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Flammability and Multi-objective Performance of Building Façades: Towards Optimum Design

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Abstract

The façade is an important, complex, and costly part of a building, performing multiple objectives of value to the occupants, like protecting from wind, rain, sunlight, heat, cold, and sound. But the frequency of façade fires in large buildings is alarming, and has multiplied by seven times worldwide over the last three decades, to a current rate of 4.8 fires per year. High-performing polymer based materials allow for a significant improvement across several objectives of a facade (e.g., thermal insulation, weight, and construction time) thereby increasing the quality of a building. However, all polymers are flammable to some degree. If this safety problem is to be tackled effectively, then it is essential to understand how different materials, and the façade as a whole, perform in the event of a fire. This paper discusses the drivers for flammability in facades, the interaction of facade materials, and current gaps in knowledge. In doing so, it aims to provide an introduction to the field of façade fires, and to show that because of the drive for thermal efficiency and sustainability, façade systems have become more complex over time, and they have also become more flammable. We discuss the importance of quantifying the flammability of different façade systems, but highlight that it is currently impossible to do so, which hinders research progress. We finish by putting forward an integral framework of design that uses multi-objective optimization to ensure that flammability is minimized while considering other objectives, such as maximizing thermal performance or minimizing weight.

Keywords: Façade, Fire, High-rise building, Cladding, Design

1. Introduction

The façade is an important part of a building, its principal front facing the open space. A façade performs multiple objectives of value to its occupants, like protecting from wind, rain, sunlight, heat, cold, and sound, on top of its aesthetic significance. Façade systems are complex and represent one of the largest construction costs for high-rise buildings, sometimes as much as 20~25% of the total (Zemella & Faraguna, 2014). Modern façades, especially in tall buildings, have become high-performance systems, designed by advanced engineering, and resulting in much greater complexity than the traditional monolithic stone, brick, or concrete facades of earlier times.

However, fires involving the façade have never been more prevalent (White & Delichatsios, 2013). In an online search of news in the English language, we found that the number of worldwide fires in tall buildings with spread via the external wall is currently, on average, 4.8 per year and the total has increased by 7 times in the last 30 years (Fig. 1). These data are biased towards very visible and large fires that are reported by the media, so many smaller façade fires have not been included, but the trend is clear: façade fires in high-rise buildings are becoming more frequent.

The primary threat to a building by a façade fire is a potential breach in compartmentation, either vertically (from floor to floor) or horizontally (e.g., from apartment to apartment). Fire strategies for high-rise buildings typically aim for the fire to be confined to its floor of origin for an extended period after its initiation (Colwell & Baker, 2013; Torero, 2018). One potential breach vertically comes from a compartment fire breaking through an opening in the façade, extending up the side of the building, and then breaking into the floors above (Colwell & Baker, 2013; Wade & Clampett, 2000). However, because modern façades are being built with varying amounts of combustible components, they can now become directly involved in the fire, and contribute to its spread instead of hindering it.

The combustible components in facades are generally formed from a wide range of polymers such as polyethylene, polycarbonate, phenolics, polyisocyanurate (PIR), polyurethane (PUR) or polystyrene, to name just a few (White & Delichatsios, 2013). Combustible components within a façade system may be included in the engineering design, or added at later stages by contractors. Combustibles may be added when a façade is refurbished or parts are replaced during the life of the property.

The degree to which a façade system might become involved in a fire is dependent on its overall flammability.

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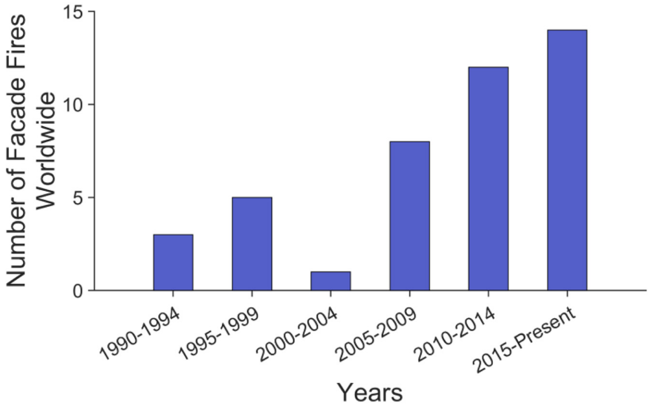

Figure 1. Data showing the frequency of large façade fires worldwide from 1990 to present day. Data found from news articles online.

By flammability, we refer to the ease of fire to ignite and spread through the façade. In UK building codes for facades, the term combustibility is used often, referring to the capacity of a given material to burn, but flammability is a broader concept that also considers how different materials are combined, oriented, and connected in the façade system, and how they interact during a fire. A good example to see the difference between combustibility and flammability is the air cavity inside a façade, which is not a combustible element, but its presence substantially alters the response to fire of a façade and the rate of spread, and so it alters the façade's flammability.

It is essential to understand how the whole façade system will perform in the event of a fire. However, there are significant gaps in our understanding of façade fires. This is for two reasons: firstly, there are a myriad of different design decisions for any facade build-up such that it complies with its multiple objectives within a building; and secondly, there is no theory, model, or comprehensive experimental data series that can reliably explain or predict from first principles how a façade will behave in case of fire. Despite the many decades of façade evolution in modern times, large-scale fire testing still remains the only possible route to gain knowledge about the flammability of a specific façade; but large-scale testing is prohibitively time consuming, expensive, and the results cannot be extrapolated to other façade designs. There is a dire need to develop a theory of façade flammability.

