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Brandforsk

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The official project report, to which reference should be made, can be found on the LTH´s website.

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A holistic approach for fire safety requirements and design of facade systems

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Abstract
Recent trends with respect to energy consumption demands have increased the use of innovative façade systems both for new construction and building renovation projects. Different types of façades systems are used in order to achieve these requirements. Many of these systems are very complex and have not only fire requirements to fulfil but also other requirements for humidity, rain protection, stability, thermal insulation etc. Also, socio-technical aspects play an important role. The overall objective of this project is to address the fire safety requirements on external façades systems through a technical holistic approach of façade systems and from a socio-technical perspective. Specific objectives are to identify the research gaps and research questions which need to be addressed in order to safeguard the fire safety of new and renovated buildings. The outcome of the project is a confirmation that considering the technical requirements a full holistic view is necessary at system level. Functional requirements for all different type of façade systems need to be further developed to complement or improve the prescriptive requirements. It is also clear that further research should be conducted by means of e.g. detailed analysis of existing system, further development of harmonised full-scale test for prescriptive solutions, optimising tests for use in advanced modelling, extension of existing risk models and further socio-technical studies.

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Preface

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Lund, January 2020.

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Michael Strömgren

Brian Meacham

Sammanfattning

De senaste trenderna när det gäller energiförbrukningskraven har ökat användningen av innovativa fasadsystem för både nya byggnader och renoveringsprojekt. Olika typer av fasadsystem används för att uppnå dessa krav. Dessa nya innovativa fasadsystem har dock flera byggnadstekniska funktioner och det är viktigt att beakta alla dessa vid valet av system. Därför är ett helhetsperspektiv nödvändigt. Samtidigt krävs det systemtänkande där teknik och sociotekniska aspekter spelar en viktig roll.
Det övergripande målet med forskningsprojektet är att behandla brandsäkerhetskraven på externa fasader system genom ett tekniskt helhetsperspektiv av fasadsystem, med beaktande av alla andra tekniska krav i systemen och ett helhetsperspektiv på byggregel- och kontrollsystemet. Särskilda mål är att identifiera de forskningsbrister och forskningsfrågor som behöver åtgärdas för att skydda människor och brandsäkerhet i moderna och renoverade byggnader.
Resultatet av projektet är en bekräftelse att en helhetssyn på systemnivå är nödvändig med tanke på de tekniska kraven som krävs. Funktionskrav för alla olika typer av fasadsystem måste utvecklas vidare för att komplettera eller förbättra de föreskrivande kraven. Det är också klart att ytterligare forskning bör genomföras i följande område: metoder för att kunna göra en detaljerad analys av befintliga system, vidareutveckling av harmoniserade fullskaliga provningar, optimering av provningarna som behövs i avancerad modellering, utvidgning av befintliga riskmodeller och ytterligare sociotekniska studier.

Contents

1. Introduction

1.1. New innovative façades systems (adapted from Van Hees et al. 2019)

In recent years, energy consumption demands have increased the use of innovative façade systems both for new construction and building renovation projects. This is a natural result of the fact that buildings constitute approximately 40% of the energy consumption in Europe (EU 2017a), and that adequate thermal insulation of buildings is an important component in support of the energy performance goals as set out in the Energy Roadmap 2050 (EU 2017b). This is largely due to the fact that façades can be a major source of heat transfer between the building and the environment, and as such, improvements in the insulation properties of façade systems can result in significant energy savings for new and existing buildings. This is valid both for winter and summer conditions (heating or cooling).

New buildings aside, it has been shown that the greatest potential for energy reduction can be obtained by decreasing the energy losses in existing buildings (EU 2017a). For this reason, numerous building renovations projects have been started, and research into building insulation systems has grown. One example of building insulation research in Sweden is the SIREN project (Sustainable Integrated Renovation) (Mjörnell 2019), which was initiated within SBU (Swedish Building University). Another example is the BERTIM project (Lasarta et al. 2017) dealing with prefabricated modules for renovation of façades. In the USA, fire performance of façade systems has gained attraction in recent years (White and Delichatsios 2014, Meacham et al. 2012, Meacham 2016), and in Spain, the University of Navarra recently completed a 3-year study on insulation of existing public housing, which included consideration of fire safety issues (Sanchez Ostiz et al. 2014). The above-mentioned SIREN project, however, is only dealing in a very limited manner with the fire problem of renovation projects.

Looking first to the energy performance issue, one of the solutions to improve the façade properties is referred to as ETICS (External Thermal Insulation Composite System) as can be seen in Figure 1 (EA-ETICS 2017). ETICS are often using an insulation material fixed to the wall structure (e.g. concrete) and then covered with a reinforced cement-based material of synthetic finish and plaster. ETIC systems designed on a wooden structure and used in so called one-step façade systems (unventilated façades) have had numerous of moisture problems both in North America and in Sweden (Samuelsson and Jansson 2009).

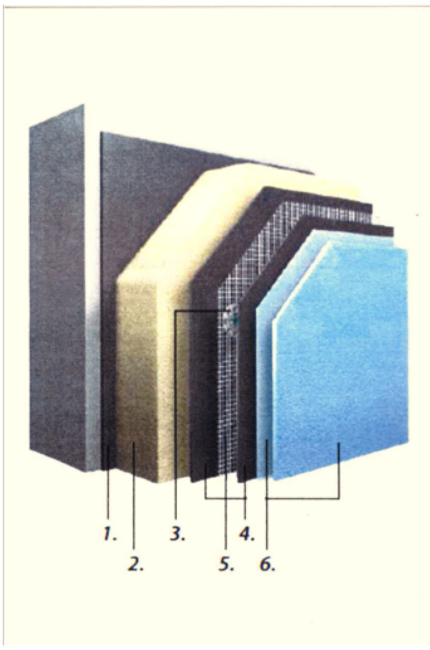

Figure 1 Example of an ETIC system (adapted from EA-ETICS 2017)

Legend to Figure 1:

1. Adhesive
2. Thermal insulation material
3. Anchors
4. Base coating
5. Reinforcement, usually glass fibre mesh.
6. Finishing layer

The system illustrated in Figure 1 is largely focused on insulation properties, but there are also other external wall insulation systems, like external cladding wall systems, that can integrate rain protection made of decorative panels (glass, ceramic boards, composite panels, wood, stone) and/or alternative energy sources, such as solar panels. The cladding systems may also include air gaps, attachment systems, reinforcement layers, different kind of insulation materials, wind protections, rain protections, etc. Examples of such complex systems can be seen in Figure 2.

Figure 2 Example of a complex rainscreen façade systems (picture courtesy ID 44710574 © Antikainen | Dreamstime.com)

1.2. Fire Risks of façades (van Hees et al. 2019).

As the complexity of insulated façade systems increase, so too might the fire risk increase, especially when combustible components are involved. Previous research and recent fires, e.g., the fire in Dubai at New Year's Eve 2015 and the Grenfell Tower fire in 2017 (Ministry of Housing 2017a) have shown that fires involving the exterior of a building should not be neglected (Peng et. Al. 2013, Wade and Clampett 2000, Wade 1995, BRE 2003, Yoshioka 2012, Messerschmidt and Fellmarn 2013, White and Delichatsios 2014, Feuerwehr Frankfurt 2014, Meacham et al. 2012). When considering façades and curtain wall systems, different types of hazards/risks can be considered (van Hees 2000, van Hees 2016a). One reason is the fact that new and innovative complex systems are introduced in new high-rise buildings, such as advanced rainscreen cladding solution and newer innovative ETICS (External Thermal Insulation Composite Systems) resulting in part from demands on better thermal insulation in new buildings as well as in high on-sight productivity in case for e.g. renovation projects. German industrial enterprises also have experienced problems in finding insurance coverage (Kothoff and Riemsch-Speer 2013) as the insurance companies are not willing to assume the risk due to combustible building insulation in some systems.

Responses such as the above illustrate that the fire problem is important. This raises many concerns, especially since several countries have started large renovation projects using also ETICS and on-site cladding systems in order to obtain the required thermal resistance insulation values on the outside of the building, without necessarily considering the fire performance aspect (Kothoff and Riemsch-Speer 2013).

