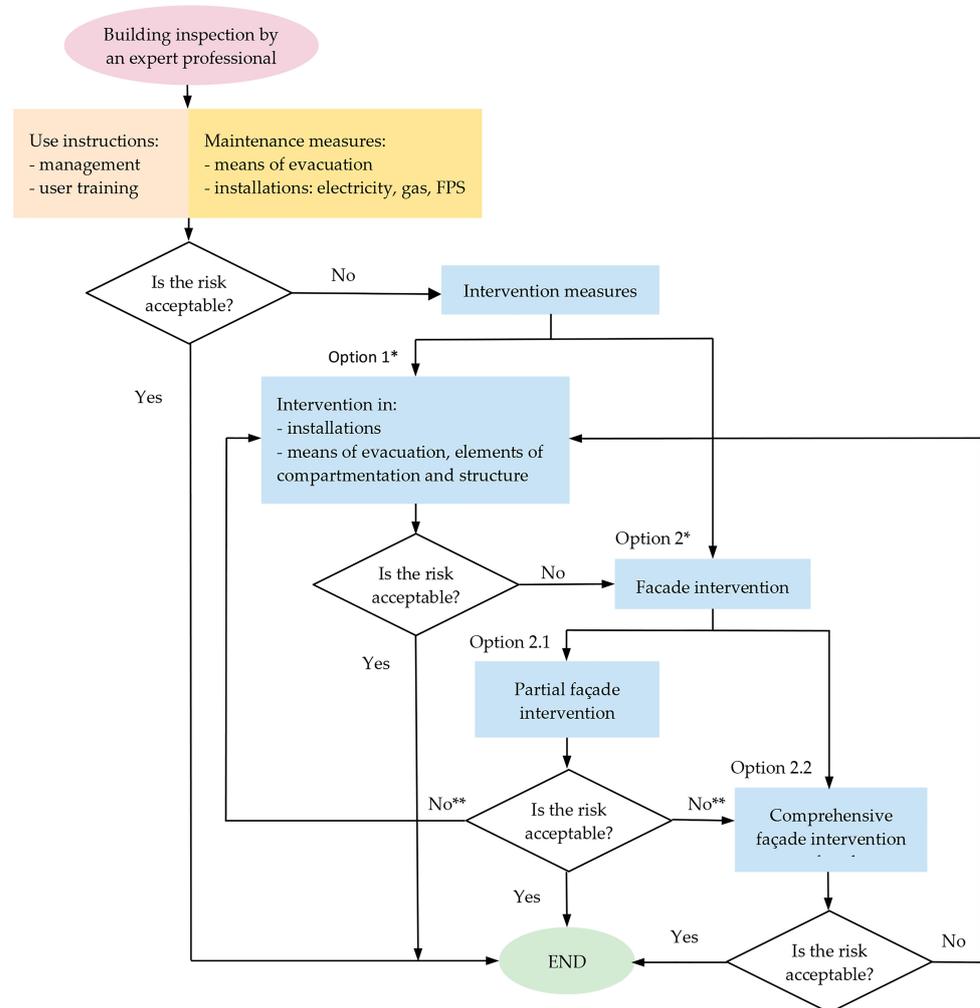
Thus, from the information gathered from experts, some COFIGHT measures can be highlighted, which are set out below, and whose implementation process is proposed in the following diagram (Figure 7).

Firstly, it is considered necessary to implement fire safety inspection protocols for existing buildings, carried out by experts with accredited training and experience in fire safety.

Until intervention measures are implemented in the building, in the short-term management measures related to prevention are considered essential to avoid ignition risks on balconies and near the building base [22], as well as periodic training of occupants on fire prevention and response, all of this having previously drawn up a self-protection plan or at least emergency instructions [16] that considers vulnerable people and includes an analysis of the evacuation strategy.