The tragic fire at Grenfell Tower in London has led to an unprecedented response in the UK. As a public inquiry is conducted (The Grenfell Tower Inquiry, 2018) policy makers and building designers are turning to fire science, searching for a better understanding of the problem of fires in high-rise buildings or, better yet, a solution to understand flammability. Unfortunately, past research into façade fires is scattered and sparse, especially for such complex systems. This could also become a problem for forthcoming research being conducted in the wake of the Grenfell Tower fire, as it is currently unclear where fire science should focus.

This paper aims to contribute to focusing the research on façade flammability by providing an overview of the

Individual Components Façade Detailing Entire Façade

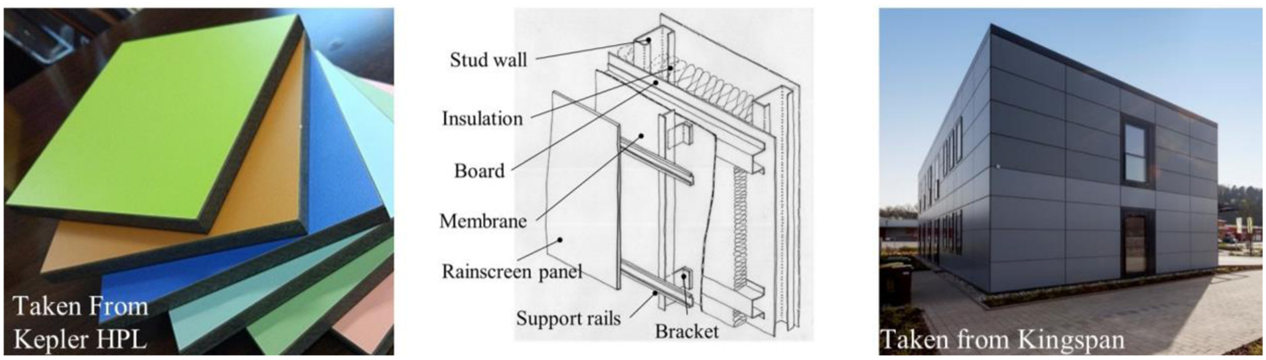

Figure 2. Images demonstrating the different levels of analysis when considering a façade. Currently, fire research focuses mainly on individual components, while large scale fire testing is used to assess façade systems.

problem. It includes a summary of the factors that have led to an increase in combustible materials inside façade systems; a discussion of flammability in various common façade designs; and some of the most important gaps in our current knowledge.

2. Why Are Façade Fires Becoming More Frequent?

A successful façade system must fulfill many requirements or objectives in regards to people's safety and comfort, such as protecting from wind, moisture, light, heat, cold, and sound. These requirements must be balanced with a façade's aesthetics and its return on investment. Overall, the broad goals can be broken down into more specific design objectives, detailed in Table 1. In order to balance these multiple objectives, façade designs combine layers of different materials (Herzog et al., 2017). The material list will nearly always include polymers in some amount, as they are high-performing, affordable, and their thermal and mechanical properties can be manipulated and tailored to meet different needs - but all polymers are flammable to some degree.

Over time, the amount of polymers used in facades has increased. In order to understand why, we need to look at the factors that have driven this change. There are three main drivers.

The first driver is a requirement for energy efficiency. After the oil crises of the 1970s, western countries shifted high-rise building design towards energy saving by reducing thermal losses (Oldfield et al., 2009). Shortly afterwards, polymers entered the building industry, providing generally better thermal performance than other insulation materials.

The second driver is sustainably. The demand for thermal efficiency has increased again in recent years with growing concerns over carbon emissions. Fig. 3 shows the legal requirements for insulation (U-Value) of external walls in the United Kingdom (UK) over two decades. The U-Value of a wall quantifies its overall thermal resistance - a lower value indicates a better insulating performance. The increasing trend in UK insulation requirements is clear, and is the result of government policies targeting energy efficiency and sustainably. This UK trend is representative of legislation across much of the northern hemisphere (EU, 2010; Shearer & Anderson, 2008). The solution to this increased demand on thermal performance is to reduce the number of openings (vents, glazing), include thicker insulation in a façade, or to increase the thermal resistance of that insulation. Polymers are suited to meet these requirements because they are very good heat insulators.

The third driver is the return on investment. In this regard, thinner and lighter façades are more desirable because they allow for more usable floor space and for shorter construction times. Polymers are suited to meet these requirements because they are light, and as composites they can be made thin while still retaining strength.

The fact that, in general, polymer foams are more flammable but more insulating than mineral insulation (Hidalgo et al., 2017) has split design philosophy in two. One design philosophy prefer thicker façades with mineral insulation, and the other prefers façades containing polymeric insulation. This, in turn, has led to a split in the insulation market, shown in Fig. 4. Around 60% of the German market divided between non-combustible mineral wool and more thermally efficient polymeric insulation, which includes both natural polymers (e.g. wood fibre insulation) and foam plastics. Although these data are from the German market, recent trends from the European (Maria & Thorkild, 2011) and U.S. (Moore, 2018) markets show a similar split between combustible and non-combustible products, suggesting a global trend.