With respect to fire hazards and risk, the first issue of concern is the type of thermal attack, or fire source to be considered (van Hees 2000, Van Hees 2016a, White and Delichatsios 2014). This thermal attack can be divided into the following four main types: fire inside of the room, fire inside of a room and outside of a window, fire at the exterior of the building close to the façade (e.g. container fire), and fire from a neighbouring building. Along with the different types of fire sources, different cases for fire spread can be distinguished as well, each presenting different hazards or risks. An overview of four different fire spread hazards/risks on the same building is given below in Figure 3 to Figure 7. The specific case of spread between buildings is not considered here.

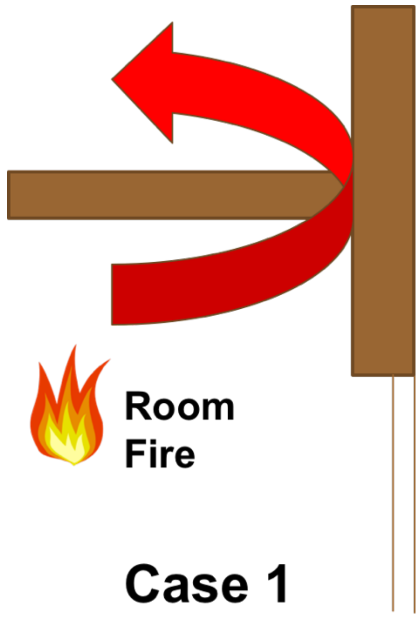

Figure 3 Cases of typical hazard/risk involving a façade. Case 1 (Reproduced from van Hees 2000)

Case 1: In this case the fire risk is associated with the penetration of the fire through the floor-façade system connection from one level to another level, e.g. via the joint between the floor and façade systems when a fire occurs inside a room. This type of fire spread hazard/risk is generally linked to the evaluation of the fire resistance of a specific system or in specific large-scale tests such as the French LEPIR test (LEPIR 2016).

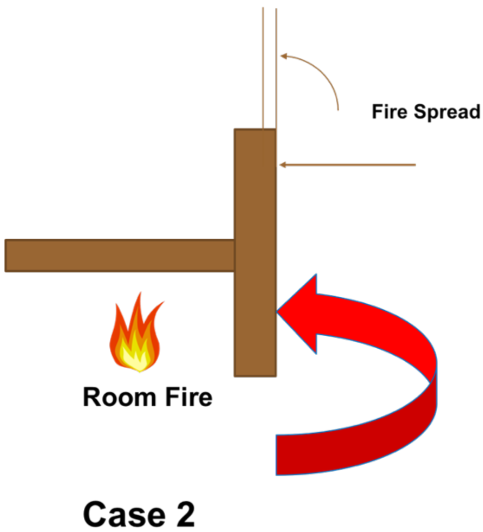

Figure 4 Cases of typical hazard/risk involving a façade. Case 2 (Reproduced from van Hees 2000) Upper part is a window.

Case 2: This case is representative when a fire occurs in a room and the flames exit the window, exposing façade material or openings above. This reflects a risk of penetration of the fire through the façade system, the glazing on the floor above, or unprotected openings on the floor above. This can occur even when joints between floor and façade systems are adequately designed to address the risk discussed in Case 1. As in Case 1, most of the risk can be covered by fire resistance tests for Case 2, along with regulation regarding the distance to adjoining parts of the building, other buildings, or between windows (see Case 2b, Figure 3). An example is given by Johansson (Johansson 2015).

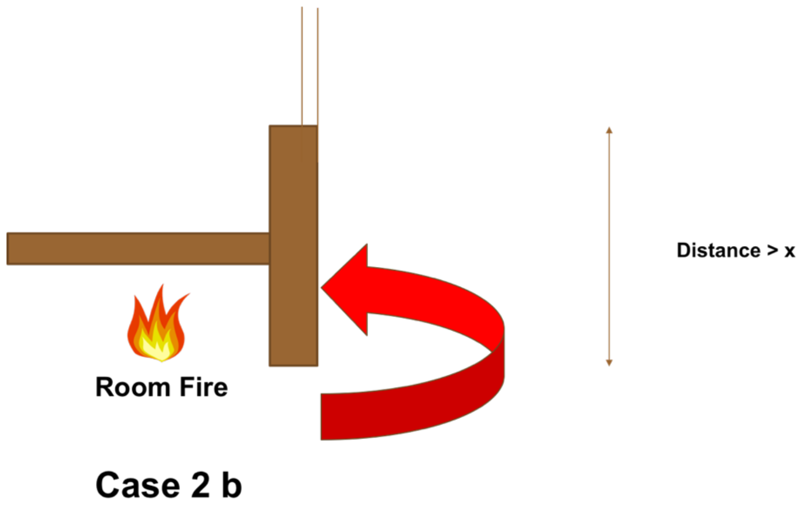

Figure 5 **Cases of typical hazard/risk involving a façade. Case 2b (Reproduced from van Hees 2000)**

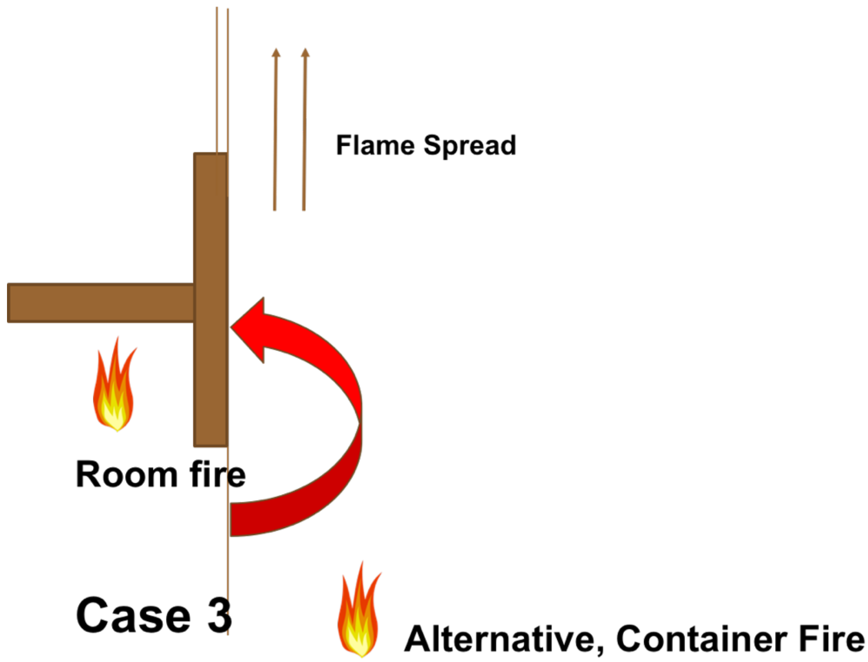

Figure 6 **Cases of typical hazard/risk involving a façade. Case 3 (Reproduced from van Hees 2000)**

Case 3: This case is representative of a fire that extends outside of the window, or is present at the exterior of the building (container fire). Here, there is a considerable risk of fire spread on the façade surface, or through the void between façade and building, if combustible materials and/or adequate void space exists. In this case the reaction to fire properties of the materials used for the façade system (i.e., cladding, insulation, rain screen, etc.) must be considered, and is an important factor, together with the possible ventilation condition in the void of the façade system.

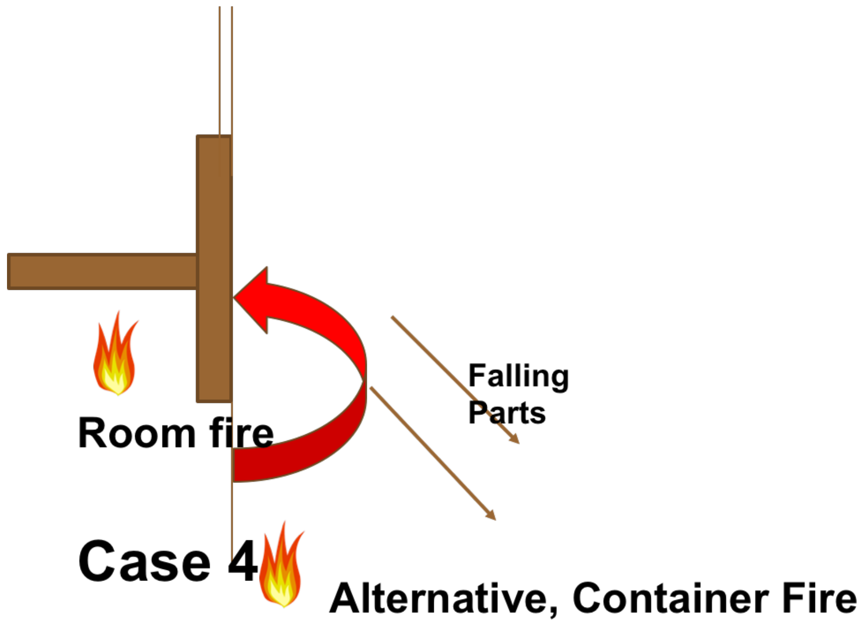

Figure 7 Cases of typical hazard/risk involving a façade. Case 4 (Reproduced from van Hees 2000)

Case 4: This case is representative of a fire which ignites adjacent material through a window, or as a result of an exterior fire on the façade of the building. However, in this case it is important that no major parts of the burning façade are falling down from the building, as this would endanger the work of the rescue teams and also cause problems for evacuation of the building, as well as spreading the fire downwards.

