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A Review of Critical Fire Event Library for Buildings and Safety Framework for Smart Firefighting

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Abstract: While occupants are evacuating from the fire scene, firefighters are entering life-threatening environments, exposed to hot and toxic fire smoke and risks of structural failures or collapses. Each year, numerous firefighters lose their lives due to fatal injuries in the line of duty and long-term health problems. Although well-established prescriptive designs for occupant fire safety are available, most codes ignore 'firefighters' safety in complex and life-threatening situations. This paper establishes a framework for smart firefighting operations based on the critical fire events or consequences. It also reviews the major causes of firefighting casualties in the building fire. A library of the critical and precursor fire events is generated to guide the future design of smart firefighting and building fire safety. The influence factors like occupancy type and construction material are also discussed. A decision event tree containing the critical events is proposed for the incident command officer to carry out risk analysis based on real-time information from the fire scene. Using the library of the critical events and building IoT sensor networks, the trained artificial intelligence (AI) models can forecast the dynamic critical events in super real-time, display the future fire scene in the digital twin, and the estimated time and probability of their occurrence. This smart firefighting framework enables a super real-time forecast of future critical fire events, provides the information to firefighters in a language that they understand and improves operational efficiency and safety.

Keywords: *Fire-fighter; Artificial Intelligence; Fire Safety Design; Smart Firefighting; Critical Fire Event*

1. Introduction

Increasing numbers of new architectural designs, such as façades in tall buildings and large open spaces, around the world have shown that the evolution of the built environment has changed the nature of the threat from fire. Urban environments are exposed to greater risk as prescriptive fire safety strategies are no longer fit for purpose. Firefighters are left facing an unpredictable hazard that they are neither trained nor equipped to deal with, as the London Grenfell Tower fire in 2017 tragically demonstrated [1] (**Fig** 1a). On top of the human cost, economic losses from fire incidents are estimated at approximately 1 percent of global GDP per year [2]. In a fire, to minimise these costs (human and property), emergency responders have to make decisions in a timely manner.

Figure 1. Some of the major fire accidents (a) Grenfell Building fire, UK in 2017 (credit: The Telgraph), (b) WTC fire, USA in 2001 (credit: Spencer Platt), (c) Ngau Tau Kok mini-storage fire, HK in 2016 (credit: Don Wong, HKFP), (d) Beijing TVCC fire, China in 2009 (credit: Arch daily), (e) Beirut explosion, Lebanon in 2020 (credit: Sky News), and (f) Tianjin explosion, China in 2015 (credit: CBS News).

Disastrous fire accidents continue to occur around the globe and have claimed the lives of hundreds of firefighters every year. The collapse of the World Trade Centre Towers 1, 2, and 7 (**Fig.** 1b) after the terrorist attacks of 11 September 2001 created a precedent for a scenario that had never been seriously considered before, resulting in the deaths of 343 firefighters [3]. The 2016 HK Ngau Tau Kok mini-storage fire claimed the lives of two firefighters (**Fig.** 1c). High-rise buildings with thousands of occupants collapsed while emergency services conducted fire control and evacuation operations. No one had any knowledge of the impending collapse of the buildings [4]. In the 2009 TVCC Building fire in Beijing, one firefighter was killed, and six firefighters were seriously injured, and the building was kept closed for more than 8 years (**Fig.** 1d). Large fires in tall buildings are currently occurring at higher rate globally and are responsible for many deaths and billions of dollars in losses [5]. In an explosion in Beirut in 2020 (**Fig**. 1e), a team of firefighters arrived at the scene after a fire in a warehouse at the Port of Beirut was reported. They had no information about the hazard (ammonium nitrate along with firework), which led to a massive explosion and took the lives of more than 200 people, including all members of the team (9 firefighters and 1 paramedic). The 2015 explosion and fire accident in Tianjin Port killed 165 people, including 95 firefighters and injured hundreds at a container storage station (**Fig.** 1f), where a flawed firefighting response exacerbated the losses. Therefore, it is critical to consider the safety of firefighters in possible fire scenarios as part of the smart firefighting design and emergency operation.

It is unfortunate that engineers learn more from their mistakes and tragic accidents. A typical example is the great fire of London in 1666, where the fire displaced a major population of the city. The incident led to setting up an enquiry to strengthen the building regulations to prevent the occurrence of such events. Since then, consideration of fire safety has evolved over time. However, due to the large uncertainties with fire and unawareness of the real-time information, fire accidents are always life-threatening. The inquiry into the fire at the 1987 London ' 'King's Cross underground station showed that an erroneous understanding of the fire growth resulted in an inadequate evacuation procedure [6]. A similar conclusion was reached by the study of the Piper Alpha fire and explosion Disaster [7]. The fires that occurred at Three Mile Island Nuclear Reactor in 1979 and Frankfurt Airport in 1996 showed the importance of proper onsite information that led to the implementation of the extensive sensor and diagnostic systems throughout the facilities. The comparison between the intervention at 1996 Channel Tunnel fires and the 1999 Mont Blanc Tunnel shows how disastrous ill-informed intervention can be. High-density populations also stretch the capacity of transport infrastructure in the event of an urban disaster requiring extremely efficient emergency management so that critical facilities, such as hospitals, continue serving the affected population. Developing a feasible and practical smart firefighting system can provide an effective solution to achieve a safer built environment.

What is more unfortunate is that the change in firefighting practices is even more difficult, as seen from previous tragedies [1]. Traditional firefighting does not use live data in support of intervention tactics because of the limited information collection (depending on data obtained by human communication), inaccurate fire modelling, and slow communication systems [8]. Different approaches have been proposed to support firefighting, such as data-analytic techniques to assist fire modelling, and direct deployment of sensors during the event for smart firefighting has been proposed [9–14]. The recent *FireGrid* system, funded by the UK Department of Trade and Industry [15], applied the analogy of weather forecasting, where sensor data assimilation with ensemble prediction is used to forecast weather [16]. Based on the High-Performance Computing (HPC) on "zone model" [17] and CFD fire models [18], these sensor-driven systems can achieve super real-time forecasting with up to 10 to 15 minutes lead time for multi-room apartments [17]. More recently, a *SureFire* system has been proposed for smart firefighting, including the latest Artificial Intelligence (AI), Internet-of-Things (IoT), and Digital Twin technologies. This system has been demonstrated for identifying the real-time tunnel fire scenes based on the sensor data [19–21] and the compartment fire scenarios based on video images [22,23]. Based on the high-fidelity fire simulation database, the machine learning methods have also been applied to achieve real-time forecast of fire development in tunnel [24], compartment [25,26], and atrium [27]. Forecasting critical events can help urban infrastructure to become more resilient to the fire hazard and make smart firefighting reliable and practical. Nevertheless, before developing a solution, the problem should be identified. Thus, it is crucial to develop a library of critical and precursor fire events based on past fire incidents and 'firefighters' experiences.

This paper presents a framework to develop libraries of critical and precursor events in a fire accident for any type of occupancy. These events are broadly associated with the evacuation, fire growth, and structural damages in the building. The paper also explains how these events can be forecasted and used by the firefighters or incident command (IC) officer to assess the risk and take decisions based on real-time information. As part of our *SureFire* smart firefighting system, a highly sophisticated model can recommend decisions to emergency responders using state-of-the-art fire modelling, big data, and AI. This paper discusses how we can learn from past incidents and propose a smart fire firefighting framework to improve fire safety designs and safe firefighting strategies to cope with unexcepted fires.

2. Major causes of firefighter fatalities and severe injuries

In a building fire, most of the time, it is the firefighters' duty to enter inside the building. Other than suppressing the fire, their major task is to search for the occupants who may be stuck in the building due to physical conditions, such as being visually impaired, unconscious, or other health conditions. The primary goal of fire safety is to carry out a safe evacuation and bring occupants out before fire becomes untenable. The fire scenarios and developments inside the building depend on various factors such as combustibles and their distribution, fuel composition, ventilation condition, and so on. A change in any of the variables would increase the uncertainties in fire behaviour. Thus, fire behaviour may change abruptly and unexpectedly and leads to critical events such as flashover, backdraft, explosion, and structural collapse that may trap the firefighters and cause fatal injuries.

Table 1. Major causes and nature of injuries lead to 'firefighters' fatalities, based on data from US Fire Administration [28].

Year	Total death	Nature of injury		Major cause of injury		
		Trauma / Asphyxiation	Heart attack/ CVA	Stress/ Overexertion	Trapped	Collapse
2010	90	30	55	55	6	3
2011	87	19	49	50	10	3
2012	85	29	42	45	1	4
2013	109	38	37	37	30	2
2014	97	22	61	61	8	1
2015	91	22	60	60	6	6
2016	92	33	44	43	2	3
2017	88	29	52	52	3	0
2018	84	29	36	37	5	6
2019	62	16	36	36	5	2

In a survey carried out by NFPA, it was found that in terms of fire deaths, the number of fatalities decreased significantly since 1980, but still, more than 3,000 people in the US die each year due to fire, as shown in **Figs.** 2a and 2**b** [28,29]. Although the fatalities of civilians (who are not firefighters) decreased, there is no significant dip in firefighters' fatalities (**Fig.** 2b) [29] **[**the data presented for the US includes the fire deaths related to wildland fires]. Around 50 to 100 firefighters die each year in the US only (except the year 2001 when 343 firefighters died in the tragedy of the WTC towers in the 9/11 incident) [29]. The major fatalities of firefighters in building fires during fireground activities are related to the trapping inside the building while responding to fire. **Fig.** 2 (c) shows the number of firefighters (per 100000 full-time firefighters) who died during fireground activities (fire attacks, search and rescue, ventilation, and others [excluding road traffic accidents for comparison purposes]) in the USA and UK [29,30]. It is worth noting that a firefighter's death due to overexertion within 24 hours is considered a 'line of duty death', while it's not the same in the UK. Some of the major factors that affect the fatalities and health of firefighters are analysed in this section. Table 1 shows the major causes and nature of injuries that lead to firefighters' fatalities between 2010 and 2019 in the US [28].

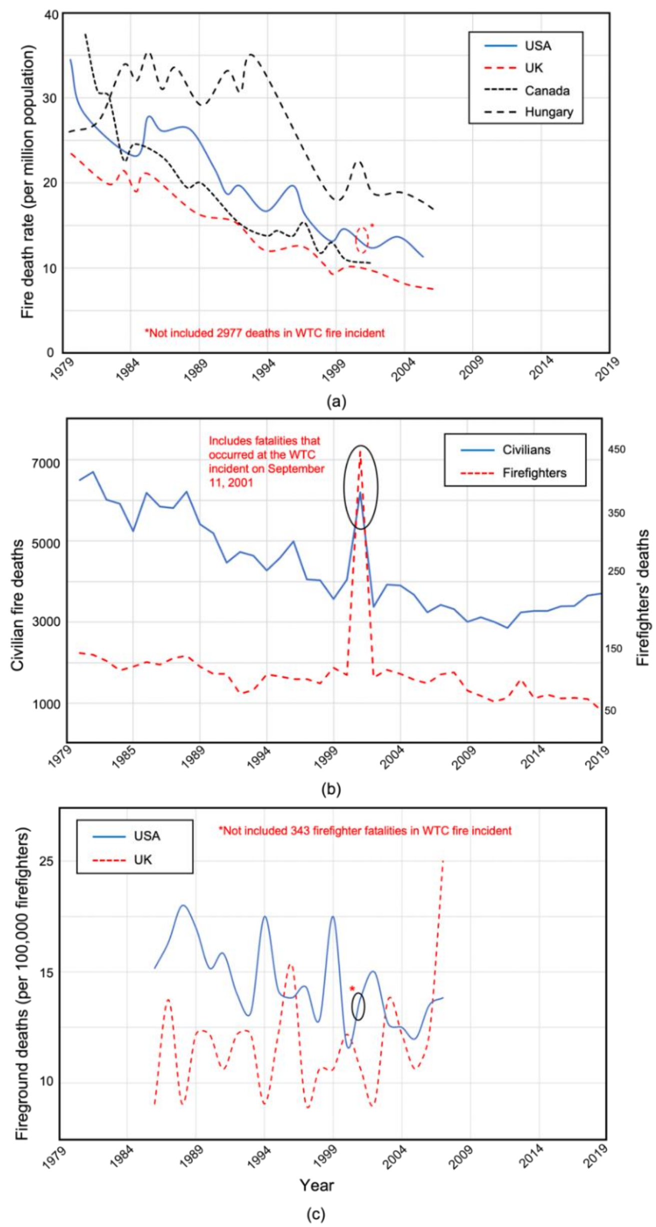

Figure 2. (a) Fire death rate (per million population) in the US, UK, Canada, and Hungary from 1980 to 2007, (b) Civilians and firefighters' fatalities from 1980 to 2019, and (c) Firefighter's deaths in the USA and UK per 100000 full-time firefighters from 1986 to 2007.