Table 1. Objectives in façade design (Herzog et al., 2017). Objectives are ordered by whether they are intended to be minimized or maximized, and from those that ensure the building is safe, to those that ensure the building is comfortable

Objective	Description
Minimal flammability	Reducing flammability reduces a façade's contribution to fire spread.
Minimal moisture ingress	Reducing water in a façade reduces mould and damp in the building.
Minimal weight	Reducing the weight of a façade reduces construction time and the amount of structural support required, allowing for more complex façade geometries.
Minimal thickness	Reducing the thickness of a façade increases the living area available inside the building.
Maximal structural stability	Increasing the stability of a façade increases its ability to withstand all loading conditions e.g., wind, self-weight, other live loads.
Maximal thermal insulation	Increasing the insulating ability of a façade increases the comfort of the building's occupants.
Maximal lighting comfort	Increasing the quality of sunlight management provided by a façade increases the comfort of the building's occupants.
Maximal sound insulation	Increasing the amount of external noise blocked by a façade increases the comfort of the building's occupants.
Aesthetics	A façade should be beautiful.
Return on investment	A façade must stay within its allowed budget.

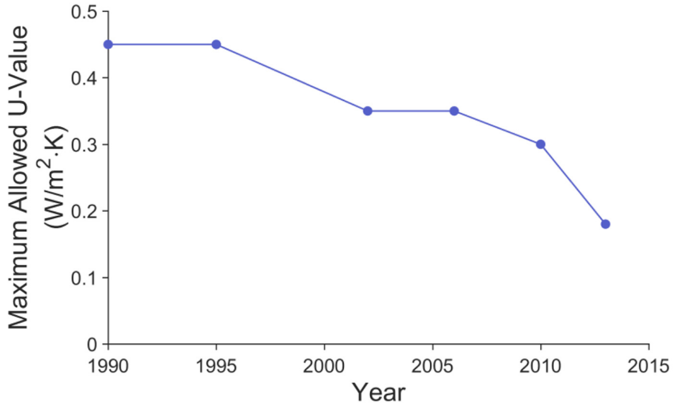

Figure 3. Maximum U-Values allowed for external walls in progressive editions of the UK building code. The U-Value of a wall quantifies its overall thermal resistance - a lower value indicates a better insulating performance (HM Government, 2016).

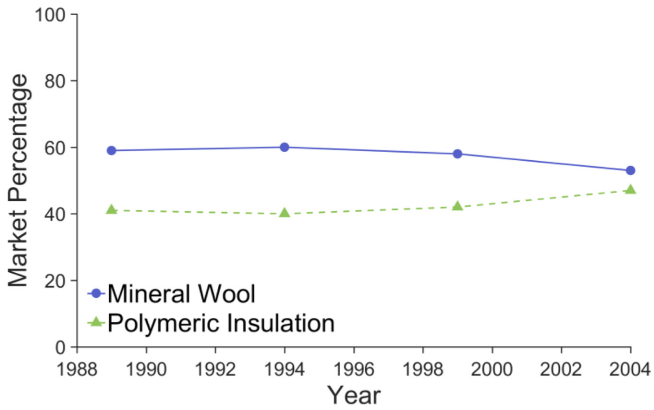

Figure 4. Market share of German insulation products from 1989-2004 (Bozsaky, 2010). The market is divided between non-combustible mineral wool and more thermally efficient polymeric insulation.

3. Fire Engineering of Façades

There are issues with some of the construction industry's current approach to façades. Fire safety engineering is often not consulted during the design and construction of a building's façade, suggesting fire safety is not always a priority. Even when fire safety engineers are consulted, the current reliance on product testing can potentially lead to oversight.

As an example, in the UK currently, a façade system can be used on a building if it passes a large scale façade test (BSI, 2015a, 2015b). However, if a façade contains combustible components that have been previously tested on a similar system and then evaluated by an independent assessor (a professional judgement) in the new configuration, then the system might be approved for use without being tested. These so called 'Desktop Studies' assume without proof or in-depth analysis two important things: a) that the same façade components will behave similarly in any scenario, and b) that there is a rule (or theory) allowing for interpolation or extrapolation between tested façade systems. These two assumptions are incorrect, and have no scientific basis. Without further research, Desktop Studies are an art that cannot be relied upon, especially in the case of safety.

Even when a large scale test is performed, it is currently done on a perfectly constructed system. In reality, the system put on the building may have had certain components swapped out on site, or may have parts installed incorrectly. These could change the system's behavior from the tested case. It is also not clear that these large scale tests accurately represent a realistic fire scenario (ABI, 2018).

It is therefore essential to understand the potential fire behavior of different façade systems, and to quantify how different materials, and their configuration within a façade system, will affect the flammability of that system. With this in mind, in the next section, we discuss the fire behavior of various façade systems using idealised sections of such systems. Although these abstractions are not perfect representations of a real façade, each one focuses on the essential elements in a façade system.