The case of spread between buildings is a specific case and is not part of this overview which is limited to spread on a single building. However, it should not be neglected.

As part of a comprehensive fire hazard/risk assessment, each of the above four cases need to be considered, and may require different type of testing and/or regulation, either from a prescriptive or a performance-based approach. Of the above type of risks, Cases 1 and 2 were thought to be rather well handled by fire resistance tests and by regulations regarding distance between floor levels. However, the recent fire in London showed that fire spread towards the inside of the building still can occur (Ministry of Housing 2017c), as has been observed in past fires, such as the 2005 Windsor Building fire (Meacham 2016).

For the surface fire spread and falling debris risk, Cases 3 and 4, testing is still less developed (van Hees 2000, White and Delichatsios 2014). Information on testing can be found in the recent conducted study on full scale test methods (Boström et al. 2019). In some countries, fire tests nominally used in prescriptive regulations for these scenarios were developed for fire spread on interior wall and ceiling linings (surfaces). However, this is not a suitable or correct approach (van Hees 2013, Stromgren et al.

2016) as it leads to incorrect evaluation of the fire risks, since the fire scenario is completely different.

Façade systems are very complex systems composed of different products and materials – that is, they are not singular materials with single concerns, such as surface flame spread – and there is need for a holistic technical approach (Van Hees 2016b). The interaction of components, for example, certain rain shields and insulation materials, needs to be investigated as a whole and not on component level. Much more know-how is needed. This can be seen with respect to intentional and unintentional air paths in the wall, for example, with respect to how these paths change in case of fire, due to damage, collapse of the wall structure, and other reactions. Any exchange and changes of one material or product to another within the façade system can be devastating as apparent in the recent Grenfell fire (Ministry of Housing 2017b). Furthermore, other innovative systems, such as the integration of solar panels into façade systems, presents the potential for combining a source of possible ignition (e.g., electrical sparks) with potentially combustible cladding and insulation, which can result in a fire. Only by considering the exterior system as a holistic system can this problem be addressed.

Recently, the EU started a process to harmonise the fire test standards and classifications for façades throughout Europe, as there is a large number of national and regional test standards (Smolka et al. 2013, DIN 2009, CAN/ULC 1992, SP 1994, Önorm 2003, BS 2015a, BS 2015b, LPS 2010a, LPS 2010b, LEPIR 2016, NFPA 2012a, NFPA 2012b, ISO 2001a, ISO 2001b) which limits cooperation on an international level. In Sweden, for example, the SP-FIRE 105 test (SP 1994) is used. Before implementation of a new system of standards, the implications with respect to the Swedish regulations need to be assessed. The challenge, however, is that the different large-scale tests are covering limited and specific cases (Macdonald 2012) and general application of them can be problematic. Alternatives are of course possible by performance-based approaches. Due to the complex construction of a façade, the knowledge on predicting and modelling of a possible façade fire is limited and needs further development. Most advanced modelling is for simpler solid materials (Janssens et al. 2003) although recent work will be listed in this report. More knowledge is indeed needed to extend the experience of fire safety engineering within a performance-based approach (Mikkola et al. 2013, Didieux 2013) for these complex systems (Zehfuß et al. 2016, Meunders et al. 2012, Asimakopoulou, 2013).

1.3. Managing risk in building regulatory systems (van Hees et al. 2019)

As Otway (Otway 1985) so clearly stated, "the risks to which society is, in fact, exposed are largely determined by the regulations and how effectively they are implemented and enforced." While humans have used regulation to help prevent hazards from impacting people for centuries, the explicit recognition and use of risk in regulation is a relatively new concept. The impetus to incorporate quantified values of risk in regulation resulted from health and safety concerns which became publicly intolerable in the late 19th and early 20th centuries, and by the seminal work of Starr (Starr 1969), who posited that historical national accident records are adequate for revealing consistent patterns of fatalities in the public use of technologies, and that such historically revealed social preferences and associated costs are sufficiently enduring to permit their use for predictive purposes (Meacham and Van Straalen 2017). The move to incorporate risk into regulation was further facilitated by the formalization of risk analysis as a discipline in the late 1960s and 1970s. Risk as a basis for regulation has worked its way into a broad range of regulated areas, including environmental protection, occupational health and safety, nuclear power, transportation, structural performance of buildings and physical infrastructure, hazardous facility planning, finance and more (Meacham and Van Straalen 2017).

However, while risk is often the basis of regulation, it is not always explicitly quantified. When quantified criteria are sought, there are a number of complicated factors which materially affect the identification, implementation and certainty of quantified risk criteria and the associated application of risk-informed and risk-based design respectively. Risk is not uniformly understood and characterized within or across disciplines, large differences in perception can exist between experts and the lay public, and implementation into law can vary widely by jurisdiction. As such, even if a common characterization of risk can be developed within a specific area and methods of quantification and assessment are agreed by experts, the acceptance by the public and politicians may vary widely between jurisdictions, and the practical implementation may be significantly affected by the rule of law (Meacham and Van Straalen 2017).

Even if risk criteria are agreed, the management of risk via regulation is subject to complex interactions between policy makers, industry (e.g. manufacturers), designers, regulation authorities, and the public. With respect to risk management, safety legislation and control of hazardous processes, for example, Rasmussen and Svedung (Rasmussen and Svedung 2000) observe that a very fast pace of change of technology is found within all domains, and that the pace of change is much faster than the pace of change in management structures and within legislation and regulation. A key aspect of this is that decision-making associated with updating rules lags behind the environmental changes impacting the system. The situation becomes more concerning since "a high degree of integration and coupling of systems and the effects of a single decision can have dramatic effects that propagate rapidly and widely through the global society," and that "companies today live in a very aggressive and competitive environment that will focus the incentives of decision-makers on short term financial criteria during economic crisis rather than on long term criteria concerning welfare, safety, and environmental impact" (citation Rasmussen and Svedung 2000 p.10). Based on their research, Rasmussen and Svedung (Rasmussen and Svedung 2000) conclude that for a proactive risk management strategy, one needs to understand the mechanisms generating the actual behaviour of decision-makers at all levels, to identify the information needs of decision-makers both with respect to the actual state of affairs and to values and objectives, and identify aspects that are sensitive to improvement and, therefore, the targets of guidelines for risk management. These are aspects of socio-technical systems. For this work a socio-technical system is defined as a system in which society and technology are integrally linked though actors, institutions and technology. The aim is to consider and optimize links between the three components (Meacham and van Straalen 2017).

1.4. Exemplar Case - Challenges with the Swedish regulatory system (van Hees et al. 2019)

The Swedish building regulatory system is performance-based (Boverket 2017, Meacham 2017, Regeringen 2010). As with any performance-based regulatory system, the concept of focusing on intended functions and performance to be achieved, rather than specifying detailed requirements for a building, can result in flexibility in design, innovation in materials, and optimization of risk and cost. However, such systems face challenges with respect to adequately defining performance measures to facilitate ease of determining regulatory compliance and allowing for suitably qualified professionals to make appropriate decisions. This balance, which is critical, between assuring safety as public policy, and allowing choice within the market, can be difficult to find. The requirement to adhere to two different regulatory systems – Sweden and the EU – can also introduce challenges. In the case of façade systems, the wide range of options could lead to unintended performance, especially if focus is given to one attribute (e.g., energy performance) over another (e.g., fire performance).