In high-rise buildings, evacuation is often only carried out from the level in which the fire occurs and from the floors immediately above and below, while occupants on other floors may remain in place if there is no vertical spread of fire along the façade [9,35]. This strategy is called 'stay put'. In the case of a façade fire, when fire is spread vertically and extends over more than two floors, this strategy is compromised [35]. In the EFFECT [24], it is argued that upgrading a fire alarm system from a 'stay-put' to an 'all-out' system (with the alarm sounding simultaneously throughout the building, not just in the dwelling where the fire originated) shall have some benefit in reducing risk, but shall not suppress it. Other authors point out that in the event of some vertical fire spread, a 'phased' or 'total' evacuation strategy based on detection and alarm may be permissible. Vertical fire spread along the façade represents a failure in compartmentation, and a switch to a 'total' evacuation strategy becomes necessary, but may not be safe due to the spread of fire and smoke throughout the building [9]. In order to determine the best evacuation strategy, it would be recommendable to contemplate the fire alarm and detection systems, the level of safety offered by evacuation routes, as well as quantify the maximum fire spread rates on façades and compare them with the expected evacuation time. Within the principles of performance-based fire safety engineering, this comparison is framed within the ASET/RSET analysis: it must be verified that the ASET is greater than the RSET [8]. This is an extremely difficult task in the case of façades with complex systems or continuous exterior cladding [9,35], as vertical spread can rapidly reduce the ASET, making the 'stay-put' strategy unsustainable. Thus, in the Grenfell Tower fire, the 'stay-put'

strategy was a critical factor in the loss of life [16], whereas in the façade fire at the Lacrosse building, occurred in Melbourne (Australia), in 2014, the existence of an interconnected alarm system, two smoke-free pressurised protected staircases, sprinklers in all flats, and a ‘phased evacuation’ strategy allowed for the evacuation of all occupants without fatalities or serious injuries. Nonetheless, an unacceptable level of damage occurred [9].



* Depending on the case, Option 1 or Option 2 (or both) may be adopted in the first instance.

** If option 1 has not been applied, the process may continue with that option or with option 2.2 (or both).

Note: For the purposes of implementing the COFIGHT measures, risk is considered acceptable when losses in each building are minimised to a level tolerable to society, considering social, economic, and environmental factors.

Abbreviations

FPS: The building's Fire Protection Systems

Figure 7. Diagram of the process for implementing measures in buildings with combustible façades.

Likewise, in the field of management, the building management should promote the carrying out of a fire drill with occupants at least once a year [26]. In this regard, the EuroFSA Action Plan designed for EU countries highlights the urgent need to pay attention to the social dimension of fire safety [25]. Several countries, such as USA and Canada, organise the Annual Fire Prevention Week to encourage people to take proactive measures to protect themselves and their homes [114,115].

Furthermore, it is essential to perform a suitable building maintenance [35]; specifically, it must be verified that evacuation routes are not obstructed, fire doors are functioning properly and fulfilling their purpose, firefighters lifts are operational and appropriately

maintained for the use by the FS, and that installations are being properly preserved in good conditions, particularly the FPS.

Should the aforementioned use and maintenance measures be considered insufficient to reduce the risk of fire-related harm to occupants to acceptable levels, a larger-scale intervention shall be necessary.

As established in the ISO 23932-1 standard [116] and supported by scientific literature on performance-based design [117] the level of acceptable risk is not an absolute value, but rather a threshold established through consensus among key stakeholders (Public Administration, owners, occupants, fire protection professionals, insurers, etc.).

A first option, prior to intervention on the façade, may consist of acting on the building's installations, in particular on the FPS and on the means of evacuation, compartmentation elements and protection of the structure.