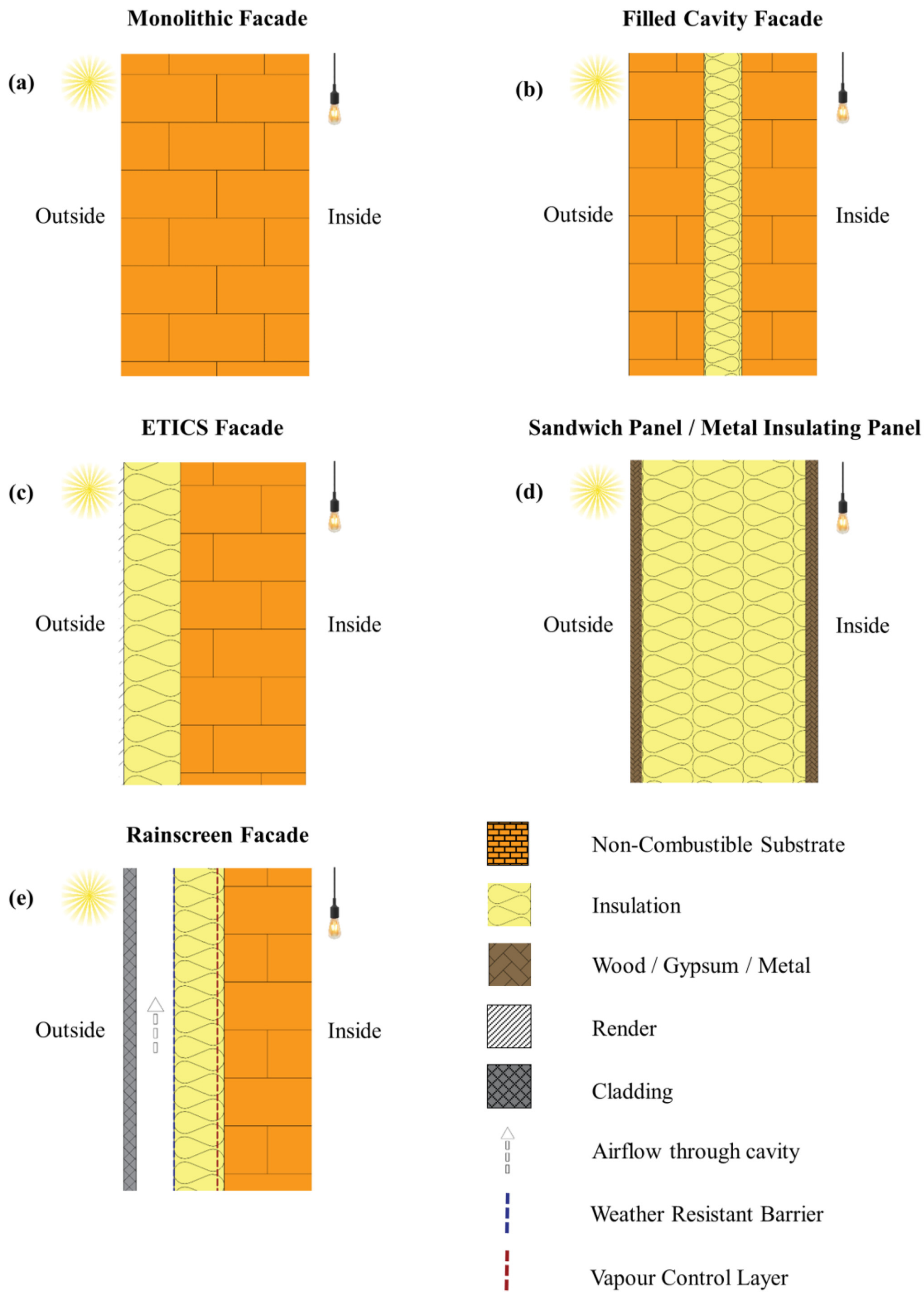

Figure 5. Simplified sections of common façade systems: (a) Monolithic Façade, (b) Filled Cavity Façade, (c) External Thermal Insulating Composite System (ETICS) Façade, (d) Sandwich Panel (or Metal Insulated Panel), (e) Rainscreen Façade. Note: The vapor control layer and weather resistant barrier in (e) are shown on the warm side of the insulation, for a climate that has an annual desire for vapor to flow from inside to outside.

4. From Simple to Complex Façades

This section provides an introduction to the fire hazards present in different façade systems, and suggests that as the complexity of a façade system increases (which is what has happened in real façade systems over time), the potential for a flammable façade system also increases. Each subsection focuses on a different façade system, shown in Fig. 5, and each section is ordered by increasing complexity (from simple to complex).

4.1. Monolithic Façades

This façade system is the simplest, and is made from a single layer of non-combustible material. This could refer to a simple concrete or brick masonry wall, or a glass façade system, such as a glazed curtain wall. Hollow brick masonry walls have been studied experimentally and numerically (Nguyen & Meftah, 2012, 2014; Russo & Sciarretta, 2013) and the main hazards they present in fire are loss of mechanical performance (though façades are often non-loadbearing) and the possibility of spalling. These papers found that spalling was the main cause of loss in mechanical performance. Spalling also produces falling debris, which could harm people standing in the vicinity of a building.