With respect to flexibility and associated decisions regarding compliance in Sweden, one should consider first the difference between mandatory provisions and general recommendations. Mandatory provisions are clear – they have to be complied with. General recommendations illustrate how one might comply with the mandatory provisions, and while legally they are not mandatory, in practice they can be viewed as such. For example, it is noted that general recommendations "state how someone can or should go about meeting a binding regulation in an Act, Ordinance or mandatory provision, but they are not required to be followed" and "a general recommendation may be seen as a toolbox presenting a method or solution. But if you choose not to do things in the manner stated in the general recommendation, you must be able to show that the binding regulations are still met" (Regeringen 2010). For a practitioner, this wording opens the opportunity to use other methods. For an enforcer, however, a higher level of surety may be perceived if there is not deviation from the general recommendations, as they present an acceptable method or solution, and no decision on an alternate method or solution is needed by the enforcer.

The Swedish regulatory system has a limited review and control system where it is mainly the building developer who is responsible for their own quality assurance. While local authorities have an oversight responsibility and power to add sanctions, they often lack expertise in technical areas. In a similar fashion, the regulation for existing buildings holds the building owner as often responsible. It has been pointed out by Larsson et al. (Larsson et al. 2011) that for the legislation of existing buildings it is problematic to point out a single actor as responsible for the fire safety. The regulation of fire safety for existing buildings is affected by many different stakeholders and there are dependencies between these. To point out a single actor as responsible may not lead to the desired outcome. In many cases it is also unclear for the building owner as to how the requirements may be fulfilled (Vilhelm 2009, MSB 2010) even though some clarifications have been made recently (Bjelland 2013). The competency of practitioners is also a concern, especially when dealing with innovative materials and systems. For example, the practitioner selecting a façade system needs to understand thoroughly the energy, moisture, acoustical and fire performance properties of the individual materials and as assembled into a system. They need also understand whether materials used – even if they carry CE markings for 'adequate' performance against individual standards or tests – meet the overall requirements when assembled into a system. So it can be important for a developer of a building to take on board this detailed competence through specialists.

In brief, the current building regulatory regime in Sweden presents some challenges and risks which requires attention to ensure that it leads to the desired outcomes. Risks in the built environment can change rapidly and technological development is fast (Bjelland 2013, Rasmussen and Svedung 2000). Examples are provided above with respect to various challenges and risks associated with façade systems. When considering the issue of façade performance within the building regulatory context in Sweden or elsewhere, one can look to the Grenfell Tower fire and associated investigations to see what type of outcomes one should avoid. In particular, the preliminary report from Dame Judith Hackitt (Hackitt 2017), concludes that the building regulatory system for 'high-rise and complex buildings' is 'not fit for purpose' and requires a major overhaul. This finding points to many similar issues as raised in this proposal – complexity of innovative façade systems, appropriateness of fire test standards, quality and accountability of building owners, practitioners, and authorities, and more. To adequately address the social, political and technical risks associated with innovative façade systems, holistic approaches are needed both in terms of façade systems, as well as the broader building fire safety regulatory system.

1.5. Technical holistic approach for façade performance (van Hees et al. 2019)

The overall fire performance of the façade systems depends on the evaluation of the whole system not of its single components. This is also the case for the aspects related to non-fire properties or functions as well. The systems can be made more fire resilient, but it is important not to lose the other vital functions of the façade performance, such as moisture protection and thermal insulation. As mentioned in the section on innovative solutions, there are a number of components each with it owns function. Examples are the rain protection of the system, wind shields, ventilation gaps, thermal insulation materials, fixing systems and support systems, etc. They all control other technical functions of the façade system such as humidity, mechanical strength and stability, insulation properties, etc. They should be maintained at the same time if changes are made for better fire protection. Introduction of fire stops (White and Delichatsios 2014) which is a common way to prevent internal fire spread in the system can cause less good ventilation and possible fungi build up. Hence it is important to take into account all technical aspects in the design. It is however possible that certain priorities need to be done.

Apart from the building properties the overall building process can affect the overall performance of the façade systems when poor quality control systems are in place. Although not yet fully confirmed by the investigation, it might be so that one of the reasons of the Grenfell fire might have been a change in type of rain shields for economical purposes (Ministry of Housing 2017b). For this reason, the overall building process should be included in order to guarantee errors during the process which are easy to make if one changes certain components. By doing so the holistic aspects are enlarged.

Finally, there are other aspects of building fire safety, within which the façade is but one component. Recently, the National Fire Protection Association (NFPA) has created EFFECT™, an Exterior Facade Fire Evaluation Comparison Tool to help proactively assess fire safety risk of high-rise buildings with combustible facades. EFFECT considers the building, the facade, and the impact of potential ignition sources such as fire spreading from inside the building, or fire stemming from an exterior fire source (NFPA 2018). With some modification, such as resulting from this proposed research, the EFFECT tool could potentially be enhanced to help assess specific façade systems (at the Tier 3 level). More information about this tool will be given later in this report. For determination of the different requirements different tools were used such as the Delphi method (Dalkey 1963), systematic failure Mode and Effect and Criticality Analysis (FMECA) method (Talon et al. 2005, Talon et al. 2008).

1.6. Scope, objective and methods

The overall objective of this project is to address the fire safety requirements on external façades systems through a technical holistic approach of façade systems, considering all other technical requirements of the systems, possible conflicts and a holistic approach to the building regulatory process, from a socio-technical perspective. Specific objectives are to identify the research gaps and research questions which need to be addressed in order to safeguard the occupant and fire safety of modern and renovated buildings.

1.7. Limitations of this report

The study should be considered as a pre-study to define mainly research gaps in the current state of art both for fire properties but also for other non-fire related properties.

This report should be read in conjunction with the specific reports of certain work packages as well as the related scientific articles. Unless open access they are available from the authors. They will provide more detail information on specific aspects.

2. Overview of the HOLIFAS project

This chapter gives a short overview of organisation the overall project. The project major core of activity is to investigate and assess the different technical and socio-technical aspects related to the fire safety of façades.

2.1. Work package 1: Collection of different façade systems in Sweden

In WP1, a collection was made of the different systems, constructed in a traditional or innovative way, the latter including either new building materials or new building techniques. Documentation include how, and of what, the systems are composed. WP1 will be done by literature reviews and a scrutiny of technical guidelines, followed by a set of interviews with building constructors as well as contractors and consultancies in Sweden. WP1 finished by a group discussion with the experts e.g. using the Delphi method (Dalkey 1963) to define the final technical properties of the different systems. It was performed as part of a PhD course. An inventory of façade design was performed through a survey and collection of project examples. Results of WP1 are an overview of the different systems which be addressed in WP2.

2.2. Work package 2: Determination of technical requirements and criteria for external façade systems

In WP2, the requirements for each of critical technical function were addressed. WP2 started with the determination of the critical technical functions by the project group. Then the assessment (both performance-based and prescriptive) were addressed as well as the criteria for the different functions. The work was done by expert group discussion using e.g. Delphi and collection of requirements via interviews with key players such as building regulators, insurance companies, industrial actors. It is important to have this larger group of different building experts to ensure the overall concept and to have an independent academic view on the problem. Other methods used were e.g. systematic failure Mode and Effect and Criticality Analysis (FMECA) method (Talon et al. 2005, Talon et al. 2008).

2.3. Work package 3: Socio-technical system considerations and regulatory system comparisons

In this WP, the building regulatory systems in England and Sweden was characterized from a holistic, socio-technical systems (STS) perspective. This was largely a function of literature review, as supplemented by a limited number of interviews. Literature within public administration (regulatory regimes), risk governance and socio-technical systems were reviewed with the intention to develop a template that may be used to evaluate building regulatory socio-technical systems in each country. Literature on the regulatory systems in each country were reviewed to identify components, including the preliminary report from Dame Judith Hackitt (Hackitt 2017). The outcome of the reviews of English and Swedish systems were scrutinized and compared. Using the STS system approach, a comparative evaluation was made, and based on published reports from the Grenfell Tower fire, parallels were drawn between identified similarities and differences between the two countries' respective systems, with a focus on addressing holistic performance of façade systems. Conclusions were made regarding the current situation in Sweden and lessons to be learned.

2.4. Work package 4: Reporting, Dissemination and Management

WP4 will report the previous work packages and will also develop a roadmap for further research, with identified research gaps and research questions. In this work package, input was given to the PhD and external course organised within the national PhD research school "Building system design and performance", supported by the Swedish Energy Agency (STEM). The project produced both articles and reports as well a number of popular scientific publication. Finally, management of the project was done in this WP.