Installing gas leak detectors in flats is crucial for prevention, so that once occupants are notified, they can act in time [40]. On the other hand, in order to achieve early fire warning, the implementation and maintenance of a detection and alarm system in homes is essential. This system should be complemented by automatic sprinklers in the flats, common areas and evacuation routes, so that elderly or disabled people may escape safely and in time [118]. In this sense, there are authors who support installation of sprinklers due to their high effectiveness in high buildings, as they help fires grow slowly or remain contained, thus limiting the consequences [35,93]. The IBC requires the installation of sprinklers in all residential buildings, in accordance with the requirements of NFPA 13 [21,107]. Some authors state that the installation of interior sprinklers, even near the façade, is not sufficient to compensate for the fire spread through combustible materials on the façade [18]. Other authors propose the installation of sprinklers on the exterior. According to the EFFECT, one risk mitigation measure could be installing exterior sprinklers on balconies [22]. Several studies have shown how the use of external fire suppression systems can reduce the risk of fire spreading [73,106,107]. The installation of sprinklers inside the air chamber of double-skin façades has also been regarded [108]. Based on the review of scientific literature, it is possible to relate the qualitative effectiveness of various types of automatic sprinklers to two types of façade configurations (it must be noted that quantifying these relationships requires specific fire safety engineering design):

- In the case of lightweight façade typologies and curtain walling with large glazed areas and other elements with weak thermo-mechanical behaviour (with assemblies located beyond the edge of the fire-rated floor slab), in addition to the presence of combustible materials and a fully developed fire scenario indoors, the installation of internal sprinklers—discharging the required water density based on the fire load [107] can control the fire source. This can guarantee the stability of these façades for a specific duration, preventing glazing failure and external fire breakout, thereby hindering fire spread to the floor above [21,73,93]. In addition to internal sprinklers, the installation of window sprinklers or external water curtains on these types of façades can maintain their integrity for a determined period [73].
- Regarding double-skin façades with a continuous air cavity and the presence of combustible elements—a configuration posing a high risk of fire spread—the installation of water—curtain sprinklers between the two skins, providing the required water flow for the combustible material's fire load, can inhibit smoke spread and prevent temperature increases within the façade cavity [108]. In these façades, besides installing sprinklers within the cavity, internal sprinklers can extinguish an indoor fire or, should the fire reach the façade, activate the water-curtain sprinklers arranged within the air cavity [73].

Another key aspect for persons' safety, which helps to define evacuation strategies, is the evacuation means available in the building and its compartmentation conditions, although this will depend on the floor plan of the existing building. In this regard, it is essential to provide fire-isolated stairways protected against smoke [9]. Likewise, the installation of emergency lighting and safety signage on evacuation routes facilitates visibility and orientation if normal lighting fails [34]. Similarly, on evacuation routes, replacing combustible interior linings with non-combustible solutions eases evacuation and reduces fire spread [74]. Furthermore, in order to limit the risk of fire spreading inside, it is regarded as indispensable to compartmentalise the building with fire-resistant elements, including all separating elements between dwellings [119] and, where appropriate, an intervention in the protection of the structure to preserve its function until the combustible material is consumed [3].

If it is acknowledged that intervention in installations and evacuation means, compartmentation elements and structure does not reduce the risk to an acceptable level, it shall be essential to intervene on the façade. Work on the façade could also be carried out before the intervention in installations and the aforementioned means and elements, or simultaneously.

Intervention on the façade may consist of partial measures to reduce the vertical fire spread (installation of barriers, protruding elements, partial replacement of cladding, etc.) [22] or total replacement of the façade system (this being the most effective and desirable intervention). If partial measures are insufficient to minimise the risk, and no action has yet been taken on the FPS and evacuation routes, action shall be taken on the latter, or the façade system may be completely modified by replacing combustible materials with non-combustible ones [22]. In any case, action must be taken to reduce to acceptable limits the risk of the building's occupants suffering harm from an accidental fire [20].

Next, by way of summary, Figure 7 sets out the COFIGHT measures highlighted above, grouped according to potential phases of application and objectives pursued (with acronyms referring to the IFSS common principles at the end of each phase), aimed at achieving an acceptable level of risk, as explained above and shown in the diagram in Figure 8.