The main hazard presented by glass façades is shattering due to the heat of a fire, which can increase the size of a compartment fire by increasing ventilation and also allow the aforementioned "leap-frogging" of a fire to occur between floors. As such, the majority of fire research into glass façades explores this phenomenon. Many types of glass fixings have been tested (Manzello et al., 2007; Y. Wang et al., 2014, 2017), and numerical models have been built to try to predict the onset of cracking or pane fallout (Nam et al., 2017; Q. Wang et al., 2014). These models suggest that the main factor affecting when cracking occurs is the temperature difference across the glass, as well as the number and location of fixings.

These systems may contain small amounts of combustible material, for instance, combustible insulation in the connecting frames in a glazed curtain wall. However, in terms of flammability, these systems pose a small hazard, as the total fuel load is likely to be small, and often without large connected areas of combustible material that flame could spread along. These systems though, are unlikely to achieve the more stringent energy efficiency requirements of modern facades with just a single material. Therefore, systems with additional complexity are needed.

4.2. Insulated Façades

These façade systems have a layer of insulation protected by two layers of usually non-combustible material that in some cases can limit heat transfer to the insulation. This insulation might not be combustible, and may have a range of heat transfer properties. If it is a combustible polymer insulation, it may char and produce pyrolyzates (for thermoset polymers), or it may melt and evaporate (for thermoplastic polymer). The properties of common insulating materials are explored in (Hidalgo et al., 2017), and the choice of these materials will affect the flammability of a façade system, with thermoplastic polymers being, in general, the most flammable.

4.2.1. Filled Cavity Façades

The filled cavity façade has a layer of insulation between two protective layers of material that prevent flames directly impinging on the insulation. This could represent a filled masonry wall, or perhaps pre-cast concrete walls with a filled cavity. These façade systems would more often be used on a low-rise building. In the case of filled masonry walls, if gaps are limited enough to prevent direct flame impingement, then flame spread along the insulation layer is likely to be limited (Rogowski, 1985). However, thermoplastic insulation, such as expanded polystyrene (EPS), can melt upon heating and form voids, increasing the rate of flame spread. Alternatively, the burning plastic could drip through gaps in the wall, providing more fuel to the fire or igniting new fires further down the façade.

In (Hidalgo, 2015; Hidalgo et al., 2015) the authors argue that the most important parameter in evaluating the flammability of these systems is the depth of the protective layers. The deeper the outer layer, the longer it will take for the insulation to heat up and then pyrolyze or melt (Incopera et al., 2013). By controlling the depth of these layers, it is therefore possible to limit the time at which substantial amounts of pyrolyzates may be produced, a characteristic that may determine the flammability of these façade systems (Hidalgo et al., 2015).

4.2.2. ETICS Façades

ETICS façades – standing for External Thermal Insulation Composite Systems – have a thin layer of render, approximately 2~12 mm (Afipeb et al., 2016; Bjegovic et al., 2016; Kotthoff et al., 2016), protecting the insulation from fire. Such a thin layer of protection can be breached more easily than the thicker masonry or pre-cast concrete walls, potentially allowing direct impingement of flames onto the insulation. Flame spread via this insulation is, therefore, much more likely than in the filled cavity façade. This is backed up by large-scale experiments performed on ETICS façades, which found flame spread along even perfectly built constructions (Hajdukovic et al., 2017). The recommendations from these findings are to add fire barriers to combat the increased fire hazard (Bjegovic et al., 2016; Kotthoff et al., 2016): layers of non-combustible material designed to limit the spread of flame along a combustible surface. However (Zhou et al., 2016) found that in a large enough fire (2 m height of façade panels burning already) even the thickest fire barriers they tested (mineral wool extending horizontally along the façade width and across 40 cm of height), could not prevent further flame spread. The destruction of the outer render can also allow burning droplets of thermoplastic insulation to fall, potentially igniting fires further down the façade.

4.2.3. Sandwich Panels

Sandwich panels, sometimes also referred to as Metal Insulated Panels, are another system where a layer of insulation is surrounded by two protective layers. For industrial facilities, these outer layers are usually made of some kind of metal to provide an inert and easily cleaned surface. For low-rise residential buildings, these outer layers can also be made of plywood, gypsum, or cement board (Allianz Risk Consulting, 2015; White & Delichatsios, 2013). These outer layers are often very thin (about 0.5 mm for metal insulating panels, 10 mm for wood or gypsum panels). If the insulating core of the panel is combustible, then there is a significant risk of it igniting and contributing to a fire.

Of particular concern are the connections and joints between individual panels. These represent a weak point of the panels and is recommended as a point of focus in industrial reports on safely using sandwich panels (ABI, 2003; Cooke, 2000). It is also where much of the academic research is focused. A recent paper by (Crewe et al., 2018) demonstrated how potential damage to sandwich panels, which can occur during transport or construction, increases their flammability, and the numerical study by (Y. C. Wang & Foster, 2017) found that a larger joint gap between panels increased the mass loss of the insulation within the panels significantly. The thesis of (Foster, 2014) also found that larger gaps reduced the fire resistance time of the panels, and suggested reducing the gap size with intumescent strips.

4.3. Rainscreen Façades

As previously mentioned, moisture control in façades is of critical importance during their design (Table 1). One common way of making sure moisture doesn't get trapped in a façade is to include an air cavity, creating a ventilated façade system. Due to pressure differences between each side of the outer wall of the cavity, air flows constantly through it, allowing the water to evaporate and be carried away from the porous insulation. Unfortunately, the addition of an air cavity increases the flammability of a façade system if it contains combustible material.