3. Collection of different façade systems in Sweden

3.1. Introduction

This chapter gives an overview of different façades systems which mainly are used in Sweden. The outcome is obtained partly by the following actions:

1. A survey performed by BRIAB at the beginning of the project as part of a market overview after the Grenfell fire, see annex A
2. A master thesis conducted by Erasmus Mundus Master student Bogdan Branisteanu, see Annex B
3. Information meetings with industrial partners.
4. Individual talks with the project members as a full meeting was difficult to achieve.
5. A literature study and input from international regulations.
6. A final discussion with the experts involved in the project during the annual meeting of SBU (Swedish building University)

While the survey gives a good overview for the Swedish system it became apparent through the interviews that some fine adjustment was necessary. It is certainly not the ambition of this report to be exhaustive and decisive. Before listing the different type of façade systems an attempt is made to define the term façade and façade system. The classification made in paragraph 3.3 is made in order to obtain data for the determination of the technical requirements for each system

3.2. Definition of façades/façade system.

From the Oxford dictionary (Oxford Dictionary 2019) the word façade is defined as "The face of a building, especially the principal front that looks onto a street or open space". The word originates from the French foreign loan word façade, which in turn comes from the Italian facciata, from faccia meaning face, ultimately from post-classical Latin facia. (online Etymology dictionary 2019). The earliest usage recorded by the Oxford English Dictionary is 1656 (Oxford dictionary, 2019). While this could be interpreted as just the face of the building, technically we mean more than just the outer face when we use technically the word façade. Therefore, we need to look further into the word in a technical context.

In ISO 13943 (ISO 2017), the definition standard in TC 92, there is no specific definition for the term facades while ISO 13784 part 1 and part 2 use the following definition and equals it with cladding.

> ***façade or cladding***
>
> *materials and constructions added to an inner structure*
>
> > NOTE *The inner structure can be of concrete, lightweight concrete blockwork, masonry, timber, etc. The cladding may be applied directly to the inner structure or may incorporate an air gap or an insulating layer. (citation ISO 13874 part 1 and 2)*

If we compare this ISO 6707-1:2017(en), (ISO 2017), which is the general terms standard for Buildings and civil engineering works, the following definition is given:

> ***Façade,***
>
> *exterior surface of a wall (3.3.2.46) enclosing a building (3.1.1.3), usually non-loadbearing, which can include a curtain wall (3.3.2.56), cladding (3.3.2.43), or other exterior finish (3.3.5.2) (citation of definition 3.3.2.44 in ISO 6707-1.)*

However, it would be better that we would use the wording façade system as we mean more than just the outer façade which is seen from the outside of the building.

For the work in the harmonisation of the full-scale tests (see Annex G) an attempt was also made to harmonise the definition between the different EU countries and the following definition was suggested (Boström et al. 2018)

> *"A complete external wall construction of any type (massive wall or curtain wall …etc.) or constitution (masonry, combustible material …etc.)." (citation Boström et al. 2018)*

In the study different national contacts were asked whether this definition adequately covered any national definition according to their building regulations. If it did not, they were asked to provide a suitable definition according to their national regulations.

The results showed that the term façade is only rarely used in the regulations. More frequently the terms "external wall", "cladding", or similar are used. This shows that most probable there needs to be more clear definitions in the international standards as technology most likely has passed the state of the art in the current regulations.

If we consider other technical definitions in literature then a suitable definition found in then steel construction definition dictionary complement these definitions from ISO and the European standardisation to be one for façade systems:

> *"Façade systems comprise the structural elements that provide lateral and vertical resistance to wind and other actions, and the building envelope elements that provide the weather resistance and thermal, acoustic and fire resisting properties. The types of façade system that are used depends on the type and scale of the building and on local planning requirements that may affect the building's appearance in relation to its neighbours. (citation Steelconstruction.info 2019)"*

In this definition structural elements and building envelope elements are mentioned as well some of the technical properties determined in chapter 4. The remaining clauses will now treat the different type of facades systems as an outcome from the work in this project and will consider as many as possible type of combination of a load bearing (e.g. masonry) or non-loadbearing wall system (where the load bearing system is a frame system of steel, concrete, wood or composite). In all cases the façades system is a major part of the building envelope, where the latter form the physical separation between the interior and exterior and that creates and contains the internal conditions (ICE et al. 2019).

Considerations that might influence the design of a façade include (according to ICE et al. 2019):

- Site, topography and climate where the building is situated.
- The relationship to the street and access routes to the building.
- The requirement for entrances, windows and other openings.

- Stylistic preferences from e.g. the architect or the style of the city district.
- Requirements for climatic modification.
- The need for security and privacy towards the building.
- Available skills and materials.
- Regulations and technical requirements (see e.g. chapter 4).
- Context and planning restrictions.

3.3. Different type of façade systems

A good overview of façades can be found in the publication from Designing buildings (ICE el al 2019) and Steel construction (Steel construction 2019). In parts of the descriptions below, citations and definitions from these references are used as indicated by the authors.

As the façade system is part of the external wall, various construction systems can be used to build this external wall, including (according to ICE et al. 2019, adapted citation):

- Loadbearing – using bricks and blocks, or reinforced concrete. Timber can be used for log cabin construction. Recently even solid timber walls can be used as load bearing e.g. when CLT (Cross Laminated Timber) is used. Exterior walls form here part of the structure.
- Framed – the exterior wall can be located around the structure, inside (thereby exposing the structure) or as infill panels located within the depth of the frame itself. Irrespective of the plane it is in, the exterior wall in these situations is usually referred to as 'cladding'. These types of exterior wall wrap around the building's structure, are typically non-loadbearing and serve as an aesthetic and climatic component. Tied back to the structure with ties, they can be made of facing bricks, concrete blocks, timber panels, glass, plastic and other lightweight materials. Accommodating thermal movements is usually required if long, uninterrupted wall lengths are involved. Insulation is often used depending on the requirements.
- Rainscreen – a thin façade made of metal, terracotta or other panel type is attached to a lightweight frame which is itself bolted to the building structure. In appearance, it is not usually possible to tell that the result is a façade of relatively little thickness. There is usually a ventilation gap between the back of the facing panel and the face (or inner wall) of the building. Rainscreens provide an opportunity to retrofit insulation to existing buildings.

So, in principle we could define the façade systems into the three types of external wall constructions but this would not facilitate to further analyse them into different specific technical requirements. Therefore, from the literature studies, interviews, discussions with experts the following subdivisions were made. It is understood by the authors that this is certainly not the only way to divide the façade systems but it was chosen to do so to facilitate the further analysis of the technical requirements.

3.3.1. Traditional Ventilated/Cavity façade systems

This is probably the most traditional type of façade system of a building in many countries where the load bearing structure consist e.g. masonry walls, concrete walls, etc. and where there is an air void in between the solid wall and the exterior façade system which is fixed to the wall. The air gap allows for ventilation in the whole wall. Originally the most common construction in Europe is were both in and outside is made of a brick wall. The construction then looks like in Figure 8. Even this construction has been widely used in the Nordic countries until the 1960ies. Considerable building stock in the central parts of our cities are for example apartment blocks, offices, schools, churches, industrial buildings.

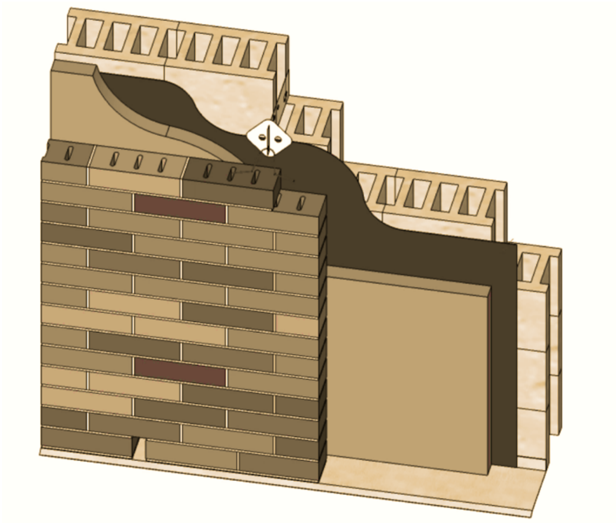

Figure 8 Traditional brick wall systems (picture redrawn from ICE et al. 2019)

In many cases the air gap prevents moisture/rain transmitting from the outer skin to the inner skin. Any moisture that reaches the cavity from the outside, runs down the internal surface of the external skin and is directed to weep holes in the outer skin by cavity trays, where it will drain to the outside as can be seen in Figure 9.