Furthermore, Figure 9 compiles the COFIGHT measures from Figure 8, sorted according to effectiveness and cost. In order to estimate effectiveness qualitatively, the EFFECT [20] and the analysis of scientific literature—based on expert reports and underpinned by various real-life cases—are taken as a reference. Measures are shown grouped into three levels of effectiveness:

- management and maintenance;
- partial intervention inside the building or on façades (active and passive measures);
- comprehensive intervention on façades (passive measure).

The final level of effectiveness shall depend on the combination of the COFIGHT measures selected and the initial state of the building. Likewise, the ranking of measures by cost is indicative, given their high variability depending on building size and initial conditions; costs are presented in ranges, as estimated euros per dwelling based on Construction Price Databases applied to a model building.

The implementation of the COFIGHT measures is contingent upon the economic and operational feasibility of the residents' management company. Under this premise, it is recommended that prevention, detection, and alarm measures (Figure 8) be implemented widely and at an early stage, given their technical simplicity and low cost.

Application phases	COFIGHT Measures
Prevention (PRE) Understanding the causes of fire and reducing risk factors to prevent and limit its effects.	Suppress fire hazards in susceptible areas In particular, at the building base (garbage containers, parked vehicles, etc.) and balconies, to prevent fires from breaking out.
	Self-protection plan (or emergency plan), training and drills Identify vulnerable occupants so that the FS can prioritise rescue, and define an evacuation strategy. Provide instructions on precautions and maintenance to reduce risks; training on how to act in the event of a fire.
	Regular maintenance of evacuation routes and installations Check evacuation routes, including fire doors and firefighters lifts. Services maintenance, in particular electrical installation and FPS.
	Install gas leak detectors in flats Position them appropriately to alert occupants so that they can take actions.
Detection and communication/Alert (DET) and evacuation (OP) Time is crucial for occupants to escape before smoke fills the evacuation routes.	Detection and connected alarm Install detection and alarm systems in all dwellings so that the alarm sounds throughout the building or in specific areas to enable total or phased evacuation, depending on the evacuation strategy.
	Ensure evacuation routes Compartmentalise evacuation routes and pressurise/ventilate stairways. Replace combustible linings with non-combustible materials. Install emergency lighting and safety signage to facilitate visibility and orientation.
Fire control: early extinguishment (eEXT) and containment (CON) Reduce the risk of fire spread horizontally or vertically.	Automatic sprinklers in flats, balconies, etc. They can be highly effective for controlling the fire at its source and preventing it from reaching the combustible façades.
	Building sectorisation, including each dwelling With fire-resistant elements, structural protection, and fire doors.
	Partial interventions on façades Replace the façade system near ignition sources, close to the building base, with non-combustible products. Install fire barriers on each floor; on ventilated façades, they interrupt the 'chimney effect' in the air cavity. Install protruding elements on each floor.
Suppress the main cause of spread (PRE, CON) Reduce the high risk of fire spread.	Comprehensive replacement of the façade system The key measure is to replace combustible panels and insulation with non-combustible systems (A1-s1, d0 or A2-s1, d0) to reduce rapid external fire spread.