2.1 Changes in the fire environment

During a fire accident in a building, various changes occur on the fire floor, such as rapid changes in thermal conditions, production of flames, smoke and its by products, and toxic gases. These environmental changes within a building are directly responsible for a significant number of fatal injuries that are reported in many previous fire accidents. It is not uncommon that while conducting a primary search in complex buildings firefighters lose their way. Such situations may require deploying another team [Rapid Intervention Team (RIT)]. In a fire accident, where a firefighter was lost inside the building while searching for occupants, who later found dead due to smoke inhalation [31]. Weather conditions can also exacerbate fire behaviour. In a building fire, two firefighters were trapped in a basement when the fire was intensified due to the heavy wind (provided an ample supply of oxygen for combustion), which took the lives of both firefighters [32]. Asphyxiation (deprivation of oxygen) is one of the major causes of the firefighters' and occupants' fatalities in a fire accident. In large fires, the oxygen level inside the compartment reaches below the sustainable level (oxygen is consumed in the combustion process). While conducting the search operation, the oxygen level in the cylinder carried by a firefighter in SCBA (Self Contained Breathing Apparatus) may also decrease, which requires the firefighter to leave the building immediately for refilling. In many fires, it was found that firefighters collapsed due to lack of air supply [28].

Smoke and flame have a natural tendency to travel in upward direction due to buoyancy and stack effect (pressure gradient, generally observed in tall buildings), which causes high temperature gases to extend towards the staircase. In many fire cases, it was observed that the temperature of the metals (stair railings, windows, or other mechanical devices) was high enough to cause severe thermal burns to firefighters even if they were equipped with proper PPE (Personal Protective Equipment). Fire and smoke in the staircases are very critical as these are mainly the means of escape for occupants and also the access for rescue operations for the firefighters. Several occupants and firefighters were found dead on the staircases in many fire accidents. In the 2017 London Grenfell Tower fire accident, many burned bodies were found on the stairs and in the lift [33]. The conditions such as backdraft (sudden rise of flame due to introduction of air) and flashover may occur during the fire that can intensify the fire enormously and can cease the means of escape of the firefighters. Another critical situation that is worth discussing is the presence of chemical hazards that firefighters may not know (generally in mixed occupancy), it can create severe damage to firefighters [34]. For example, a fire in the HK Wai Lun Weaving Factory (August 1977) poisoned the skin of the firefighters due to the presence of toxic chemicals (acrylic rollers of weaving threads generated acrylic cyanide due to thermal decomposition) [35].

2.2 Structural damages and collapses

The collapse of structural components such as beams and columns is quite common. Such collapses hinder firefighting and rescue operations. The collapse of beams in timber structures is observed at much earlier stages. Although timber has self-extinguished properties, the failure of unprotected joints or connections can cause failure of the structural components [36]. Structural damages and collapses are also responsible for a considerable number of fatalities and injuries [37,38]. Due to prolonged heating, structural components lost their strength, get damaged and collapsed. In the case of a fire-damaged structure, it may take only a few seconds before firefighters realise that a structural member is going to fail. Once they fail, the collapse debris can block the egress path and impede the travel time of the firefighters, and in worst cases, it can fall over the firefighters. In the Plasco Building collapse in Tehran (2017), many firefighters died when the slab of upper floors directly fell over them [39,40]. In many situations, firefighters are trapped in collapsed debris that causes fatal injuries. Fire, sometimes, can lead to an explosion in case of storage of hazardous material, though not very common but occurs (**Figs.** 1e and 1f). Explosions are generally catastrophic in nature and result in multiple fatalities. In a fire accident in a fertiliser occupancy, a massive explosion occurred once the fire reached stored chemicals. The explosion killed nine firefighters and five civilians and damaged around 500 nearby structures [28].

2.3 Firefighting actions

There are some issues that are related to the firefighting action, which can also cause trouble for firefighters. Firefighters apply a stream of water (at a flow rate of hundreds of GPM [gallon per minute] or LPM [Litre per minute] from one stream of hose [41]) in a high temperature zone, which creates a huge volume of steam (volumetric expansion of water is around 1700 times at 100 °C), in addition of contrating the hot fie gases. Fire and steam together can be dangerous for trapped individuals. Furthermore, it is possible that while the firefighters apply a jet stream of water through the windows, breaking the window or creating an opening, it allows more air to come inside that can elevate the fire size inside the compartment.

Sometimes, a very large volume of water can be accumulated in a cavity such as a lift, a small compartment that can influence the firefighting process. For example, in a storage facility fire in HK (1978), the collapse of the staked goods from the firefighting jet created a cavity where a large amount of water was accumulated, and one firefighter was struck in a water depth of over 1m [35]. RIT was required to recuse the firefighter. In another fire incident (1996 HK Garley Building fire), a firefighter drowned when water accumulated in the lift [35,42].

2.4 Psychological and physical conditions

A significant number of fire fatalities are related to the pre and post conditions of the firefighters who responded to building fires. According to a study carried out by US Fire Administration [28], a large number of firefighters' deaths are due to overexertion or stress. Some of the fatalities have occurred after the incident, however, it cannot be ignored that their deaths are linked to the fire that they have faced. Firefighting is an intensive strenuous physical activity that demands extreme strength from the firefighters. While responding to a fire, rapid change in the environment, exposure to the extreme thermal environment, and stresses may affect the physical and mental condition of firefighters which can lead to strokes and heart attacks. Post-incident deaths are also generally due to cerebrovascular accidents (CVA), cardiac arrest, trauma, or strokes. According to a study, due to receptive trauma exposure, firefighters suffer from high rates of mental disorders or Post-Traumatic Stress Disorder (PTSD) [43,44]. During the firefighting operation, firefighters may have been exposed to incidents that can give them psychological injuries, such as seeing their colleagues getting seriously injured or dying. The mental trauma and other psychological injuries caused by the fire incidents may lead to such fatalities. Although these fatalities are not directly linked to the fire incidents, such as the growth of the fire and structural collapse, these are the outcomes of the firefighters' exposure to such incidents. Having a-priori information of the critical incidents, such as thermal environment, and probability of sudden change in a fire condition can provide more confidence to the firefighters who are going to suppress the fire. Eventually, we can reduce the number of fatalities and injuries listed in **Table 1**. From the above discussion, it becomes clear that it is imperative to identify and predict the critical incidents that can occur in a specific building. The later sections of the paper provide a framework for generating a detailed library of such incidents and forecasting them using a well-trained AI model and provide the information to the firefighters to revise the fire safety strategies.

3. Critical and precursor events in building fires

The major tasks of this paper are (1) to generate a library of the critical events that come after translating the data from what engineers understand, such as temperatures, heat flux, smoke layer, yielding of steel and crushing of concrete into the language (phrases) that firefighters can understand (hot surfaces, collapse of structural components, low visibility); (2) recommending a method to forecast these events by utilising the current technological advancements in AI, big data, machine learning, and (3) how forecasting of such events can assist firefighters in decision making during the fire.

3.1 Typical building fires

The threat of fire is pervasive, from structures to automobiles fires occur every day. In terms of building fire or confined structural fire, the first few minutes of the fire played a critical role in determining the probability of the occurrence of future events. If the fire is not controlled during early stages of fires (failure of detection [human or dtectors], failure of sprinkler susytems), the fire may become larger and can become uncontrollable. **Fig.** 3 shows the various stages of the fire from its occurrence, through the firefighting operation, to its decay. Fire detection and active fire protection systems (wet/dry sprinkler systems or others) are designed to operate in the very early stages of the fire to notify the occupants and initiate the fire control. The safe egress time for the occupants depends on their actions (if installed). This time is very critical for the occupant's life safety, a small delay can be life-threatening due to the rapid rise in temperatures and the enormous smoke generation that can make occupants unconscious or cause fatal injuries (fourth degree of burn). According to a study, most deaths in residential building fires primarily occur due to smoke inhalation and thermal burns [37,45]. The smoke generated from the burning of various materials (plastics, mattresses, wood, and many others) contains harmful gases and particles that can affect the internal organs such as lungs and airways within the body. The tremendous heat and toxic environment in the fire region can render an individual unconscious. In case of a fire accident, even the firefighter who entered the building donned proper PPE with self-contained breathing apparatus (SCBA) and was later found dead. It is mainly because of asphyxiation (lack of oxygen), if their facepiece is detached [31]. In many fires, the firefighters equipment including PPE also failed which led to severe injuries and fatalities [31,46,47].

If the fire department is notified on time, it might be possible that upon their arrival, the fire is already in a life-threatening stage or has reached a flashover. It is quite common in uncontrolled fire scenarios that the whole floor (or many floors) is engulfed with the flames before the firefighters arrive at the scene, and they encounter heavy smoke and flame conditions when entering the building, as reported in the Grenfell Building fire and the Plasco Building fire accidents. Due to huge uncertainties associated with fire behaviour in a building, firefighters can hardly be certain of the actual situation.

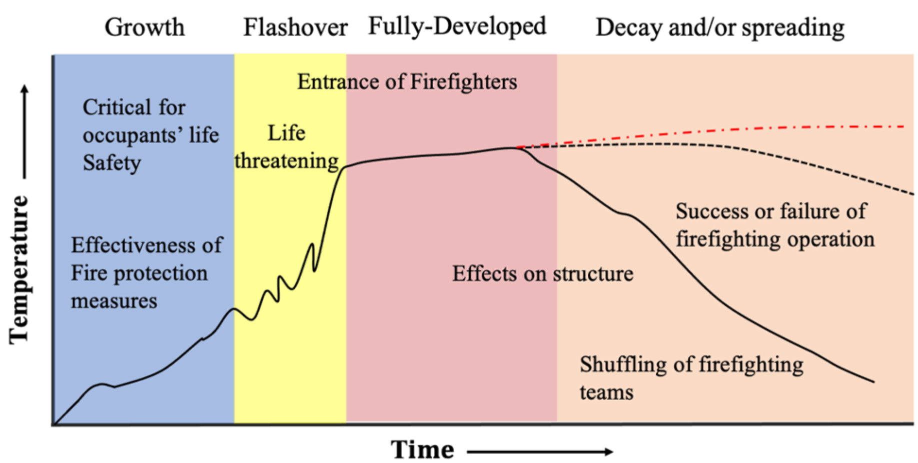

Figure 3. Growth of fire in a typical building compartment (when the fire is not controlled during the early stages of fire).