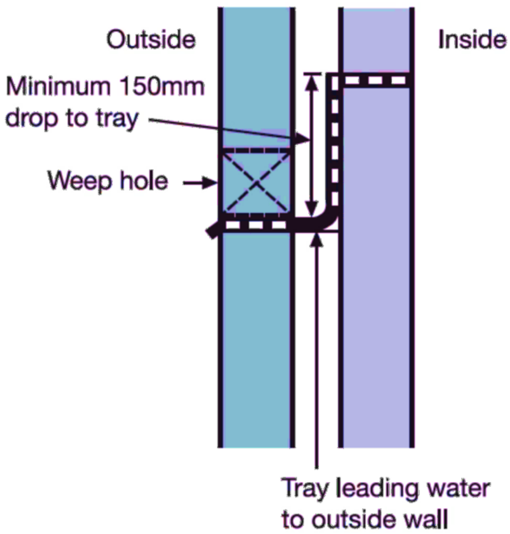

Figure 9 Example of removal of moisture from the airgap (picture redrawn from ICE et al. 2019)

Some applications result in so called brick veneer systems where the brick wall acting as façade is constructed by ties to the main structure of the building. Here low ventilation is obtained through air gaps in the front wall. An example is given in Figure 10.

Figure 10 Example of a brick veneer building – LTH administration building (picture Lund University)

Another common type of these type of façade systems is seen in wooden buildings as can be seen Figure 11 and they are very common in Sweden (Träguiden 2019). Different types of construction are possible depending on the type of panels used and the type of construction needed for the building.

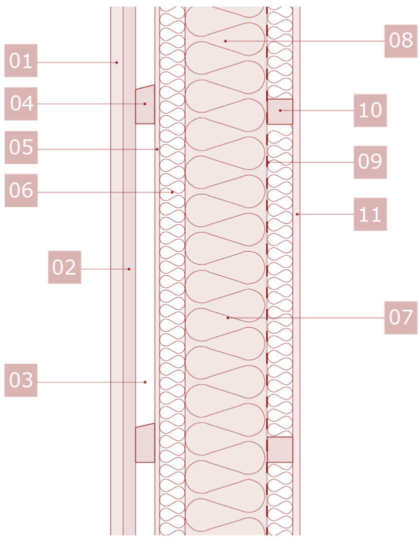

Figure 11 Example of a wooden building. (picture redrawn from Träguiden 2019)

Legend to Figure 11:

7. External closing panel
8. External base panel
9. Air void
10. Fixing stud
11. Wind barrier of inorganic material
12. External Insulation
13. Vertical studs
14. Thermal insulation
15. Vapour barrier
16. Horizonal stud
17. Inner panelling

Important to note here is that it was decided to have a specific group for the so-called rain screen claddings which are a very specific type of ventilated/cavity façade systems which are sometimes even called high ventilated façade. They are treated in paragraph 3.3.5.

3.3.2. Rendered façade systems

3.3.2.1. Composite concrete systems

These systems are characterised by composite walls of e.g. insulation encapsulated into two concrete walls. On the outside a similar render as for the ETICS can be applied or different claddings or front façade materials such as bricks, panels etc. In the Nordic region today mainly in small and medium scale construction – single family houses, schools, offices, industry buildings. Render and clay bricks alternate in being the most popular façade material. Figure 12 is given an example of the composite wall systems without the render. In this case a PU insulation has been used.

Figure 12 Example of a light weight composite concrete wall system (without rendering) Picture Miklos Molnar.

As render system both organic and inorganic renders are used. Inorganic renders are most frequent and the following systems are typically used:

- Cement and lime are commonly used as binders.
- Different admixtures and surface treatments are used – plasticizers, pigments, hydrophobic agents, paint. The total organic content < 10%.
- The render adheres directly to the inorganic masonry substrate – sometimes with a pre-treatment and a typical render thickness is between 5-20 mm.
- Steel or glass mesh is often laid in the reinforcement in the render to limit the effects of render shrinkage.

As Organic renders complex compositions are used with fillers, polymers etc.

3.3.2.2. ETIC Systems

ETICS is the abbreviation for External Thermal Insulation Composite System. ETICS can be used to improve the energy efficiency of both new and existing buildings. (ETICS 2017). They were mainly introduced to the Nordic Region in the 1970ies and were used at large scale since the 1990ies. The systems were used in both new developments and for renovation. The system is composed of a thermal insulation on which a render system is placed. Renders are quite often similar as in the previous paragraphs but often better fixing systems to adhere the render to the insulation are needed. An example of a build-up of an ETIC system is given in **Fel! Hittar inte referenskälla.**. An example of a building with an ETIC system is given in Figure 14.

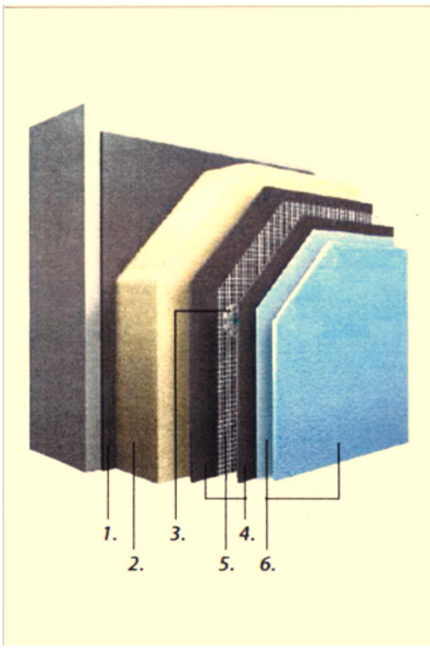

Figure 13 Example of an ETIC system (schematic adapted from EA-ETICS 2017)

Legend to Figure 13:

1. Adhesive
2. Thermal insulation material
3. Anchors
4. Base coating
5. Reinforcement, usually glass fibre mesh.
6. Finishing layer

Figure 14 Example of an ETICS system (thin render on EPS) (picture Miklos Molnar)

3.3.3. Panel systems

Sandwich panels (sometimes referred to as composite panels or structural insulating panels (SIP)) consist of two layers of a rigid, quite often insulation material bonded to either side of a lightweight core (ICE et al. 2019). The three components act together as a composite; that is, the combination of the characteristics of the components results in better performance than would be possible if they were acting alone as single products. Quite often the two rigid (often steel) components also have a finishing layer by mean of paints or coatings to improve the technical properties of the panel.

The lightweight core keeps the two faces in the correct position, resists the shear forces, and provides also insulation, while the two faces provide durability, weather and impact resistance, and resist in-plane forces of tension and compression.

Sandwich panel systems include different components i.e. the panels, the joints between them, the possible joint finishing, the fixings (often concealed) and a support system to fix the panel. An example can be seen in Figure 15 .

Figure 15 Example of a sandwich panel system (picture Patrick van Hees)

Sandwich panels were in the beginning popular in vehicles, such as trains, and planes to reduce weight, but they were also largely introduced in buildings especially in industrial buildings. Lately they were also introduced in single and multi-storey buildings. They are quite often produced off-site and mounted at the building site onto the supporting structure.

Building types that commonly feature sandwich panels include (ICE et al. 2019):

- Industrial buildings and processing plants.
- Temporary buildings.
- Storage buildings.
- Clean rooms.
- Agricultural buildings.
- Shopping centres.
- Sports facilities.
- Transport buildings.

The outer faces of sandwich panels are most commonly made of metals such as (ICE et al. 2019):

- Hot-dip galvanized steel sheet.
- Aluminium.
- Zinc.

However, other materials that can be used include (ICE et al. 2019):

- Precast concrete, sometimes clad with other finishes such as brick.
- Cement board.
- Glass fibre reinforced polypropylene.
- Poly vinyl chloride (PVC).
- Magnesium oxide board (MgO).
- Plywood.
- Oriented strand board (OSB).
- Glass reinforced plastic (GRP).

Cladding systems typically include a rigid polyurethane (PUR) core, but other core materials include (ICE et al. 2019):

- Expanded polystyrene (EPS).
- Extruded polystyrene (XPS).
- Mineral wool (rock or glass fibre) (MWRF).
- Modified Phenolic foam (MPHEN).
- Polyisocyanurate (PIR).

- Folded metal, paper, aramid and carbon fibres.
- Honeycomb materials (such as Polypropylene).