The most common type of ventilated façade system in high-rise construction is the rainscreen façade, where a layer of opaque material (the rainscreen) is used as the outer wall of the cavity to protect the insulation from adverse weather conditions and provide a decorative finish for the façade. This outer layer is usually referred to as cladding and can be made of many different materials, including metals, ceramics, or polymers. In the latter case this cladding could contribute to fire spread. Therefore, there are two main factors differentiating the rainscreen façade in terms of flammability, the cladding and the air cavity.

The effects of a cavity on fire dynamics have been documented for a long time (Babrauskas, 2018; J. Kim et al., 1974). Qualitatively, three factors enhance flame spread in a cavity vs. a simple vertical surface: radiation being enhanced by the cavity, increased upward spread from the chimney effect (where temperature differences inside and outside of the cavity drive increased upward flow through the cavity), and a decrease in the amount of convective cooling from external air. This has the effect of extending flame heights in a cavity (Colwell & Baker, 2013) and makes the ignition of any combustible materials in the cavity easier (Babrauskas, 2018), which increases the flammability of the façade system.

The sensitivity of these factors to the width of a cavity was quickly realized by researchers. The effect of cavity width on the level of heat flux impinging on a wall was studied first in the 1990s in the context of warehouse fires (Foley & Drysdale, 1995; H. Y. Wang et al., 1999), and again more recently in the context of ventilated façades (Lacasta et al., 2013; Livkiss, et al., 2018). These studies found that the heat flux on parallel walls increases with a smaller distance between them, and that flame height is extended through the cavity. However, line burners were used in these experiments to release heat into the cavities, which resulted in an amount of heat independent of the cavity width (which was greater than the width of the line burner). The authors hypothesize that in a real fire a larger cavity width could mean that more hot air and flammable gases are drawn into a cavity, and would therefore increase the amount of heat within the cavity.

Fig. 6 illustrates this hypothesis with plots showing how the heat release rate into the cavity (influenced by the chimney effect) and the heat flux on the walls of the cavity (influenced by the enhanced radiation) are dependent on the cavity width. These competing effects come together to affect the flammability of a particular system. The authors hypothesize that there is an optimum cavity width at which the two effects converge to minimize the increase in flammability caused by the cavity, however this would be different for different fire conditions.

The effect of the cladding on the flammability of the façade system will depend on what materials are used. In many recent fires, the cladding consisted of flammable aluminium composite panels (ACP) (Wahlquist, 2017). These panels consist of two sheets of aluminium laminated to a plastic core. This plastic layer reduces the volume of aluminium needed to achieve the same structural performance, but also increases the flammability of the panel. This flammability can be reduced by increasing the mineral content within the plastic layer. There are a range of ACP products available on the market, containing cores ranging from 100% plastic to around 10% plastic, with the rest of the core made from minerals and fire retardants (NFPA and Arup, 2018). Other metals can be used in place of aluminium too, such as copper or zinc. An increasing concern of flammable cladding is leading to increased research into ACPs and similar materials, yet so far published studies are limited. A report by (Agarwal, 2016) found that some setups using ACP that passed the UK large-scale fire test did not fare well when subjected to more intense heating conditions, potentially closer to a real fire scenario. Meanwhile, the paper by (Guillaume et al., 2018) performed intermediate-scale experiments on systems with plastic and mineral cored ACP and with different types of insulation and found that the results of the test were mainly dependent on the type of ACP used.