Further events related to fire spread will depend on the size of the compartment. The fire may reach a fully-developed stage for relatively smaller compartments or travel all over the floor if the floor is large ('travelling fires'). However, in both cases, the fire is capable of affecting the structural integrity (**Fig.** 3). Load bearing (beams, columns, slabs, some walls) and non-load bearing (windows, walls) structural components may fail while firefighters are trying to control the fire and hinder the firefighting operation. The conditions such as success or failure of the firefighting operation, de-compartmentation, fuel load will affect the fire growth behaviour. Without the intervention of external efforts (firefighting operation or active fire protection system), the growth of the fire depends on fuel load and ventilation conditions. If enough air is supplied to the compartment, the fire will continue the fire will continue to grow until it becomes ventilation controlled. The fire will keep on burning in a steady state until a large portion of the fuel is consumed. On the other hand, if the supply of air is deficient, the fire will decay and may self-extinguished. Firefighting operations may also be able to suppress the fire, and their success is very critical from both life and property safety point of view. If the fire is suppressed in a time and firefighters are able to evacuate the building with no major injury, the operation can be considered successful in terms of life safety. The fire may spread further becomes uncontrolled and damage the structure which may not be considered a successful operation in terms of property safety. The fire can reach adjacent compartments or upper floors and travel both in horizontal and vertical directions. Sometimes fire reaches the hidden location, which is generally undetected by the firefighters, such as false ceilings, false floors, metal enclosures.

Once the fire becomes uncontrolled and spreads to other floors, it may require more firefighters to be deployed. Uncertainties with the fire increase with the duration of the fire, especially in terms of critical incidents such as failure of structural components due to long duration of fire exposure, blocking of the egress path to evacuate, exposure to very high temperatures and heat fluxes for a longer period. Occupants can come in contact with flames, hot surfaces, high temperature gases, and hot liquids that can cause thermal burns. Temperature and fluxes due to incident radiation from the flames and surfaces may even penetrate the PPE of firefighters. Therefore, these fire spreading stages are very critical for the further actions and decisions that need to be taken by the emergency responders based on the probability of the occurrence of future events. If these events can be known a-priori, it can reduce the likelihood of serious injuries or fatalities during the firefighting operation and allow revising the firefighting strategies before the occurrence of a critical event . Therefore, to forecast such events, it is necessary to have a library that contains most of the possible fire events. This paper generates an exhaustive list of major critical events that may occur in a fire accident. The list can be updated and enriched in future with the experience of firefighters and unique fire scenarios. **Section 3.5** describes a framework and process of generating an event library for different occupancy type (business, ambulatory, shopping mall, and so on).

When fire initiates and progresses in a building, hundreds of events may occur, as discussed in the previous section. These events can be broadly classified into three major domains. First domain is related to the evacuation process - which includes the ingress of the firefighters to carry out the firefighting operation and the safe exit of occupants and fire fighters. Second domain is linked to the growth and spread of the fire, and finally, the third domain considers events related to the structural changes, such as de-compartmentation or glass breakage which may change the fire scenario entirely. During a fire, there will be some events that indicate future failures, which are referred to as precursor events, for example, the excessive downward deflection of the beam is an indication that it may fall due to failure by rupture of steel (steel beam) or fail by crushing (concrete beam).

3.2 Evacuation

The primary goal of any fire safety strategy is to evacuate all occupants from the building. Modern buildings are equipped with advanced detection systems that can detect the fire in the early stages of the fire and notify the occupants. However, they may fail due to various reasons such as poor maintenance, and blockage of the detectors. In some cases, failure of the detection systems may eventually lead to failure of the fire suppression systems, as these systems may be interfaced with detection systems such as deluge systems, pre-action water-based systems, and gas suppression systems [36]. If the fire remains undetected and unable to suppress, it affects the travel time for safe egress. It is possible that the main exit is blocked due to the fire location, which prevents the occupants from exiting safely from the building. It is also possible that the main entrance for the firefighters is blocked due to the fire location, and they may have to change their entrance plan. It has another implication, current codes and practices require at least two *means of egress* in modern buildings, which are designed based on the capacity of each floor [48]. Blocking an exit may overcrowd another exit which can increase the travel time for the occupants and firefighters.

It is also not uncommon that mechanical devices such as latches on fire doors, panic bars, are failed during the fire. It might put the life of the occupants and firefighters at risk and require updating the evacuation plan for a safe exit. Many times, firefighters are trapped in a fire due to blocked doors [28]. In a fire accident in HK, two firefighters were seriously burned when they found the roof exit was locked [49]. In another fire accident in the USA, a firefighter was caught by the fire while trying to escape and encountered a blocked door [28]. In a recent fire accident in Maryland, USA (January 25, 2022), three firefighters died inside a three-storey building fire (**Fig.** 4). The building partially collapsed during the fire, and firefighters were trapped inside [50]. Table 2 shows some critical events that hinder the safe evacuation of the occupants or reduce the Available Safe Egress Time (ASET).

Figure 4. Fire in a three-storey vacant house in Baltimore (Maryland), USA (2022) [credit (a) CNBC (b) CNN].

3.3 Critical fire events

As discussed in section 3.1, fire spreads rapidly and may reach flashover even before the firefighters arrive at the scene. **Fig.** 5a shows the flashover phenomenon presented by a test presented by US Fire Administration [51]. Many events arising due to the fire spread that increase the threat for the firefighters are discussed in this section. Any change in the fire behaviour and its affects requires revising the firefighting strategies.

The information on the effectiveness of the active fire protection system affects the initial incident planning of firefighters, e.g., if sprinklers opened during the fire or not, if yes, were they able to control the fire to some extent. This piece of information along with the exact location of the fire (which is generally available at the annunciator panel at the entrance location of the firefighters) allows the firefighters to develop initial plan to tackle the fire. The intensity of the fire and height of the fire compartment played an important role in the generation of smoke and soot concentration that can reduce the visibility and block the travel path of firefighters while they are carrying out the firefighting operation and searching the occupants. Each year a significant number of fatalities and injuries are occurred, where firefighters were trapped or caught in building fires (Table 1). One of the critical and dangerous situations encountered by firefighters is when the fire reaches false ceiling. The fire in false ceilings or false floors is generally undetected, and the fire keeps spreading without any intervention by firefighters. The fire can reach adjacent compartments from false ceilings, which may make the firefighting operation more difficult and complex.

In the Plasco Building fire accident, the false ceiling was open and had no separation between the compartments (**Fig.** 6), which led the fire to reach adjacent compartments and other parts of the building [39,52]. In the later stages of the fire, the fire reached other parts of the building and burned all combustible presents on many floors (**Fig.** 5b). In some fire accidents, it was observed that although smoke was visible, the firefighters had to open the ceiling to look for the fire, and the fire was present in concealed spaces [28].

Fire is able to reach upper floors through openings (windows), such situations require more firefighters to control the fire. Due to the increasing size of the fire, the probability of the fire being uncontrolled is increased. In some cases, fire may reach lower floors through local collapses and openings in the slab systems (Windsor Tower fire in Madrid, 2005 [53]). While temperature is increasing in the compartment, it is not uncommon that the temperature sometimes reaches at a level that can penetrate the PPE of firefighters (knowledge of metal temperature to them can be helpful to firefighters). The continuous rise in temperature and heat flux that may penetrate the PPE can be considered a precursor event. A precursor event may not be a threat to life safety and property protection in itself but it can lead to events that are a serious threat (critical events). The metals with higher thermal inertia present in the fire compartment may be very hot due to prolonged heating. Spreading of fire towards the high fuel content region (even same occupancy, there can be different fuel load densities for different compartments, e.g., archive room and meeting room in an office building) is another example of a precursor event.

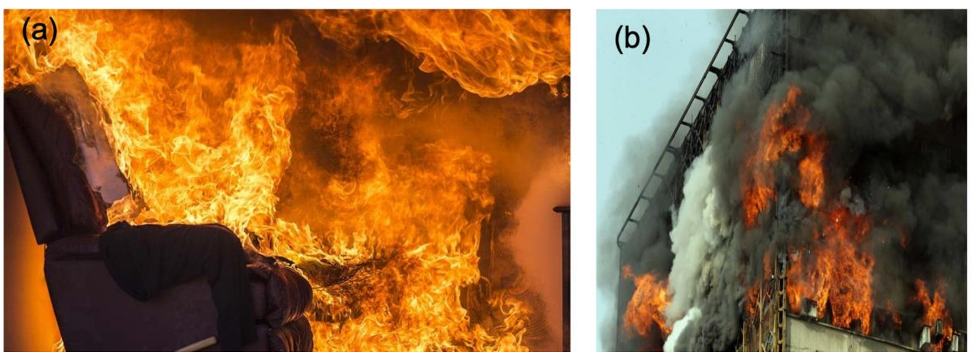

Figure 5. (a) Flashover phenomenon presented by US Fire Administration (credit [54]), and (b) compartment engulfed in flames in the Plasco Building fire accident (credit [55]).

Figure 6. The 2017 Iran Plasco Building fire, (a) Open and continuous false ceiling, and (b) fire reached different floors of the building (credit [55]).

3.4 Structural/Architectural changes

Architectural and structural changes that occur during fires have many adverse effects on fire spread that can exacerbate the rescue operation and safety of the firefighters. Failure of compartmentations or removal of fire barriers increases the fuel load and allows the fire spread towards the adjoining compartments, which makes the control of the fire more difficult and increases the demand for water supply and firefighting units. One of the most common structural/architectural change that occurs during a fire is the breakage of windows. Windows glazing can fail at very low temperatures [56], which allows a large amount of fresh air to get inside, which intensifies the fire to grow rapidly. In tall building fires, where chances of delay in firefighting operation are higher, the backdraft phenomenon is quite common because of the architectural changes such as failed doors and windows. In 2014, two firefighters died while carrying out a firefighting operation in a residential building in Massachusetts, USA [57,58]. The failure of the basement door and windows created an unrestricted flow and triggered the rapid change in fire progressions, as shown in **Fig.** 7a [58]. **Fig.** 7b shows the backdraft phenomenon presented by US Fire Administration [59].

Failure of the structural components such as beams and columns are also observed in many fire accidents. Support beams or compartment walls may also collapse during the fire, which can block the passageway for the firefighters. In the worst case, these beams may fall over the firefighters. These local collapses are uncertain and difficult to predict even by a very experienced firefighter. Deflection of structural components such as a beam or local buckling of the columns can be precursor events during the fire that tell about the onset of collapse of the structural components. In some fire accidents, the application of water on the fuel increases the dead load of the floor especially due to the presense of absorbent materials (like cotton).

Flames and smokes have a tendency to move towards oxygen-rich environment. In most fire accidents, the fire reaches near vertical shafts (stair or elevator shafts) during the early stages of the fire (e.g., the 1996 HK Garley Building Fire). The stack effect can explain the physics behind it. Other than affecting the evacuation of occupants due to flame and smoke in the exit stairs, stairs may fail or collapse, and the collapsed debris can block the main exit, as found in the case of the 2017 Iran Plasco Building fire [39,52].

One of the most severe structural failures is the collapse of floors. Due to prolonged heating of floors, slabs may collapse, which can be fatal to the firefighters or occupants. Such incidents (failure of floor slabs) are reported in many fire accidents [52]. **Figs.** 8(b) and (c) show the collapse of slabs in the Plasco Building fire accident. As discussed in section 3.1, structures are generally affected or fail during a fully developed fire or when the fire is large enough to raise the temperature of the structural components to its failure limit (reduction in strength), which is generally more than the minimum evacuation time needed for the occupants (RSET-Required Safe Egress Time). Therefore, generally, occupants who are trapped or become unconscious would be inside the building during these stages of the fire. However, in terms of firefighters, they would still be carrying out firefighting operations. **Fig.** 8 shows the local and final collapses of the Plasco building and WTC Towers, where numerous firefighters died due to trapping inside the building and crushing under the collapsed debris of the structures. Table 2 summarises some of the critical events, an exhaustive list of the critical events can be found in the supplement material. Table 2 shows only some of the most common critical events, a comprehensive list of critical events can be found in the supplementary material of this paper.