Abbreviations

PRE: Prevention

FS: Civil Protection and Fire Services

FPS: The building's Fire Protection Systems

DET: Detection and communication

OP: Occupants protection

eEXT: Early extinguishment

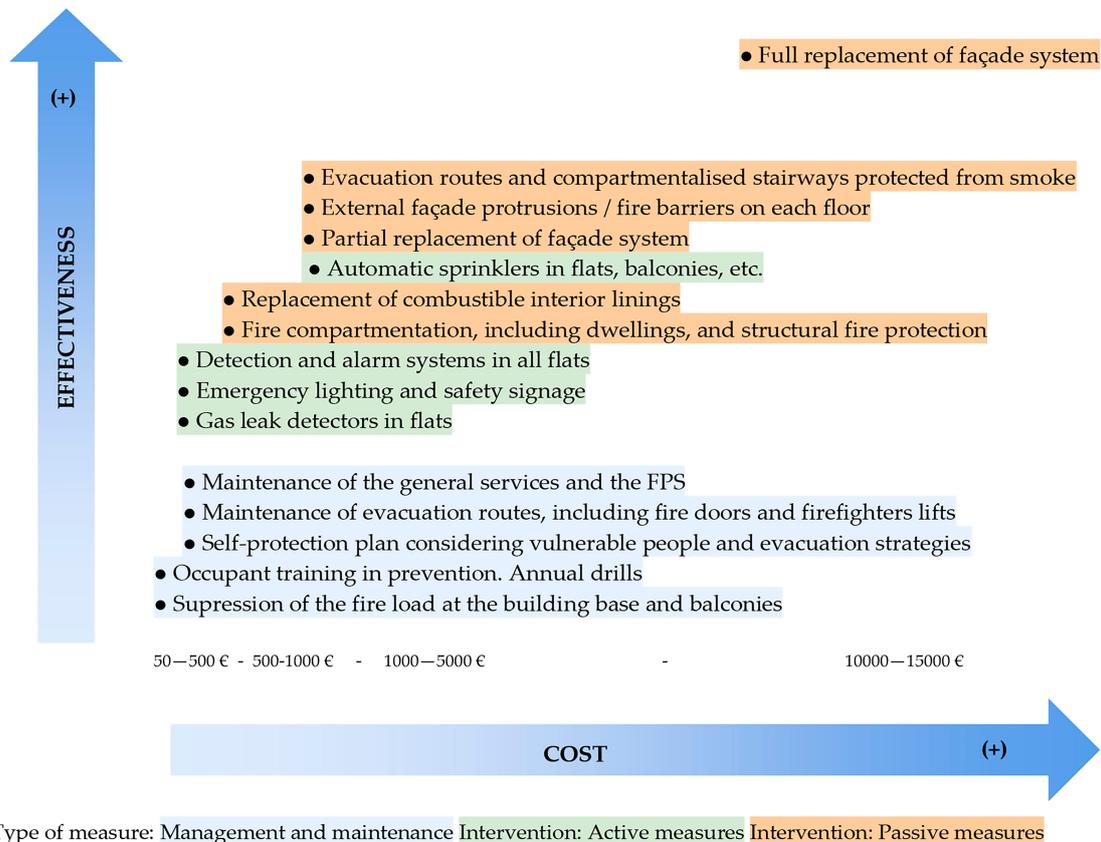
CON: Containment

Figure 8. Relationship of the COFIGHT measures according to potential application phases.

Furthermore, the installation of sprinklers stands out as an effective measure for early suppression and represents an affordable cost in the initial phases of action; it is also fundamental to ensure the compartmentation of evacuation routes and smoke-free protected staircases as long as no intervention is made on the façades.

Nevertheless, the strategic priority must focus on façade intervention to mitigate external fire spread, despite the significant investment typically required. It is essential to understand the inverse relationship governing the COFIGHT system: the lower the degree

of façade intervention, the greater the requirement and critical relevance of the remaining measures to guarantee occupants' safety.



Abbreviations:

FPS: The building's Fire Protection Systems

(+): Increase in effectiveness/cost

Figure 9. Effectiveness and cost of the COFIGHT measures.

In any case, the risk assessment of each building with a combustible façade system must be conducted by competent fire safety engineers through the PBD analysis and the use of CFD tools to determine the best strategy to adopt [9,10]. Under the PBD approach, the effectiveness of the set of measures is strictly interdependent. The success of the strategy does not lie in isolated measures but in their operational synergy; for instance, the effectiveness of smoke control systems is contingent upon the integrity of fire doors and the correct operation of the sprinklers.

Given the importance of ensuring safety within the building stock, public authorities should incentivise these actions through financial support mechanisms, such as grants, to substantially alleviate the economic burden on owners.