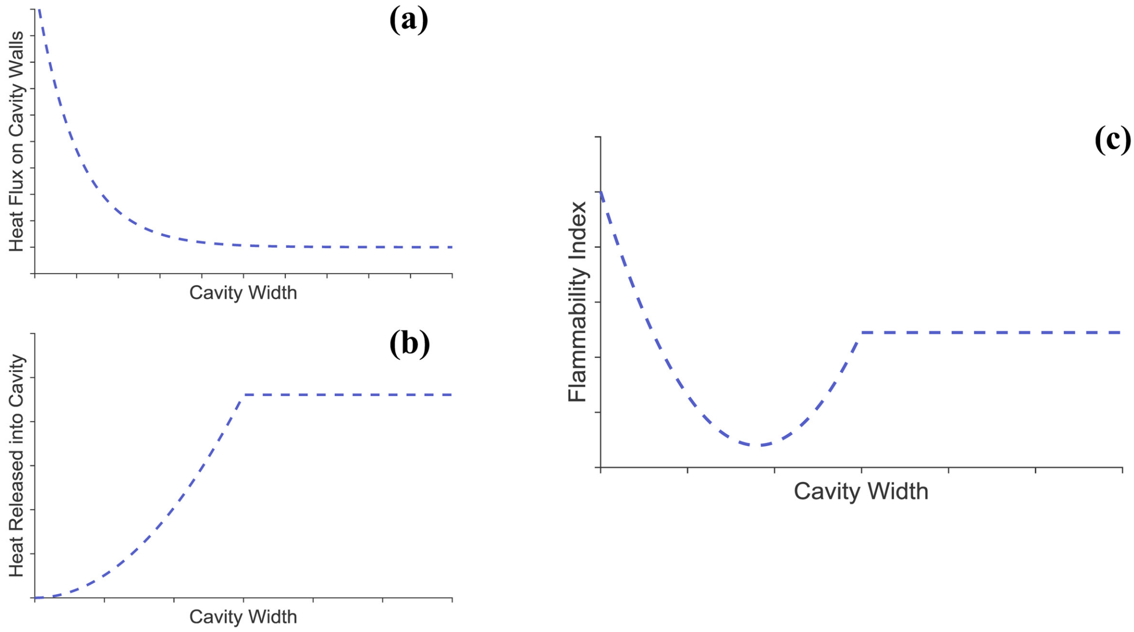

Figure 6. Plots illustrating how cavity width could hypothetically affect: (a) the heat flux on the cavity walls (radiation enhancement), (b) the heat released into the cavity (chimney effect), and (c) the total flammability (combination). The "flammability index" plotted in (c) is a hypothetical variable that quantifies the flammability of a facade. Currently, no such variable exists, but our research aims to create one.

High Pressure Laminate (HPL) panels are another type of cladding that can contribute to fire. These panels consist of layers of cellulosic fibers (similar to paper) impregnated with phenolic resin. They are lightweight, weather resistant, and can be printed with almost any design, but are also flammable. Their fire performance varies with their thickness and the adhesives used (International Commitee of the Decorative Laminates Industry, 2009) however, so far, no independent research has been conducted into these materials.

When employing these systems in colder and wetter countries, the insulation is often also protected by a weather resistant barrier (WRB): a polymer mesh that allows water vapor to pass through and leave the insulation, but prevents liquid water from entering. These WRBs are always made of plastic, and can therefore ignite. This increases the flammability of the façade system, however, as far as the authors are aware, no published research into their fire behavior as part of a façade system is available.

The addition of a ventilated cavity, cladding, and a weather resistant barrier offers superior moisture protection to the previous types of façades, while remaining thin and thermally efficient. However, the flammability of these systems increases. This type of system is the most complex in Fig. 5, the most modern, and also the most flammable. Notably though, these discussions about the cavity were of idealizations of real systems. In a real system cavity barriers and fire stops are usually required to be installed. These can help to limit fire spread through a cavity, though the installation of these barriers, as well as other elements of the system, is not always perfect and can create further challenges to fire protection.

4.4. Openings, Fixings, and Interfaces

The systems in Fig. 5 are simplified, and in reality would need to be fixed onto a building's structure. The method of how these systems are fixed adds complexity to the problem. Glass curtain walls were mentioned in the section on monolithic façades, but in reality the opaque areas between layers of glass have insulation in them, and the systems are often fixed so that there are voids and cavities present too. (Colwell & Baker, 2013) also mentions how railing systems could lose integrity and cause parts of the façade to fall. These problems are currently not being tackled in the research.

Different areas of a building can have different façade systems. These systems connect, leading to additional complexity at the interface. This scenario has not yet been studied from a research perspective, but is also not considered in safety tests for façades, which test each façade system individually, rather than seeing how they interact together.

The geometry of a façade can differ from the straight vertical walls shown in Fig. 4, and present different fire behavior. (Lay, 2007) notes how a convex sloped façade could trap hot gases from an external fire and experience more severe fire conditions, while (An et al., 2017) found that a concave structure increased vertical flame spread along EPS insulation. Therefore, it seems any deviation from the vertical case has the potential to increase the flammability of a façade, yet our understanding of other geometries and orientations is limited.

Real façades contain windows and openings to allow air and light into the building. Currently, there has been a large body of research detailing how the geometry of an opening will affect the nature of fire impinging on the façade from a compartment fire, which has been reviewed by (Asimakopoulou et al., 2017). However, there is no research into how installing a window changes the flammability of a façade system. Gaps in protection around a window may make the system easier to ignite, or plastic elements used in the window itself could present a problem. The areas where the complexities of construction deviate from idealised design are likely to be one of the weakest points of the façade from a fire safety perspective, but so far there is little research into what problems they may pose.

4.5. Other Façade Types

Not all façade systems have been presented in Fig. 4. Double-skin façades are one example, where two layers of glazing are separated by a large cavity. The cavity here is much larger than in a rainscreen system, and it exists to limit heat transfer and control light levels, rather than for moisture control. As there are very few combustible materials present, this façade system does not pose the same hazards to flame spread as the other systems. However, it can provide a channel for enhanced smoke spread between floors, and the physics of the heat and mass transfer has been studied (C. Chow, 2014; W. Chow & Hung, 2006; Ji et al., 2016).

Another façade system increasing in popularity is the green façade. These are composed of a wall of vegetation growing through a reinforced mesh or growing out of some kind of substrate, which is commonly made of a combustible polymer. Although there is very little formal research into this type of façade, the current fire safety strategy is concerned with making sure the plants do not dry out, and that the types of plants used are generally more difficult to burn (DCLG, 2013).

Finally, there is the rise of photovoltaic or solar façade systems, which use solar cells to generate additional power for the building. These cells pose an ignition hazard to combustible materials within a façade system. To date, there is little published research on the fire behavior of vertical solar panels available, but there is movement towards establishing safety strategies and test guidelines for these façade systems as they increase in popularity (Mazziotti et al., 2016).