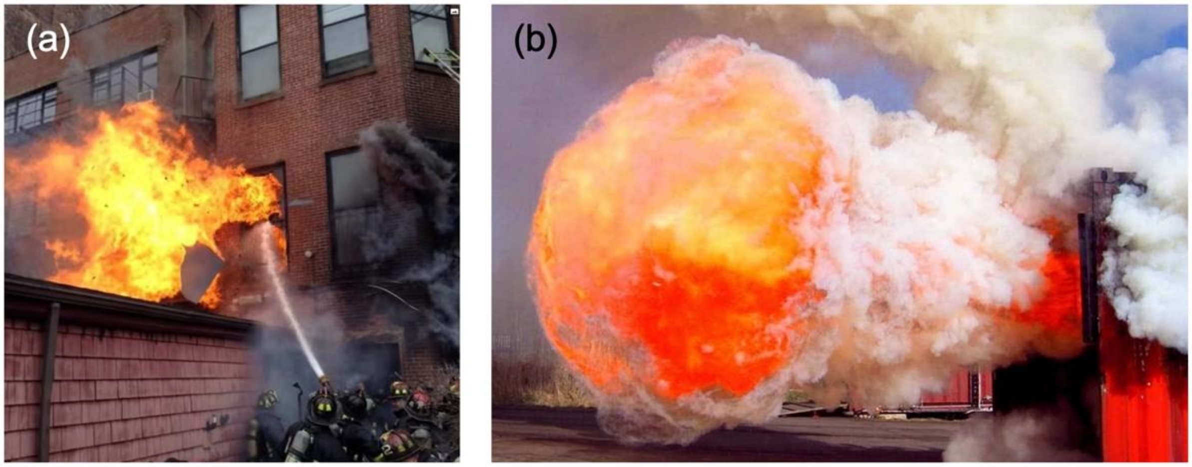

Figure 7. (a) Four storey residential building fire in Massachusetts, USA (2014) [57] (b) Backdraft phenomenon presented by US Fire Administration (credit [59])

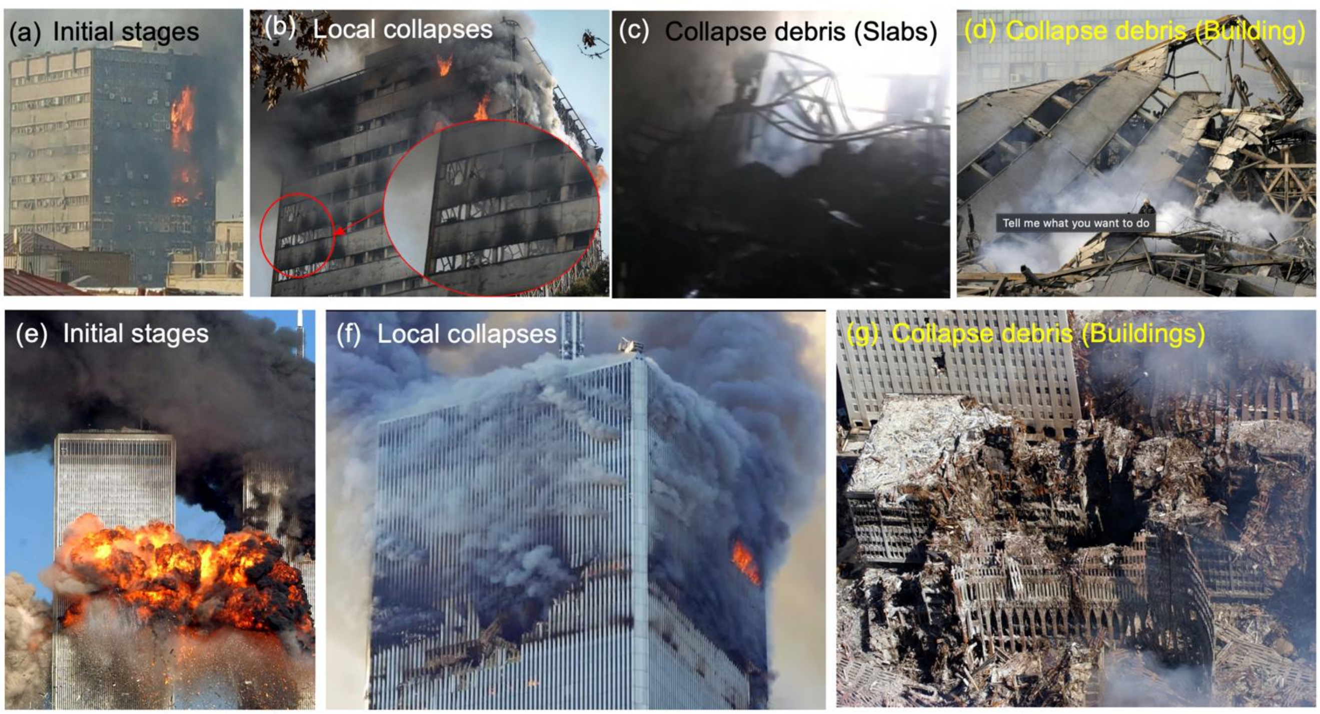

Figure 8. The 2017 Iran Plasco Building fire accident [(a) Initial stages of the fire (b) & (c) Collapse of the floors, and (d) Total collapse of the building] (credit [55]), and WTC fire accident [(e) Initial stages of the fire (credit: Spencer Platt) (f) Local collapses (credit: David Karp), and (g) Collapse of the entire buildings (credit: Eric J. Tilford)]

Table 2. Selected critical and precursor events (comprehensive lists can be found in Supplementary Material).

Fire Stage	Evacuation	Fire Spread	Structural changes
Critical Events	• Block of main exit • Overcapacity of the one exit • Failure of the fire doors • Smoke in area of refuge • Delay in arrival of emergency responders • Failure of notification devices • Locked or in-operable doors along the exit route	• Failure of active fire protection • Smoke blockage (smoke layer height and soot concentration) • Fire reached into false ceilings and/or false floors • Fire reached different floors (Upper and/or lower) • Non-Operational standpipe system • Temperature and/or flux (differ for everyone: Mayday is called) reaching their PPE	• Failure of compartmentation / fire barrier • Windows breakage (lead to backdraft) • Failure of support beams • Failure of stairs (blockage or collapse) • Collapse of floors (slabs) • Loss of fire resistance • Collpase debris in the exit route
Precursor Events	• Fire reaching towards corridor • Rise of the concentration of CO, NOx	• Firestop devices or system failures • Fire spreading towards high fuel load region • High temperature of metals	• Deflection in beam • Local buckling of columns • Failure of fire resistive joints

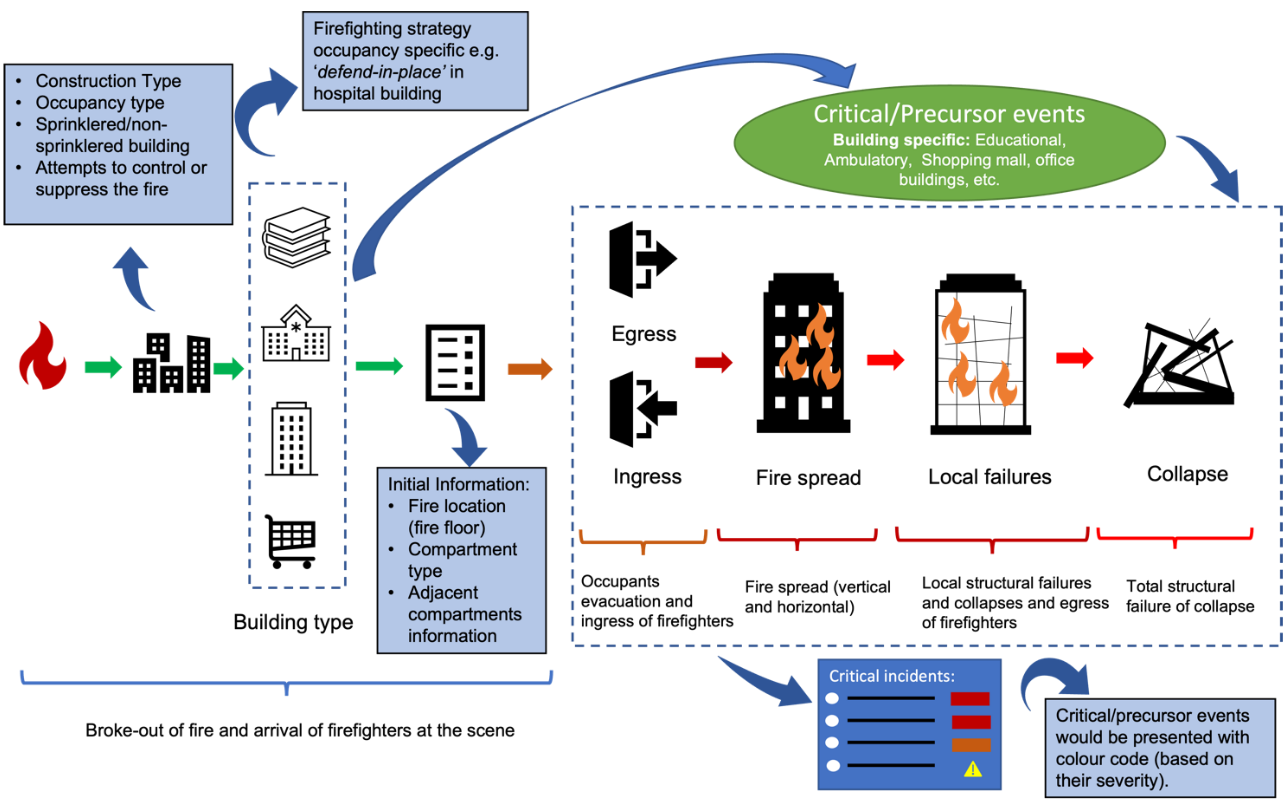

Figure 9. Framework for developing Critical Event Library

3.5 Framework for critical event library generation

Previous subsections discuss some of the events that occurred during various stages of a fire (Table 2). Given the uncertainty associated with the fire and the uniqueness of each building and fire scenario, there may be numerous events/failures that can occur in a building fire. To forecast such events, firstly, it is necessary to generate a library for each building type. **Fig.** 9 presents a framework to create a library of the critical events that can be used to forecast them using the AI engine (explained in detail in section 5). While developing an critical event library and dealing with a life threatning situations, the the philopshical idea presented by Murphy Law – anything that can go wrong will go wrong – can be helpful to underatand possible failures and events in a fire situation.

Once a fire occurs in a building, the fire department may be notified directly (in modern buildings, in some countries, fire alarm control panels are equipped with a transmitter to report the fire). Failing to report the fire department during the early stages of the fire may lead to a disastrous fire. There may be some attempts to suppress the fire during the initial stages (using fire extinguishers or fire hoses). However, if these attempts are failed to contain the fire, the fire will progress further. How the fire is going to affect the structure and progress further will depend on the basic information of the building, such as construction type (steel frame, timber, composite), occupancy type, and if the building is sprinklered or not. The firefighters generally can get this information before they arrive at the scene. Firefighting strategies very much rely on the occupancy types, such as it may require a different strategy for the office building than the hospital where re-location of the patients should be carried out by trained staff (defend-in-place strategy) [48].