4.2. Requirements That Should Be Incorporated or Amended in Spanish Regulations

As previously stated, within the context of fire safety in existing residential buildings in Spain, the CTE DB SI [20] is the applicable standard. In the event of intervention in existing buildings, the CTE DB SI requires solutions that allow the highest possible level of effective adaptation to the requirements for newly constructed buildings. Based on this premise, this section proposes new conditions for high-rise residential buildings (generally those over 18 m in height), as well as modifications to some conditions required for this type of building in the version of the CTE DB SI in force at the time of writing (version of 4 March 2025).

The conditions proposed are confined to the following issues: external propagation via the façade, internal propagation, evacuation of occupants, fire protection installations and intervention by the FS.

4.2.1. External Propagation Through Façade

It is proposed to increase the demand of the type of fire reaction for façade construction systems, which is currently B-s3, d0 for façades higher than 18 m. Based on the scientific documentation studied, it is clear that this class should be at least A2-s1, d0. Thus, façades would be practically non-combustible and would not contribute to the fire by requiring class A2. Furthermore, by requiring an s1 classification, smoke emissions would be reduced, and the d0 class requirement would help to reduce fire spread due to falling burning droplets.

Until the incorporation of new façade systems or continuous exterior cladding, the usual methods for lessening the risk of fire spread from the floor in which it started were based on a combination of factors: the use of non-combustible materials, incorporation of balconies or horizontal projections above windows (flame deflectors) and the inclusion of non-combustible panels between the top of the window on one floor and the window sill on the floor above (spandrels) [9]. Regulations should require that the minimum vertical dimension of these elements be adequate to prevent the spread of flames from the lower floor to the upper floor (not only between different fire compartments), based on emerging research conducted in tests that contemplate a more realistic fuel load and a variety of internal ventilation conditions [9,94].

On the other hand, the height of the building should not be the only parameter to bear in mind when requiring a certain fire reaction class for façade construction systems. It should also be regarded whether the building houses vulnerable persons, whose evacuation in the event of a fire or other emergency may entail additional difficulties.

In the event of ventilated façades, if the system does not have a fire reaction class of A1 or A2, the air cavities should be equipped with horizontal fire barriers on each floor. This condition should also be required in façades with continuous exterior envelopes, if the system does not have a fire reaction class of A1 or A2.

Finally, specific conditions for the execution of works should be established, particularly for façades with panel systems and continuous exterior cladding, as all types of joints, seams, etc., are weak points through which a fire can spread to interior layers that may be more combustible.

4.2.2. Internal Propagation

Currently, ceiling and wall lining in occupied areas (areas with persons and unprotected circulation areas, excluding interior of dwellings) are required to have a fire rating of C-s2, d0, and floor coverings must have an EFL rating. Also, it would be advisable to strengthen this requirement throughout all evacuation routes, so that the required class is at least A2-s1, d0 for ceilings and walls, and A2FL-s1 for floors, in order to lessen combustibility, smoke emission and a potential fall of flammable droplets, thereby contributing to a safer evacuation.

Moreover, it would be recommendable that, in addition to requiring that compartmentalisation between dwellings be EI 60 [20], the same fire resistance (EI 60) is required for compartmentalisation that separates dwellings from any other part of the building. Likewise, it is desirable that access doors to dwellings be fire doors, with a minimum fire resistance of 30 min [32].

4.2.3. Occupant Evacuation

With regard to the detection and alarm system, it is suggested that this be mandatory for buildings with an evacuation height of 18 m or more, since it is currently required

for heights of 50 m or more, which is excessive according to most of the codes analysed. Likewise, its installation should be required both in the common areas of the building and inside all dwellings. It should also be specified that alarms must provide both audible and visual signals throughout the building, and not only in the area of each sector in which fire detection systems are installed, in order to enable, where appropriate, a 'total' evacuation strategy. In addition, the fire detection system is essential to activate light signals for warning whether the protected stairways are smoke-free or not [75].

Regarding detection, the most suitable type of detector (smoke, heat, flame, CO) should be implemented according to location, in order to have better response to fire and also avoid false alarms [120].