5. Quantifying Flammability

It can be seen in this body of research, presented in the previous section, that the current research into façade systems gives only a partial understanding of how different elements of these systems behave during fire, such as the cladding (ACP), insulation, or the effect of a cavity. There are also basic qualitative studies into large scale systems, but the conclusions are broad, and the experiments are too few to make definitive claims. What is missing is an understanding, or body of theory, of how different elements of a façade system interact with each other, and what parts of a façade system will be more important in determining the flammability of that system as a whole.

While exact prediction of ignition and flame spread in façade systems is probably a long way away, the potential to quantify the relative flammability of these systems is achievable. (Hidalgo, 2015; Hidalgo et al., 2015) proposed quantifying the relative flammability of an insulation material as the temperature at which its rate of pyrolysis peaks, and then extended this to the flammability of a larger system by calculating how long heat transfer would take through different thermal barriers to protect the insulation. This is a simple system, but such approaches could be extended. Recently, NFPA released a tool that ranked the perceived fire risk to buildings with façades containing combustible components, in order to prioritise work on said buildings (NFPA and Arup, 2018). It is possible that their approach of collating expert opinion could be extended to a more specific quantification of this perceived risk.

The advantage of quantifying the relative flammability of these systems comes in the form of optimization. Optimization methods are ways of finding points of maxima and minima in usually complex and non-linear functions. If a particular design objective can be quantified as a function, for instance the desire for a façade to be as thin as possible, then optimization can be used to find a design that maximizes that objective within certain constraints – in this case finding the thinnest possible façade that still meets the requirements for thermal performance. The function used to quantify a particular objective is called an *objective function*, and the point where it is maximized or minimized is the *optimal solution*.

In cases where multiple objectives need to be maximized, multi-objective optimization can be used instead. Here, optimization will try to find permutations of a design where, across multiple objective functions, at least one objective cannot be improved, which can be difficult, as often improving one objective may impair another. These particular designs where an objective cannot be improved are referred to as *Pareto optimal* solutions, and if enough of these solutions are found then it is possible to plot these on a graph comparing the two objective functions as a *Pareto front*. It is then possible for different parties involved in the design to choose a particular optimal solution from this front, based on how important each objective is.

The advantages of multi-objective optimization in design have been laid out by (Evins et al., 2012), and it is an

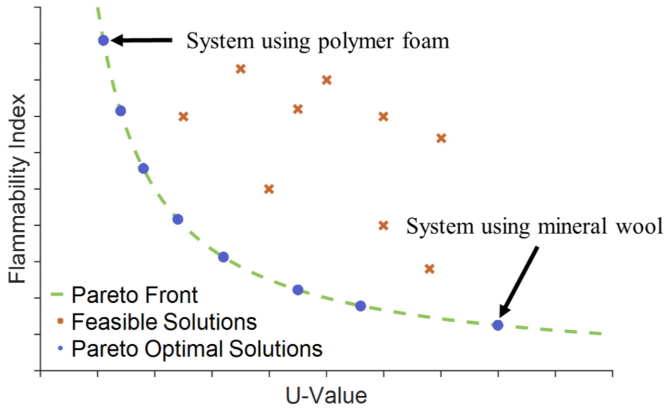

Figure 7. Example of a Pareto front, minimizing flammability vs. U-Value. Each solution represents a particular façade system design. Crosses represent solutions that are feasible, but not optimal. Labels show where hypothetical systems using polymer foam or mineral wool insulation might fall. The "flammability index" plotted in (c) is a hypothetical variable that quantifies the flammability of a facade. Currently, no such variable exists, but our research aims to create one.

approach that has already been applied to the problem of façades (J. Kim, 2012; Shan, 2014). Looking at the objectives in Table 1, it is clear that façades are a multi-objective problem, and an optimization approach could improve modern façade design. Fig. 7 demonstrates a hypothetical Pareto front of solutions trying to minimize the U-Value and the flammability of a façade. Designers could pick the solution that best reflects what is demanded by the project. For a small building in a cold country with a low-risk of fire and multiple escape routes, one might pick the minimum U-Value without regard to flammability, while for a high-rise residential building a solution that scores lower in flammability would be required.

This approach to design is referred to as *Optimum Design* (Arora, 2004). It is an approach where designers can be certain that they have chosen a design that is close to optimal in some regard, and one where a large focus must be put on the choice of design objectives. While fire safety is only one factor affecting the design of façade systems, a process that encourages a deeper consideration of the interaction between all possible design objectives (Table 1) would be a step in the right direction, and one that we are beginning to move towards.

6. Conclusions

With increasing numbers of façade fires occurring worldwide, understanding the flammability of high-rise façades has never been more important. The complexities of façade design, where many different objectives need to be considered, require a balanced design approach. By looking at the flammability of common façade systems, it is clear that as these systems have become more complex over time, so too has their flammability increased. Unfortunately, the increased complexity of the problem has not been followed with an increased body of research, and many key aspects of façade flammability are not well understood. This is particularly true in regard to the additional complexities of constructing a real façade – how these systems behave when they are damaged, or include additional fixings and openings.

By quantifying flammability alongside other façade design objectives, a new approach using multi-objective optimization can be taken to façade design. In taking such an approach, not only would a near optimal design solution be guaranteed, but it would also make sure that fire safety is always considered as an integral part of the design process.

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