Once the emergency responders arrive at the scene, they can have initial information - such as fire location, use of fire compartment - from the witnesses or addressable (or intelligent) fire alarm control panels (FACP). If FACP is installed, its failure to initiate the alarm and transmit the signal would be the first few events that may delay the response to control the fire. Further events will be building specific (supplement material with this paper generate exhaustive lists of the events and provide a generic template), as discussed earlier, they will be highly influenced by the fuel load, fuel type and its arrangements, and architectural geometry. For example, the fuel content of a hospital may be very much different from an office building, as a hospital may have a lot of plastic, chemical (including medical gases) and equipment whereas, in an office building, the major fuel would be furniture. Any failures during initial stages of the fire will reduce the ASET. The events during the initial stages of the fire would be related to the detection of the fire, operation of the sprinkler system, egress, and ingress of the occupants and firefighters (Figs. 3 and 9).

As shown in **Fig.** 9, colour coding of the critical events makes it easier to identify the severity of each event, e.g., red colour is assigned for the most severe events (its occurrence may cause the most severe damage to firefighting strategies and threat to life safety) such as blockage of fire exit or failure of the emergency elevator. Amber colour represents events that may not be as severe as red but may have detrimental effects on life and structure safety, such as illumination failure (exit signs), and zone notification failures. The precursor events that provide the indication or lead to severe events are represented by a yellow colour. It may require the attention of the firefighters to revise the fire strategy such as the excessive vertical deflection of structural beams, fire moving towards the corridor or exit path (**Table 2**).

In the further fire growth, the events or failures would be mainly related to fire spread, and structural changes in the building (discussed in the previous section), as shown in **Fig.** 9. If the sprinkler system fails to suppress the fire, the fire may keep spreading and travel to other parts of the building. The fire may reach upper floors (Grenfell Tower fire, the Plasco Building fire), which requires more firefighters to be deployed, as discussed earlier (Section 3). With very long exposure to the fire, the structural components may fail, which may lead to local collapses, which can hinder the mobility and egress of the firefighters, such as failure of the beams, slabs, and columns. Such local collapses were observed in many fire accidents (WTC and the Plasco Building). If the fire continues and is unable to be suppressed, the progressive collapse of the structure may happen, as in the case of the WTC towers, the Plasco Building, São Paulo Building. **Fig. 10** shows the steps for generating a critical event library. Below are the six steps needed to develop the critical event library:

Step 1- **First-hand information**: Once a fire occurs in a building, the information of the structure and occupancy type must be available. Information such as if the building is sprinklered or not, helps firefighters to make initial firefighting strategies.

Step 2 - **Fire Location**: The location of the fire is very critical for estimating the fire spread and must be known to firefighters to evaluate the potential of the fire growth. The exact geographical location of the fire compartment provides information of the presence of the fuel load and its type. Such information also allows for estimating the time required by the firefighters to reach the fire compartment. The information of the adjacent compartments and windows' location can suggest the potential severity of the fire e.g., if the fire is initiated in the meeting room and the adjacent compartment is the printing room, the chance of the fire becomes suddenly larger are very high as soon as it reaches compartments with more hazardous material. Similarly, in hospital occupancy, if the fire from the patient room reaches the chemical storage area, the fire may become significantly bigger.

Step 3 – **Occupant Evacuation**: The events or failures that may hinder the evacuation process must be listed (**Fig.** 9). During this period, it might be possible that firefighters are attempting to enter the building (**Figs.** 3 and 9). Supplement material listed a number of critical events that may impede the evacuation process.

Step 4 – **Fire Spread**: Fire has a tendency to extend towards the high oxygen region. The fire can travel to adjacent compartments or reach upper floors. In a fire accident, with each passing moment when the fire is not contained, it is becoming more difficult to control. Failure of the manual fire suppression process, fire reaching upper floors, and high temperature of the handrails are some of the critical events that must be included in the event library (**Fig.** 9 and supplement material).

Step 5 – **Local failures**: Uncontrolled fire for a long duration raises the temperature of the structural components that causes the local collapses. All possible events associated with the local failures in a building must be listed in the event library.

Step 6 – **Structural Collapse**: In the last two decades, a number of buildings have collapsed or failed in fire accidents. Prolonged heating of the structural components reduces their strength and eventually may lead to the collapse of the entire building. It is possible that firefighters may have been trapped inside the building during this period, as happened during the collapse of the Plasco Building, where more than 16 firefighters died when they could not come out of the building and the whole building collapsed. If such information (reduction of the strength of the structural components) can be predicted in the early stages, severe injuries and fatalities can be avoided.

While listing the critical events to develop a library of events with colour coding, it is necessary for the developer to discuss with the fire department (it gives proximity and typical response time of the fire department) and go through architectural drawings. Predicting the fire events may break the chain of events and provides more time to the firefighters to act based on the real-time situation. So, it is critical to have information of all possible events or chances of failures in a building fire. Using the above framework, one can enumerate critical events by collecting data from the fire accidents and requirements presented in codes and standards. Section 6 explains how the critical events listed in the library can be forecasted based on real-time information.

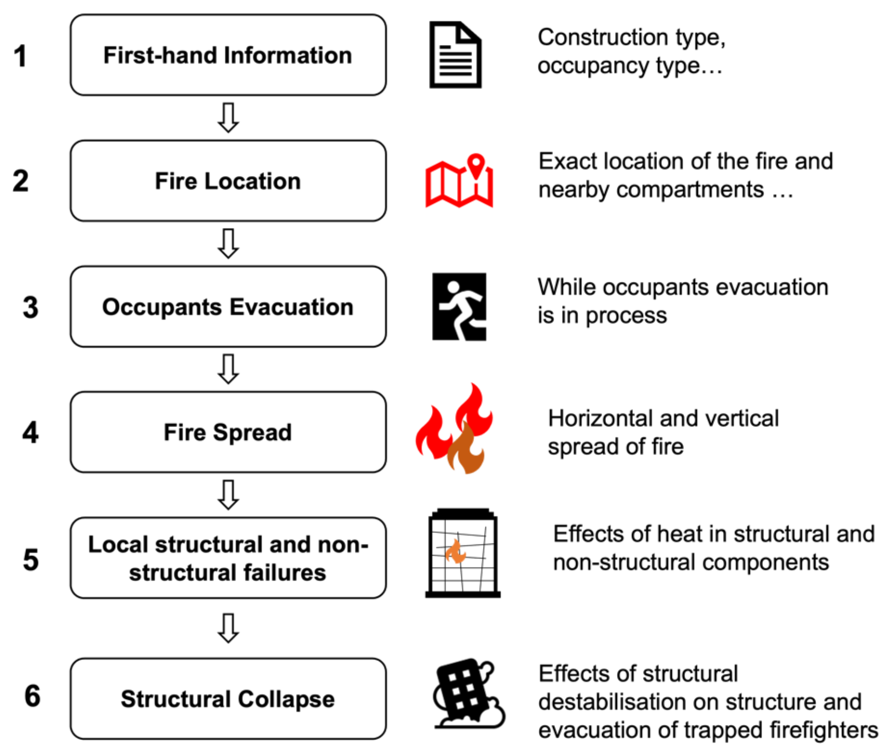

Figure 10. Steps for developing Critical Event Library

4. Major Factors influence the criticality of the fire accident

The probability of the occurrence of the above-mentioned critical events would be influenced by various factors such as type of occupancy, fire load, life of the building (**Fig.** 9). Some of the vital factors are discussed in this section.

4.1 Occupancy Type

The type of occupancy, such as business occupancy, hospital, school, played a critical role in fire strategies, fire protection, and structural designs. For similar buildings but with different occupancy types, the fire behaviour would be entirely different. For a building, fuel load is assigned according to occupancy type. In codes and standards, generally, the value of fuel load is presented based on statistical data [60,61]. Although fuel load is usually considered the primary factor in structural design to evaluate the "*fire resistance*" of the structure, this is not the only factor in deciding the intensity and duration of the fire [62]. According to a study carried out by Culver [63], it was found that even for the same occupancy, the use of the compartment is critical. For example, in an office building, fuel load in the admin region would be different from the archive room or printing room. From the survey, it was found that the fuel load values were much larger in some regions of the building [62,64]. This non-uniform distribution will increase the uncertainty in the fire behaviour. So, it is necessary to know the use of floor and compartment type of the fire location to predict the fire behaviour.

Another critical factor associated with the occupancy and use of the floor is the type of combustibles. The burning rate, generation of smoke and soot, and other gases depend on the chemical composition of the material, such as plastic will burn more intensely and generate more poisonous gases than papers. Due to the use of computers and printers, the presence of plastics is generally unavoidable in all types of occupancies. In the fire accident of the Grenfell building, most of the fatalities were mainly due to the inhalation of poisonous gases [1], which was primarily associated with the material used in the construction of the building.

While designing the sprinkler systems for buildings, NFPA 13 classified the occupancy based on the combustibles present, e.g., *light hazards*, *ordinary hazards*, and *extra hazards*. Light hazards are the buildings where fuel load would be relatively lower, such as office buildings, whereas library (due to the presence of the higher combustibles) comes in the category of ordinary hazard, and printing areas comes in the category of extra hazard due to the presence fuel with high flash point [41]. Such information allows the firefighters to anticipate the potential of the fire and some of the requirements for the firefighting operation, such as the amount of water needed for fire suppression.

Some buildings may require special attention, such as the preserved historical buildings where the evacuation methods and requirement of egress path (sometimes egress path can be odd) may not match with the modern codes and standards, especially the active and passive fire protection, size and width of stairs, number of staircases. It is necessary that firefighters have full information about such buildings.

4.2 Building design and construction

Construction type of the building is another criterion that is necessary to take into consideration. Structural response would depend on the construction material and '*fire* '*resistive*' rating provided during design. NFPA [65] classified building construction broadly in five categories from Type I to Type V (classification is based on the combustibility of construction materials and fire resistive ratings), which are further classified on the time of the fire-resistive ratings provided to different structural and non-structural components (exterior and interior walls).

In steel frame buildings, the failure of beams and floor system is not uncommon in fire accidents, which may fall and get into the travel path and block the passage for the firefighters or delay rescue operations. The recent advancement in the construction of timber structures raises concerns in terms of structural safety [66]. Although timber has a quality of self-extinguishment, it also adds fuel. In a recent fire accident, a motorcycle museum constructed from timber in Austria burned to the ground [67]. The use of light timber structural members (trusses) can lead to catastrophic collapse during a fire accident [68]. The timber trusses are generally highly stressed and can be consumed in the fire, which can lead the total collapse in a very short duration. According to the NFPA Fire Investigation report, around 30 firefighters are killed in between 1977 and 1995 in the US in the structures having timber trusses [36].

4.3 Occupancy inside building

Informal settlements pose a severe threat to life safety, as observed in some of the recent fire accidents [69–71]. Responding to fire in informal settlements is a severe challenge due to the presence of a large amount of combustible material, flammable construction materials, ignition sources (cooking methods), and high population density. Due to the complexity associated with the fire dynamics and human behaviour during a fire in informal settlements, carrying out firefighting operations is a quite challenging task . The narrow escape[72] route and delay in fire detection make it difficult to carry out evacuation and firefighting processes which endangers the lives of occupants and firefighters. Fire accidents in informal settlements are quite common in developing countries. Many fires are reported in South Africa, India, and Bangladesh. In a fire in Bangladesh (2019), more than 1200 tin shacks were destroyed, leaving thousands of homeless people [73].

4.4 Age of the building

The age of the building can be a critical factor, especially for structural response to fire. Construction materials generally lose their strength with time, so the structural components in older buildings may fail earlier than expected. Failure of walls or slabs in old buildings is relatively fast compared to newer buildings as reported in many fire accidents, which is responsible for the death of many firefighters [74].