Likewise, the installation of local or general manual alarm buttons and verbal communication devices should be required, as vital safety should not depend solely on a single safeguard [34]. The installation of manual push buttons should be required both inside flats and common areas of buildings.

With regard to exit doors on evacuation routes for residential buildings, the CTE DB SI requires that they open following the direction of evacuation if the expected occupancy is over 200 persons for residential use, and 100 persons in other cases. To facilitate evacuation, it is suggested that the same condition be required for residential use.

Regarding the ventilation of protected stairways, entrance halls and protected corridors, the CTE DB SI allows three systems: non-automated operable windows, two natural ventilation ducts for smoke extraction and air intake, or a differential pressure system. The first two systems are based on the principle that smoke enters the area that is theoretically intended to be protected, and is evacuated to the outside naturally, so ventilation may be compromised depending on the height of stairways and environmental conditions. Differential pressure system is based on preventing smoke from entering the protected area. According to some authors, for high-rise buildings, only a differential pressure system should be required to prevent smoke from entering for a longer duration [75]. Other authors emphasise the need for better sizing of this system, to take into account realistic evacuation scenarios, number of doors and floors, and expected evacuation time [76,77]. On the other hand, some research questions whether the pressurisation system will function as intended if the restrictions and assumptions inherent in the design are not clearly defined, and propose ventilation methods based on the needs and risks of each building, by using a performance-based approach conducted in collaboration with fire safety experts [78].

With regard to the number of firefighters lifts currently required, one per thousand occupants or fraction, it is advisable that this provision is increased [32].

Concerning evacuation signage, floor numbers should be displayed on each landing within stairways and in a clearly visible location on corridors and lobbies. Such signage should be visible for the FS, both under normal conditions and in scenarios of low lighting or smoke [16,32]. In addition, it is proposed that a prohibition sign in accordance with EN ISO 7010:2020 (pictogram P020 with the text 'Do not use the lift in case of fire') be required near firefighters lifts so that it is visible on all landings [82].

4.2.4. Fire Protection Systems

It is proposed to reduce the evacuation height above which automatic fire extinguishing systems are required in residential buildings, currently set at 80 m. This requirement is significantly lower than that of other regulatory frameworks; e.g., France sets the limit at 50 m [121], the US at 23 m [122] and the UK at 11 m [32]. The IBC requires installation in all multi-family buildings [21].

Furthermore, it is recommended to specify that such installation should consist of sprinklers inside dwellings and also in common areas of the building, excluding those that do not contribute to fire spread [32].

4.2.5. Fire Service Intervention

It is advisable to provide requirements that improve communication between members of the FS and building occupants. Thus, installation of sirens or similar devices should be needed so that the FS can send an evacuation signal to all or part of the building. In addition, installation of a two-way telephone service for use by the FS is proposed in each lift cabin and lobby, and on each floor level of exit stairways.

On the other hand, for the information of the FS, in high-rise buildings it is suggested to provide a box containing up-to-date information on fire safety procedures, a copy of the updated floor plans for each floor and information on each firefighters lift. A panel may also be required to enable the fire safety officer to monitor and manage the fire safety systems of the building.

4.2.6. Energy Retrofit of Buildings

Decarbonisation policies should adopt a balanced and holistic approach, financing actions to improve sustainability in existing buildings that simultaneously enhance and maintain fire safety. In this regard, it is fundamental to document fires in sustainable buildings to identify the aspects of energy retrofitting that may act as risk factors in fire ignition or spread, thereby avoiding unintended consequences of regulatory measures [123].

5. Conclusions

This study highlights the need to address fire safety in the high-rise building stock with combustible façades through a holistic and PBD approach, grounded in the IFSS common principles for fire safety.