Example of a building is given in Figure 16

Figure 16 Example of a building with sandwich panels (picture ID 76945687 © Viktoryia Strukouskaya Dreamstime.com)

3.3.4. Curtain wall claddings

Curtain wall systems are non-structural cladding systems for the external walls of buildings. They are generally but not always associated with large, multi-storey buildings.

Curtain walls separate the interior from the exterior, but only support their own weight and the loads imposed on them which can be wind loads, seismic loads, etc.). They transfer back these loads to the primary structure of the building. This is in different to many forms of traditional construction in which the exterior walls are a major part of the primary structure of the building (ICE et al. 2019).

Typically, a curtain wall system comprises a lightweight aluminium frame onto which glazed or opaque infill panels can be fixed. These infill panels are often described as 'glazing' whether or not they are made of glass (ICE et al. 2019).

Curtain wall systems emerged in the 19th century with the development of large glass panels and became more common from the 1930's when aluminium was made available as a construction material for the first time (ICE et al. 2019). The style is now widely spread for use in tall buildings around the world.

The infill panels for the curtain wall systems can include (ICE et al. 2019):

- Vision glass (which may be double or triple glazed, may include low-e coatings, reflective coatings and so on).
- Spandrel (non-vision) glass.
- Aluminium or other metals.
- Stone or brick veneer.
- Terracotta.
- Fibre-reinforced plastic (FRP).
- Louvres or vents.

Figure 17 Example of a curtain walling system with glass panel (Image ID: 158518730 Copyright Askar Karimullin Dreamstime.com)

Frame and panel designs are very complex, as they need to perform multiple functions (ICE et al. 2019):

- Transferring loads back to the primary structure of the building.
- Providing thermal insulation and avoiding cold bridging and condensation.
- Providing fire, smoke and acoustic separation. This is particularly difficult at joints between the curtain wall system and interior walls and floors.
- Creating a barrier to water penetration.
- Accommodating differential movement and deflection.
- Preventing panels from falling out of the frame.
- Allowing for opening windows.
- Preventing the accumulation of dirt.

Good technical information about the design of curtain wall systems can be found on the Whole Building Design Guide website (Vigener et al. 2019) including typical details.

Figure 18 Curtain walling system under construction. (Picture courtesy Steelconstruction)

3.3.5. Rainscreen claddings - Façade void system with high ventilation

These type of façade systems are commonly used a cladding to an existing structure and can be considered quite similar to curtain walling or as panel system. Due to the increased use of these systems they are considered in this report as a specific group.

The structure can either be a frame-based structure or can be solid wall (load bearing system). The latter is often used in renovation projects where the façade system is mounted on the existing structure to enhance the performance of the building envelope most often for better thermal insulation.

A rainscreen cladding (sometimes referred to as a 'drained and ventilated' or 'pressure-equalised' façade) is part of a double-wall construction that can be used to form the exterior walls of buildings.

Rainscreen cladding systems were in fact first investigated in the 1940s. They were first used in practice in the 1950s and became more commonplace in the 1960s. (ICE et al. 2019).

The Centre for Window and Cladding Technology (CWCT) defines a rainscreen cladding system as *'...a wall comprising an outer skin of panels and an airtight insulated backing wall separated by a ventilated cavity. Some water may penetrate into the cavity but the rainscreen is intended to provide protection from direct rain'. (IEC et al. 2019)*

Typically, rainscreens are formed of relatively thin, pre-fabricated panels. The rainscreen itself simply prevents significant amounts of water from penetrating into the wall construction. Thermal insulation, airtightness and structural stability are provided by the second, inner part of the wall construction which can be very complicated as can be seen in figure

There are two basic types of rainscreen claddings (ICE et al. 2019):

- Drained and ventilated rainscreen cladding systems allow any penetrating moisture to drain or evaporate and vent to the outside. In this case it is necessary to detail the façade so that any penetrating water cannot cross the gap between the rainscreen and the internal wall construction.
- Pressure-equalised (PE) rainscreen cladding systems allow the movement of air between the inside and outside of the rainscreen. This equalises the pressure across the rainscreen so that water is not driven, or sucked through the joints.

The difference between the two systems relates to how much water can penetrate the joints, with drained and ventilated systems allowing more water to penetrate. For this reason, the systems are often called high ventilated façade systems as there is need or occurrence of higher ventilation as compared to the low ventilated façade systems.

Rainscreen systems are often fabricated from metal sheets such as aluminium, stainless steel, zinc, copper, etc. or can be a formed from metal composite materials (MCM) which consist of two skins of metal (such as aluminium, or ACM) bonded to either side of a lightweight core such as polyethylene (PE) or polyurethane (PUR), a profiled metal core or a mineral core. Materials, such as terracotta, brick slips, stone, timber and so on are also used. (ICE et al. 2019)

Rainscreens are cost-effective, lightweight, and easy to install, maintain and replace. Some systems are simply 'clicked' onto supporting rails without the need for additional fixings (ICE et al. 2019). They can be used on new-build and refurbishment projects. An example is given in Figure 19.

Figure 19 Example of a rainscreen cladding under construction (picture courtesy ID 44710574 © Antikainen | Dreamstime.com)

3.3.6. Special type of façades systems

During the research a number of specific type of façades were found in the literature and during discussion with experts and reference group. They are listed below. In some case they can be included in the systems given in paragraphs 3.3.1 to 3.3.5.

3.3.6.1. Solid Wooden façades

With the introduction of CLT (cross laminated timber) and solid wooden buildings a specific type of buildings where the major core of the building envelope is made in solid wood has gained popularity. The solid wood is often combined with insulation material and on top of that any type of façade system is attached which can be either a wooden veneer system, a rainscreen cladding or a render system. Figure 20 gives an example of a building.

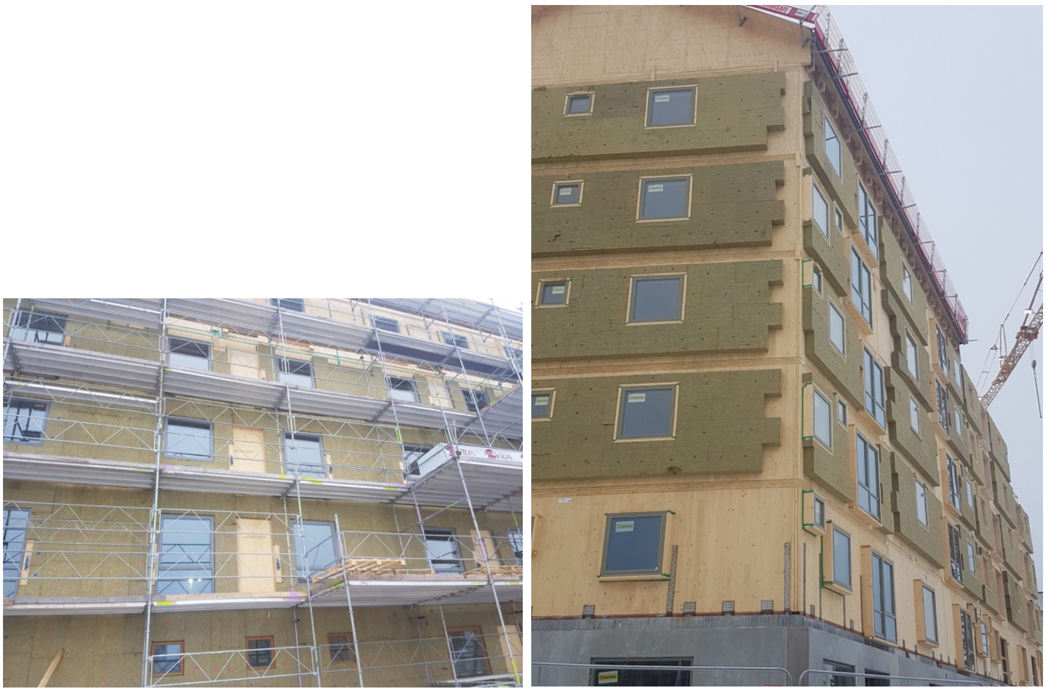

Figure 20 example of a building with a solid wood enclosure by means of CLT (picture courtesy Petter Wallentén)

3.3.6.2. Façades with energy production.

Recently there is also an increase of introduction of energy production by means of putting solar panels within the façade system. In this case energy production is obtained through the solar panel system. The façade system is however more complex where a mixture of solar panels, glass panels and even traditional composite panels are attached to the structure. Figure 21 is an example where panels are introduced in the façade of a building.