5. Application of AI, IoT, and digital twin in smart firefighting

A-posteriori investigation of major fire disasters has invariably exposed the inadequacy of response, usually caused by poor decisions due to lack of useful information from the incident location. Modern buildings generally contain complex data generating networks that enable real-time monitoring of the performance of urban environments. Detailed analysis of this data can deliver information that continuously determines the state and evolution of systems and diagnoses emergent pathologies. Effective diagnosis requires professionals capable of curating this data and a framework for translating it into useful and actionable information and knowledge. As discussed earlier, this concept was demonstrated on the scale of a three-room apartment in the FireGrid project (2006-2009). Using the current technological advances such as MicroGIS (Geographic Information System), Computer vision, IoT (*Internet of things*), BIM (Building Information Model), and fire simulation tools, it is possible to generate data for real-time data analytics based on AI and machine learning techniques to provide rapid decision support information to responders during an emergency. The forecasting of fire growth and spread is a complex nonlinear multivariate spatiotemporal prediction problem [75], similar to weather forecasting, including wind [76], temperature [77], and air pollution [78]. Such forecasting lower scale has been demonstrated in the FireGrid project and for a small tunnel [79]. To demonstrate the **FireGrid** concept, the zone model was used to simulate in parallel a large number of instances of the single room fire faster than real-time over many nodes of the HPC cluster using the inherently parallel Monte Carlo approach [17]. Ensemble forecasting simulations (akin to weather forecasting) were run and rerun continuously based on sensor feeds from the remote test location. This approach cannot work for a large and complex building as this would require significantly more intensive computations, only possible using CFD tools. Even with state-of-the-art HPC hardware, current CFD tools will not enable super real-time predictions [17,80]. The concept of *Event Library Forecasting* (ELF) is based entirely on big data analytics and AI/machine learning techniques. A big data-driven modelling framework - associated machine learning algorithms – is proposed in this paper. It explained how *real-time* data can be used for forecasting critical events, which can further be used for smart firefighting.

Use of sensors in the urban environment is becoming pervasive, but little use of this information has been made to manage emergencies effectively. The general perception that sensors can provide useful information to emergency responders is contrary to reality, as the sensors provide too much "raw" information to be assimilated during an emergency. However, this information coupled with simulation models could potentially forecast the evolution of the emergency in real time. Forecasting a fire event is extremely complex. The evolution of a fire is determined by the geometry of the building, the materials of construction, and building contents and systems. The geometry has fixed components, such as walls and ceilings, but it also has variable and dynamic components, such as doors and windows that can be at different positions at the onset of the event (discussed in critical events). Their position will alter air supply and thus affect the evolution of the event. Dynamic components include fuel packages (e.g., furniture, paper, appliances, etc.) or systems with variable operating conditions (e.g., air conditioning systems, automatic vents, shutters, etc.). While static components can be part of a pre-assessment, variable and dynamic components must be established at the onset of the event. A model that incorporates static elements and can assimilate sensor data to configure, when required, the variable and dynamic components represent the "digital twin" of the building. Once as-built geometry has been captured using MicroGIS (spatial data acquisition and coupled with the BIM model), the valuable experience of applying computer vision in the construction and building industry can be used in automatic acquisition, analysis, and decision making based on visual data that can be used to build, update, and maintain a digital twin to facilitate smarter emergency response.

Using computer vision technology, the indoor state of each building can be sent back to command and control in real-time objectively and automatically. Computer vision and natural language processing technology based on a series of deep learning algorithms are capable of delivering various important functions needed for real-time information. For example, information of indoor objects, visual sensing data (collection of real-time pictures or videos for the follow-up training of prediction models to provide case data for model validation), indoor scene recognition and interpretation[81].

It will be necessary to mark special objects (i.e., fire protection equipment, various fuels, electrical appliances, etc.) in the pictures of the training set, according to the actual requirements of firefighting in advance. For scene recognition and interpretation, a corresponding data set of the indoor space and image captioning data set may be needed. The image caption is a system to realise automatic text descriptions of images. Such information can be obtained using the *Deep Convolutional Neural Network* (DCNN). DCNN has achieved incredible success in object and scene recognition [82]. For data communications, sensor data can be routed through reliable wireless and/or wired communication networks to remote computers for processing. The emergence of 5G technology, *Cyber Physical System* (CPS), and edge computing make it possible to address the above communication network demands.

The process of obtaining the data and application can be summarised as follows:

- Communication networks for data collection: Data from the emergency location is collected from sensors and relayed to emergency response command and control (C&C). Currently available addressable (intelligent) fire alarm control panels are capable of carrying out this objective. Using state-of-the-art devices and AI data it can be done much quicker.
- Data analysis, incident simulation, and forecasting: State-of-the-art sensors can steer "simulation tools" on supercomputers to predict the evolution of the fire and establish its impact on the structure and analyse intervention alternatives and evacuation strategies. All of this can happen faster than the evolution of the emergency in real-time (analogous to weather forecasting).
- Feedback to incident venue: Updated forecasts are relayed continuously to actuators, C&C, and incident commander (IC) in forms easily assimilated by the recipients for aiding decisions or using the AI trained model suggestion can be displayed on user-interface (**Section 5.1**).
- Smart emergency response: Effective coordination between C&C, IC, and firefighters using unambiguous execution support aids help them implement effective responses without delay.

The advanced tools and technologies discussed above can only be helpful if it is known what information must be known a-priori. Without knowing "what can go wrong in a fire or what is going to happen" we cannot exploit the full use of these state-of-the-art tools. Therefore, an event library (presented in **Section 4**) for a specific building must be generated with all possible events that can happen in a fire that will change the course of the fire.

Fig. 11 shows the framework of employing the critical event library to forecast the events using sensor data and machine learning algorithms.

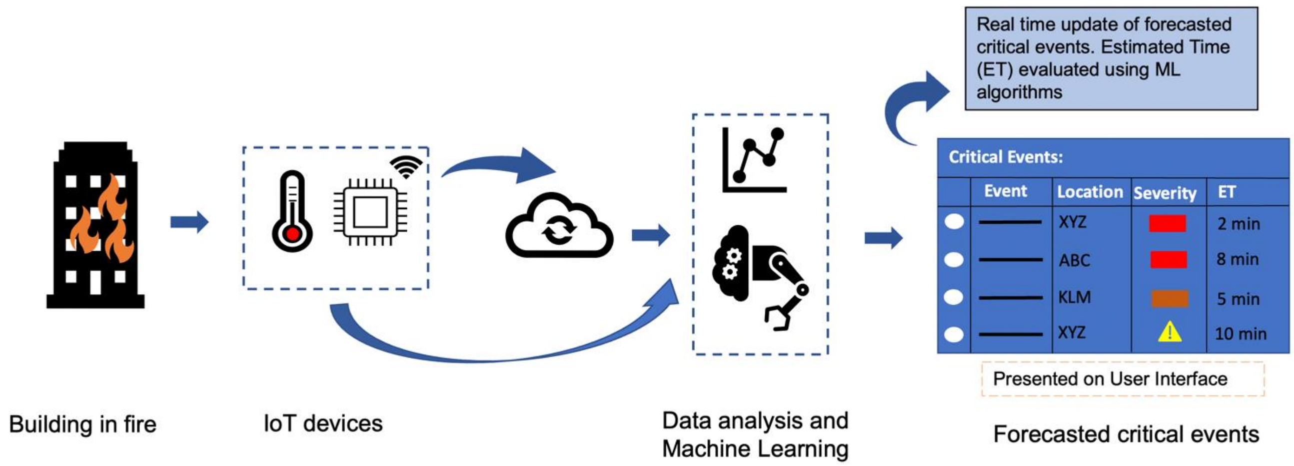

Figure 11. Flow of Critical Event Forecasting

5.1 Event library forecasting (ELF)

The predictions of critical events can be derived from a purely data-driven approach using heuristics, AI, and machine learning technologies to provide forecasts by matching real-time data streams with a large database of stored simulations. Sensor data (mostly images and readings from active control systems) can be used to discover (via suitable pattern recognition schemes) the variable and dynamic conditions at the start of any significant event. This information then can be used to establish the library data sets that most closely match the impending scenario. Furthermore, data analytics can be used to identify potential alternative scenarios (associated with sensitivity and with potential erroneous identification) and establish adequate corrections. Additionally, the continuous feed of real-time data from the sensor network can keep generating new scenarios and events. This process will provide a a potential variance to the forecast. Using live sensor feeds and having a sufficiently large set of acquired data could potentially enable real-time forecasting. The aim of this work is to develop a library of critical events that could potentially enable real-time forecasts.

Fig. 11 demonstrates how the events generated in the section 4 can be forecasted, and decisions can be made to alleviate the potential injuries and fatalities.

- The sensors (IoT devices) network - installed in the building - will keep collecting the relevant information continuously, such as temperature data (thermal sensors), heat generation (radiant energy sensors), images (CCTV or more sophisticated cameras during dense smoke layers), toxic gas concentration (CO, NOx, O_2, etc.), and so on. Sensors network should be able to provide both static and dynamic data.
- The data obtained from the sensors can be read at the server over the cloud or processed by the component of IoT devices (edge processing). The data can be stored in the standard format in the cloud and unwanted data from the raw data will be removed.

- Using the machine learning (AI component of the framework) and data analysis algorithms, the refined data will be used to identify the situation and forecast or predict the events presented in the Critical Event Library (**Fig.** 9 and Supplement material), presented in section 4. AI engine enables the digital twin and automates the process for firefighters to tackle the fire by providing information about the fire scene in advance (provides time to revise the firefighting strategies based on the real-time data).
- A user interface will fetch the output of the AI engine and present the critical events with the estimated time of occurrence of every possible event with the colour code (**Fig.** 11) based on the severity, as discussed in **Section 4**. Based on the real-time data, the events will be kept updating, furthermore, the colour code will also be updated as soon the estimated time decrease below some pre-defined limit.

The whole process of creating an event library and forecasting using the AI engine creates a smart firefighting digital twin for buildings.

5.2 Data repository

Developing AI models for predicting events requires a large database. Besides the reduced-scale and full-scale fire tests, fire models also provide a better understanding of the fire behaviours and structural performance. Full resolution of the gas-phase fire process generally requires CFD models to the microscale and with millisecond time scales. Comparatively, the solid-phase decomposition and deformation are generally analysed using *Finite Element Models* (FEM) at much greater time and length scales. Thus, the coupling of these models is very complex. Khan et al. [83] and Orabi et al. [84] developed open-source packages to carry out the CFD-FEM coupling for structural analysis. A case of the Plasco Building is presented using the OpenFIRE tool developed by Khan et al. [39,85]. In addition to the enormous cost, uncertainties in input values, numerical formulations, and other variables diminish the value of resolving the gas phase over the full range of spatial and temporal scales. Simplified formulations are thus necessary, but these need to be calibrated for each specific modelling exercise. Very large number of CFD and FEM simulations need to be carried out for each target building to generate its corresponding big data repository. The repository shall contain an exhaustive range of critical events as recommended in this paper.

5.3 Fire digital twin

The concept of the *Digital Twin* was introduced in the early 2000s. Arguably NASA was the first to adopt the Digital Twin while attempting to improve the physical model simulation of spacecraft in 2010. In recent years, the digital twin has been applied to aircraft engines, manufacturing processes [86], and large infrastructures. Once Digital Twin of a building is incorporated with BIM, the Digital Twin can be regularly updated by the fire risk information, such as the fuel loads in each fire zone and the transport of high fire hazardous materials inside the building, and issues related to maintenance and testing.

The building-fire Digital Twin can be coupled with a pre-established fire database that is used to train the AI engine. The fire database includes thousands of high-fidelity CFD-based fire simulations, FE simulations, experimental data, and empirical correlations of the specific building. With real-time information, such as data from the temperature sensors and cameras, a pre-trained AI engine can quickly recognize, visualize and render the fire scene in the Digital Twin. **Fig.** 12 demonstrates the conceptual Digital Twin model of the Plasco Building fire, where the database can be generated from large CFD simulations. A demonstration intelligent digital twin system has been developed for fires in a reduced-scale tunnel with AI and IoT sensor networks to identify the real-time fire size and temperature distribution [79].