5.1. Main Findings

Safety in these buildings does not depend on a single solution, but on the synergy of active and passive protection measures. This research provides a curated synthesis of 100 measures, termed COFIGHT; furthermore, a critical perspective is offered for certain measures. Based on the study of this synthesis, several improvement measures are highlighted, implementation strategies are proposed, and key measures are ranked according to their estimated effectiveness and cost. A summary of safety priorities is provided:

1. Immediate actions for prevention, detection, and alarm:
 - Management and maintenance.
 - Installing detection and alarm systems throughout the building.
2. Early suppression and protection actions:
 - Installing sprinklers for early suppression.
 - Ensuring that staircases and evacuation routes are smoke-protected and correctly compartmented.
3. Definitive measure: The most effective solution is the replacement of the combustible façade.

The total replacement of combustible façade systems with Class A2-s1, d0 materials is identified as the most effective passive measure to eliminate the risk of external spread. Until façade interventions are undertaken, the early implementation of detection and alarm systems throughout the building is considered essential. Additionally, the installation of sprinklers stands out as an effective measure for early suppression at an affordable

cost in the initial phases, while ensuring the compartmentation of evacuation routes and smoke-free protected staircases remains fundamental.

Furthermore, the study derives that vertical spread via the façade represents a critical failure of traditional compartmentation, necessitating a re-evaluation of evacuation strategies (such as the shift from stay-put to total or phased evacuation), based on the ASET/RSET analysis.

Likewise, it is observed that the Spanish fire safety regulations must evolve to improve fire reaction requirements for materials in high-rise buildings and reduce the threshold heights for mandatory sprinkler installation.

5.2. Limitations

The catalogue of 100 COFIGHT measures is preliminary and qualitative in nature. The actual effectiveness of each combination of measures depends intrinsically on the specific conditions of each building and the evaluation conducted through performance-based design for each specific case by expert fire safety professionals.

5.3. Future Lines of Research

- Improving the behaviour of building occupants regarding fire safety is an open field.
- Creation and implementation of internationally agreed-upon supervision and risk assessment protocols for these types of buildings.
- Influence of new energy retrofit solutions on fire dynamics, aimed at preventing the creation of new risks not accounted for in current statistics.
- Robust regulations for the refurbishment of existing buildings based on common international principles, thereby establishing the main objectives that must be met in terms of fire safety.
- At least one internationally agreed-upon testing method is required for the systems and products mentioned. Small-scale test methods are available for assessing the reaction to fire of façade materials. However, these methods are not suitable for construction solutions involving heterogeneous products. To this end, there are various standardised medium- and large-scale fire reaction test methods available. However, these cannot be used in their standardised form either, as they are not representative of reality, and are not sufficiently defined to determine fire spread. Furthermore, the differences in the methodology of each trial prevent results from being compared.
- Development of data repositories on product and material testing, representative fire reports, and academic knowledge as a resource for designers, such as the ‘Cladding Materials Library’ at the University of Queensland.

For all these reasons, training expert fire safety professionals is a key factor for providing appropriate solutions. In this regard, Fire Engineering needs to be updated with the latest technologies in building construction, sustainability and the goal of zero emissions. In addition, attention must be paid to potential risks that are not yet reflected in fire statistics, regulations or the tools used by fire protection engineers.

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Abbreviations

The following abbreviations are used in this manuscript:

IFSS	The International Fire Safety Standards
CTE DB SI	The Basic Fire Safety Document of the Technical Building Code
IBC	The International Building Code
COFIGHT	Combustible Façades in High-Rise Residential Buildings: Holistic Treatment
EFFECT	The Exterior Façade Fire Evaluation and Comparison Tool
NFPA	The US National Fire Protection Association
PRE	Prevention
DET	Detection and communication
OP	Occupant Protection
CON	Containment
EXT	Extinguishment
eEXT	Early extinguishment
EuroFSA	The European Fire Safety Alliance
PA	Public Administration
FS	Civil Protection and Fire Services
FPS	The building's Fire Protection Systems
EFHs	Fire hydrants
GRP	Glass-reinforced polymers
HPL	High-pressure laminates
MCM	Metal composite materials

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