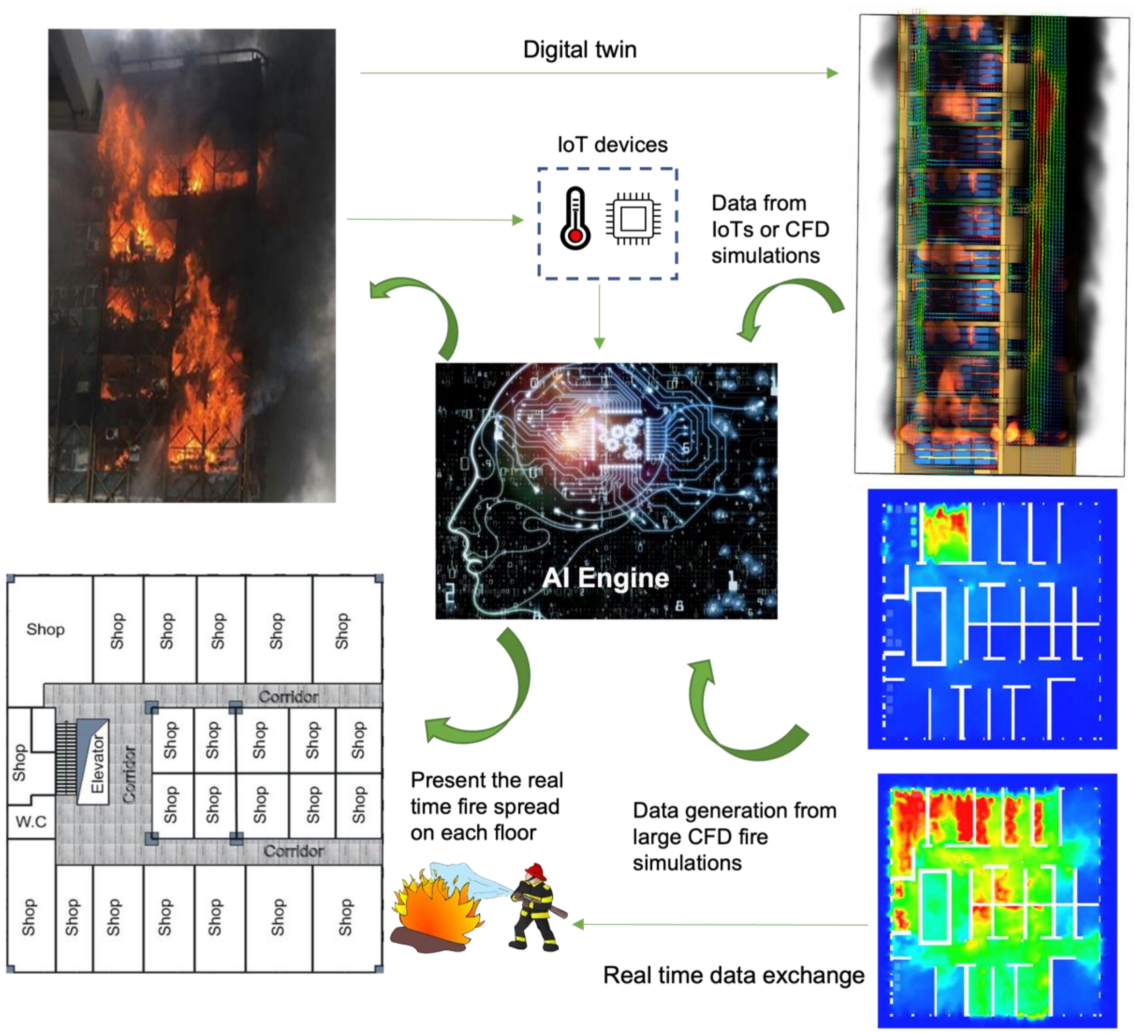

Figure 12: A conceptual *Digital Twin* model of the Plasco Building for smart firefighting

5.4 AI-driven smart firefighting

Since the recent booming of big data and deep learning in the 2010s, AI approaches, as well as other cutting-edge technologies such as remote monitoring, high-resolution sensor, high-speed computation, and data-driven methods, have been increasingly applied in fire safety engineering. The principle of these AI approaches is essentially the multi-dimensional fitting methods based on artificial neural networks (ANNs). By training the database of fire tests [26,87] and numerical fire simulations [22,25,27,88,89], the real-time fire information, such as HRR and the probability of flashover, can be identified and forecasted based on the limited sensor data.

So far, different machine-learning algorithms [90–93] have been proposed to train databases and pre-establish the complex relationship between sensor data and fire to achieve the real-time fire forecast. Recurrent neural networks (RNNs) are specially designed for the prediction or classification of temporal data, and particularly, the Long short-term memory (LSTM) RNN loop structure can be unfolded into a chain of cells. RNNs-based AI algorithm is particularly useful for identifying the fire scenario information and forecasting future critical fire events [13,19]. In terms of the forecast fire scenes and images, Convolutional neural network (CNN) algorithms are more applicable to support the decision making by fire commanders and firefighting operations in the field [94,95]. Therefore, combining an LSTM model and a DCNN model can generate images showing the distribution of temperature, smoke visibility, and gas concentrations in fire scenes.

Currently, the application of AI in fire engineering and firefighting is still relatively less mature. Nevertheless, future AI codes are expected to be further customized and optimized to help firefighting with a more user-friendly interface. Eventually, AI engine will predict complex fire scenarios in super real-time and reveal in-depth information from the enormous database and be used as widely as ' 'today's CFD fire modelling tools. Together with the development of building IoT and digital twin, a mature AI-driven fire forecast engine should be implemented into every building to identify and forecast fire scenes and support smart firefighting.

Technological changes affect the lives of firefighters in many ways, creating the challenges associated with the training that firefighters have had. The inclusion of the new methods and devices in smart firefighting requires the firefighters to be familiar with the technologies that would be embedded with it (Fig. 13). Continuing education throughout one's career helps unravel the differences. Training programs and demonstrations should be carried out to help train firefighters and improve decision making of fire commanders. **Fig.** 13 shows the whole process and modules discussed in this paper for designing smart firefighting system for 'firefighters' safety.

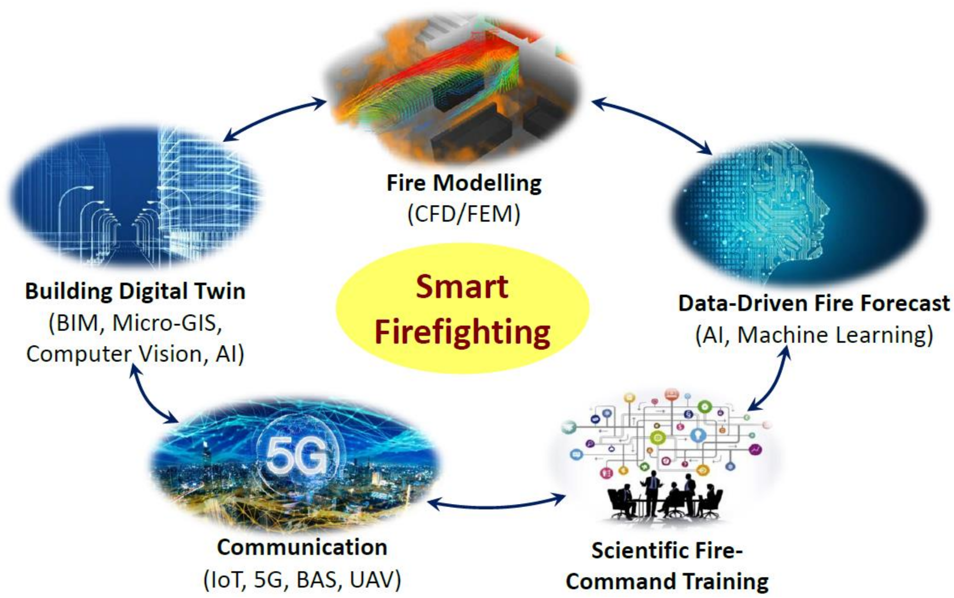

Figure 13: Various modules of smart firefighting

5.5 Forecasting and software development

The current paper discusses the development of critical event library and prediction of such events. In a fire accident, it is required to present the information about the occurrence of any event to the firefighter in the analogue form (texts or messages), such as location of the fire, event, severity and predicted time (and probability). **Fig.** 14 shows the framework for overall development of the software to obtain the information presented in the critical event library. Data from various sources such as CFD/FEM models, will be added to central system. The central system includes the digial-twin of the building. Once the real-time information is obtained from the IoT devices (or sensors) [in the form of temperatures, HRR, live feed of images, soot volume, and so on], AI trained models will be able to predict the critical events which are added to the software (**Fig.** 14).

For some cases where prediction is not possible or sensors failed to get data, a knowledge-based data will be added, as shown in **Fig.** 14. The knowledge-based data can be added based on the information gathered from previous fire accidents, interviewing experienced firefighters and other sources. The data to train the AI models can be labelled as temperature, HRR or images of fire to predict the events. When the IoT sensors provide the real time information, the AI trained model can predict the critical events that may occur based on the information added from the critical event library. The software can translate the information in the analogue form which a firefighter can read the detailed information about future events, as shown in **Fig.** 14.

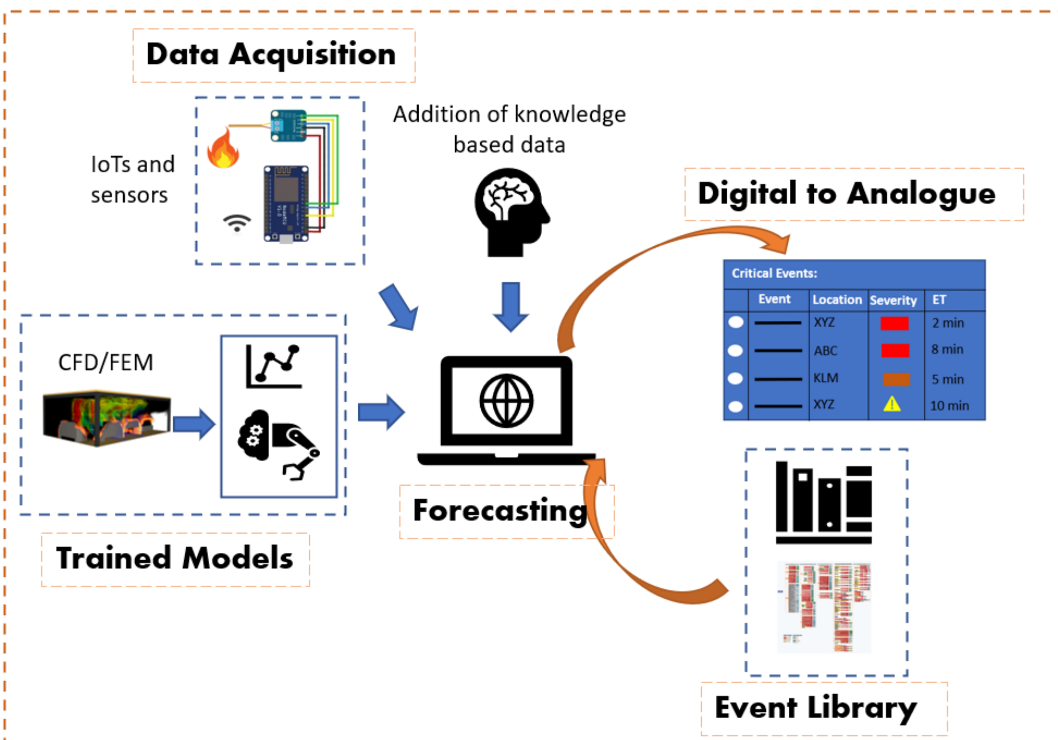

Figure 14: Forecasting and obtaining the information of critical events (Development of software to present critical events)

6. Decision making and smart firefighting practice

During an emergency such as a fire accident, terrorist attack, and mass shooting, the IC officers require to make decisions. In terms of a fire accident, even highly experienced firefighters may not be familiar with the situations that arise during the accident (due to the uniqueness and uncertainty of the fire) [96]. They may require to improvise the strategies based on the real-time data. The framework presented in this paper provides real-time information with the forecasting of critical events. This section discusses how using the current technologies can propose decisions to the IC officers. **Fig.** 15 shows the decision-making event tree in a building fire accident.

6.1 Risk Assessment (Pre-Incident Information, Initial Assessment, and Dynamic Risk Assessment)

As soon as the fire department is notified about the fire incident, the deployed team may have initial information such as type of building, presence or absence of active and passive fire protection, building type, and so on. Such data can be termed as ***Pre-Incident Information***. Based on their experience and initial information, emergency responders come with pre-incident planning [97,98]. This pre-incident planning can be helpful for initial actions by firefighters and can provide them an idea of the probable extent of the fire.

As soon as the team arrives at the scene, the firefighters can know the exact location of the fire either through an annunciator panel (NFPA 72) (generally installed at the entrance of firefighter's lift) or from the witnesses. Once the fire floor and exact location of the fire are known, the information of the 'use of the floor' such as archive room, printing room, office area, can provide the size and probable spread rate of the fire. This information helps firefighters in conducting an ***Initial Assessment*** of the situation to evaluate the risk.

Fire behaviour is very uncertain even a small variation in environmental conditions may affect it enormously. From the literature and experimentally observed data, it is well known that fire behaviour is affected by fuel load, fuel type, ventilation condition and fuel distribution pattern, and many other factors as discussed earlier. In an experimental study [99], it was found that due to the presence of the soffit beam, heat feedback from the accumulated hot smoke resulted in local flashover. Based on the real-time information about the changes in fire behaviour, structural changes, and environmental conditions inside the building, firefighters can review and revise the initial planning and update the firefighting strategies. This approach of evaluating the risk is referred to as ***Dynamic Risk Assessment*** (DRA). For the occurrence of any critical event discussed earlier in this paper (Section 4 and 5), they need to re-evaluate the risk and change the firefighting strategies. Having such information in advance will reduce the time required to carry out the evacuation process, and chances of coming out safely from the building will increase, and the risk of serious injuries will be minimized.

6.2 Decision Making Event Tree

Although the decision making during a fire accident can be a very subjective exercise, however, based on the data obtained from the various fire accidents and experiences of the command officers, an AI model can be generated that can provide suggestions based on the forecasted events (Section 6). This section presents how developing an event tree based on the predicted events can provide suggestions to make correct decisions. As discussed earlier, decisions from the IC officer are generally based on past experience and trainings, however uniqueness of the fire and building create a unique fire scenario. Timely decision is necessary to avoid casualties, which requires to have real-time information. As discussed in earlier section, using the available advanced tool and big data, it is possible to have real-time information about the fire for dynamic risk assessment. Some of the efforts have been laid down to use GIS [100,101] and AI-based systems [102] for decision making while responding to emergency situations, such as monitoring the risk of oil pollution [103], predicting the course of hurricanes [104], and decision support during flood emergencies [105].

An event tree diagram can help firefighters to make the decision and revise their firefighting strategies. From the latest information obtained for a predicted event(s) presented in the event library, the event tree diagram can suggest the possible decisions. These events can be determined from thermal or structural conditions. An example of an event tree diagram is shown in **Fig.** 15.

Fire detection: Once a fire is detected, it transmits the signal to the fire department. In case of the failure of the fire detection system, a call from the witness can provide the time of the occurrence of the fire, as shown in **Fig.** 15.

General information: Fig. 15 shows the pre-incident information (general information), which is necessary for the initial risk assessment of the fire accident. The initial decision and the level of the threat can be predicted from this information, as discussed in previous sections. Type of building such as concrete, steel, or timber helps to understand the strength of the building, especially to understand the structural response to fire. The next question comes to the type of occupancy (business, hospital, education, ambulatory, and so on), it provides information of the possible fuel type and fuel load. From such information, the extent of heat generation can be predicted. The information of the 'use of a fire floor' tells about the possible rate of fire spread as well as the intensity of the fire. In the risk assessment and planning categories, it can be considered as 'general 'information' and must be available to the fire department.

Initial Assessment: Now, an initial assessment of the fire needs to be carried out based on the availability of fire protection systems in the building, such as; if the fire floor has an active fire protection system. If it was installed, whether it was able to control the fire or not. From a survey in the US, it was found that fire protection systems failed in around 12% of fire accidents [106]. So, the firefighting strategies cannot be developed based on the "controlled fire" scenarios.

Dynamic Risk Assessment: Now, the possible events from the critical event library come into the picture that are related to evacuation, fire growth, and structure, as discussed earlier (**Fig.** 15). Occurrence of any of the events requires new strategies to deal with the fire and bring the occupants and firefighters alive before the fire makes the environment untenable. The uncertainty associated with the complex nature of fire due to the new materials, fuel distribution, even highly skilled and experienced firefighters cannot predict such events before their occurrence. The decisions made by firefighters are generally based on past experiences or training, which is generally carried out at controlled environment. The suggested tool can forecast the timing of such events that can help firefighters in decision-making process and provide the real-time information of the fire compartment in the language that fire fighters can understand as discussed in previous sections. Based on the predicted event(s), the trained AI model or incident command officer can suggest the decision, as presented in **Fig.** 15. As these decisions are generally based on the forecasted events, so they can be categorized as dynamic risk assessment.

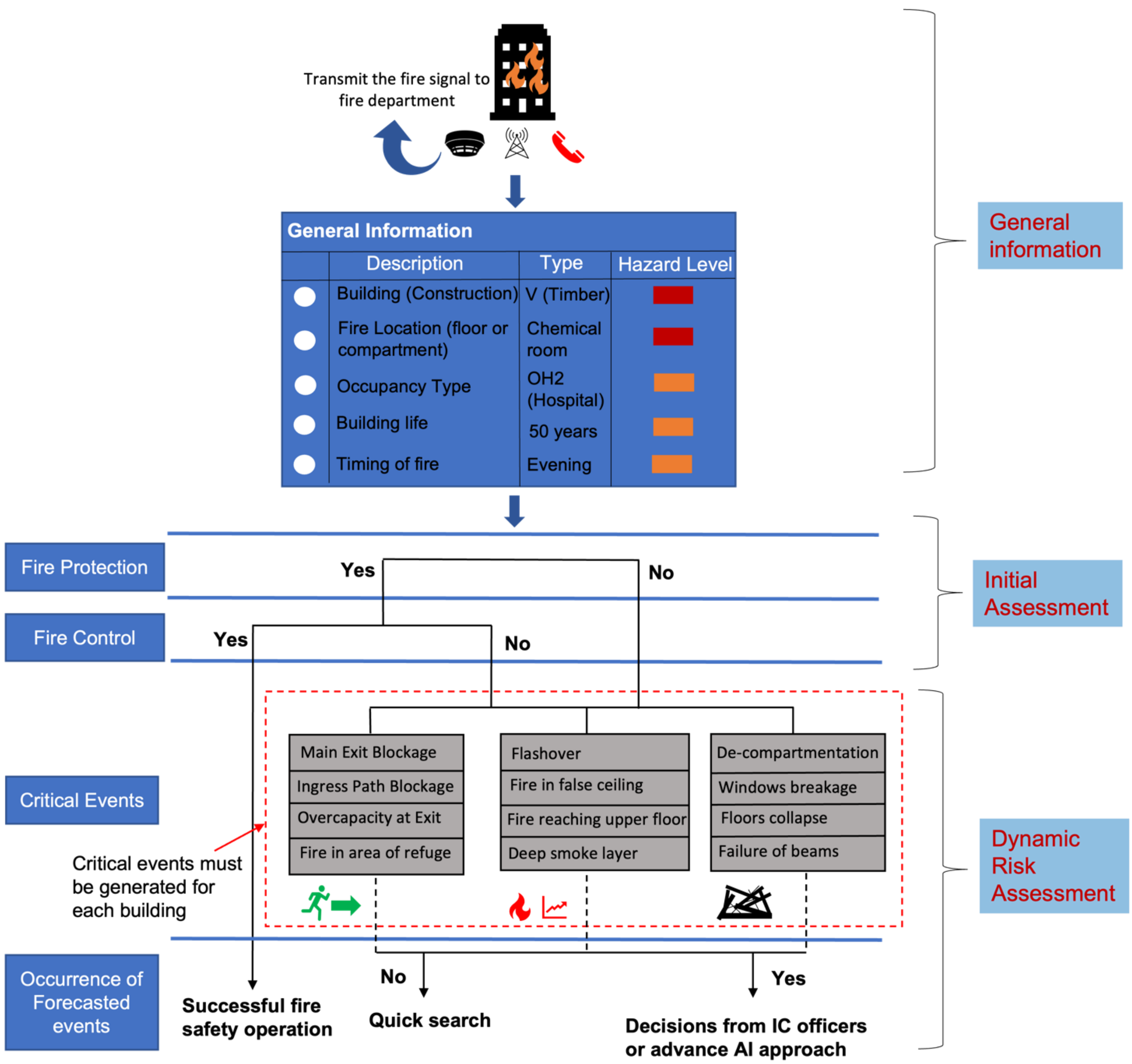

Figure 15. Decision-making tree

7. Conclusions

Each year thousands of fires are reported, and in most of the fires when firefighters arrive at the scene, the condition is already untenable, sometimes resulting in the death of hundreds of firefighters. Current codes and fire safety practices include safety measures for 'occupants' safety, but most ignore 'firefighters' safety. This paper establishes a framework for smart firefighting and develops a critical event library. Various aspects of firefighting are discussed in this paper, some of them are listed below:

- Even equipped with sophisticated PPE, due to the uncertainties and uniqueness of each fire, firefighters are exposed to life-threatening situations. Many firefighters die due to overstress and trapping in the structure.
- The framework presents a method of generating a library of precursor and critical events that can occur in a fire, especially a building fire. This library provides a fundamental understanding of the exposure to various conditions that firefighters may face during a firefighting operation. This will guide the future design of smart firefighting and building fire safety.
- The critical events are divided into three major domains, i.e., (1) the events that affect the evacuation of occupants and ingress of firefighters, (2) the events related to fire growth, and (3) the events influenced by the structural changes.
- The probability of the occurrence of the critical events presented in the paper would be influenced by various factors such as type of occupancy, fire load, and life of the building.
- The paper explains how the predictions of critical events can be derived from a purely data-driven approach using AI, and machine learning technologies by matching real-time data streams with a large database of stored simulations.
- Using the current advancement in IoTs, MicroGIS, and Computer vision, a digital twin of a building can be generated that can be used to guide firefighters during an emergency.
- The current paper proposed a 'decision event 'tree' for the incident command officer to carry out the risk analysis based on real-time information from the fire scene. The information about an event a-priori provides the officer more time to evaluate the situation and make the 'dynamic risk 'assessment' more effective in a life-threatening situation. Having a large database from previous fire accidents, a highly sophisticated AI model can propose a solution or guide the officer in making decisions.

In short, the smart firefighting framework presented in this paper enables a super real-time forecast of future critical fire events, provides the information to firefighters in a language they understand, and improves the efficiency and safety of the operation.

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