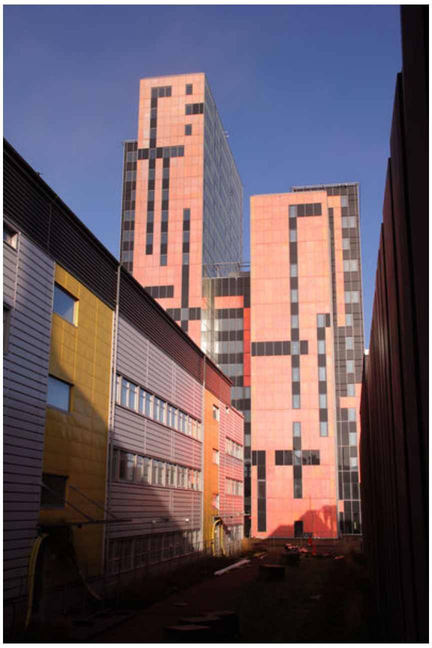

Figure 21 Example of a façade system including solar panels, Ideon Gateway building (picture Lund University)

Figure 22 Example of solar system integrated in the façade (picture courtesy ID 152117419 © Vtt Studio | Dreamstime.com)

3.3.6.3. Green Façades

Sustainable development trends have also resulted in so called green façades where the building envelope is foreseen with a vegetation. That vegetation has been placed mainly by cassette systems or a steel supporting structure in which the vegetation is placed. Examples are given in Figure 23 for a climbing plant on a façade and in Figure 24 for vegetation which is placed in cassettes systems.

Figure 23 Example of a Building with vegetation. (picture courtesy ID 162733442© Jordi Clave Garsot| Dreamstime.com)

Figure 24 Example of a green façade system by adding plants on the outside of the façade (picture courtesy ID 64493637 © Jordi Clave Garsot| Dreamstime.com)

3.3.6.4. Double skin façade systems

Double-skin facades originated in northern Europe and are formed of two glass walls separated by a cavity mostly on south-facing elevations and are used to reduce the energy consumption of a building (Steelconstruction 2019). Within the cavity, shading devices are usually mounted and, all depending on its width, walkways for access and cleaning are mounted in this cavity. This type of façade has many variations in arrangement. The variations relate according to Steelconstruction 2019 to:

- width of cavity;
- type of glazing (single/insulating) for the inner or outer skins;
- division of the cavity horizontally and vertically;
- natural or mechanical ventilation of the cavity;
- integration of the cavity ventilation with the building services;
- use of opening windows into the cavity.

The two skins form a thermal buffer zone and passive solar gains in the cavity reduce heat losses in winter. If the cavity ventilation is integrated with the building services, air heated by the sun can be introduced into the building, providing good natural ventilation and reducing the heating load. In summer, the heated air in the cavity is ventilated to the outside, conducting heat away from the building and reducing the cooling load. The design of the double skin façade must be integrated with the design of the building services to be most effective. (Steelconstruction 2019). These systems are sometimes mixed with curtain wall systems.

Figure 25 Example of double skin façade system (picture courtesy SteelConstruction.info)

3.3.6.5. Dynamic Façade systems

A very specific type of façade system is a so-called dynamic façade, also known as a responsive façade or intelligent facade. This is a building exterior that can change in response to the environment around it to maximise its performance to the environmental aspect which can be sun, wind or rain. As such it controls better the interior environment within the building and can e.g. minimise the energy consumption of building services systems. In this way, the 'skin' of the building is not static or constant, but dynamic and will transform itself according to requirements set by the designer of the building. (ICE et al. 2019).

The responsiveness of the façade can be either at a macro scale, which involves changes in its configuration using moving parts, or at the micro scale which involves changes affecting a material’s structure.

Macro responsiveness might include adjustable ventilation or moveable solar shading, used to optimise the amount of solar heat gain and visible light that is admitted into a building, or daylight lighting systems which can help to maximise natural daylight. Micro responsiveness might include smart glazing or phase change materials (ICE et al. 2019).

Some dynamic facades also include methods for generating energy, such as solar photovoltaic panels as it was explained under paragraph 3.3.6.2.

Dynamic systems can reduce a building’s reliance on heating, cooling and ventilation systems as well as artificial lighting and energy requirements (ICE et al. 2019).

3.4. Summary

The following list is summarising the type of façade systems listed in the previous paragraphs and is used for further evaluations.

- Traditional Ventilated/Cavity façades
- Render systems (composite concrete or ETICS)
- Panel systems
- Curtain wall claddings and rainscreen claddings
- Special type of façades (Green façades, Integrated Solar panel system, double skin, dynamic façades, Solid wood, etc.)

4. Determination of technical requirements and criteria for external facade systems

4.1. General requirements for external façade systems

For the different facades systems defined in the previous chapter a number of general technical requirements were obtained by input from the different experts and discussed at an expert meeting during annual meeting of the Swedish Building University. Results were also obtained during a PhD course in December 2018. Finally, literature was consulted (Steel construction 2019, ICE et al. 2019) in conjunction with building regulations in Sweden. (Boverket 2019a). For the fire requirements a detailed overview is given in a separate paragraph which lists the different possible solutions in order to construct or prescribe a fire safe façade. It should be noted that the list is a collection of different requirements for different façade systems and that they are not linked to the specific type of façade system. This would need a much deeper study.

4.1.1. Esthetical requirements

While maybe not immediately considered as a pure technical property, the esthetical requirements are important for the look of the building. This part is especially important for the architects and includes a lot of technical requirement with respect to design, geometry, integration of windows, ventilation, etc.

4.1.2. Insulation criteria

Insulation has recently become again more an important factor for a building. The requirement on insulation of the facades has become of importance during the last years due to the requirements to reduce energy consumption as well as CO_2 emissions. Minimum U values depend of course on the regulation and respective country and can be found in the Swedish Building regulations (Boverket 2019a) and guidance from Boverket (Boverket 2019b). As a comparison U-values in the UK building regulations are equal to 0.35 W/m^2K for walls and 2.2 W/m^2K for windows and curtain walling when it is related to façades. (Steelconstruction 2019). For wooden buildings information can be found in specific literature (Träguiden 2019).

4.1.3. Humidity requirements

An important function of the façade system is protecting the building from incoming humidity. The physical processes are complex and depend on day and night situations and the local climate. The processes are given in Figure 26 and Figure 27.

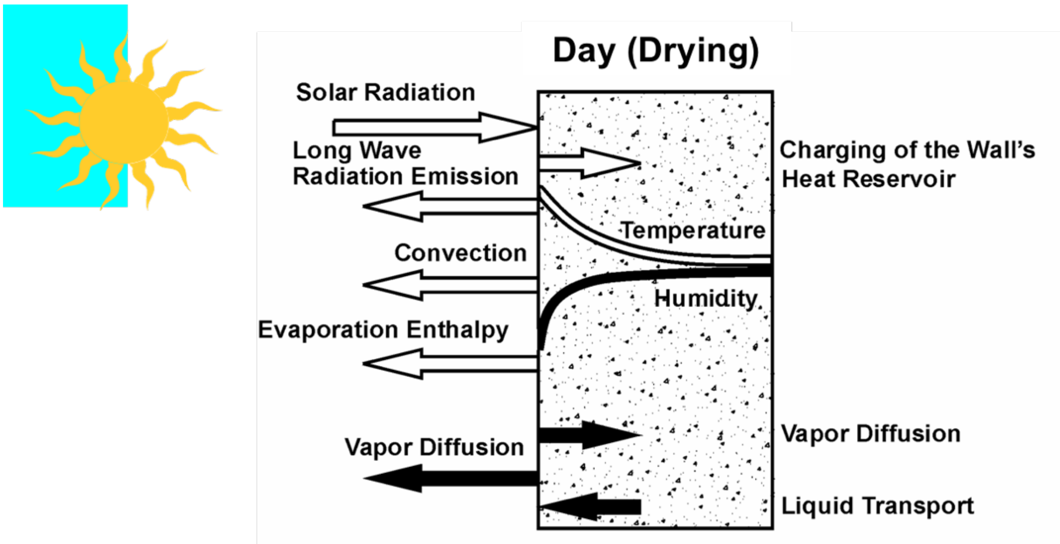

Figure 26 Physical processes of water transport during night conditions (Picture Petter Wallentén)

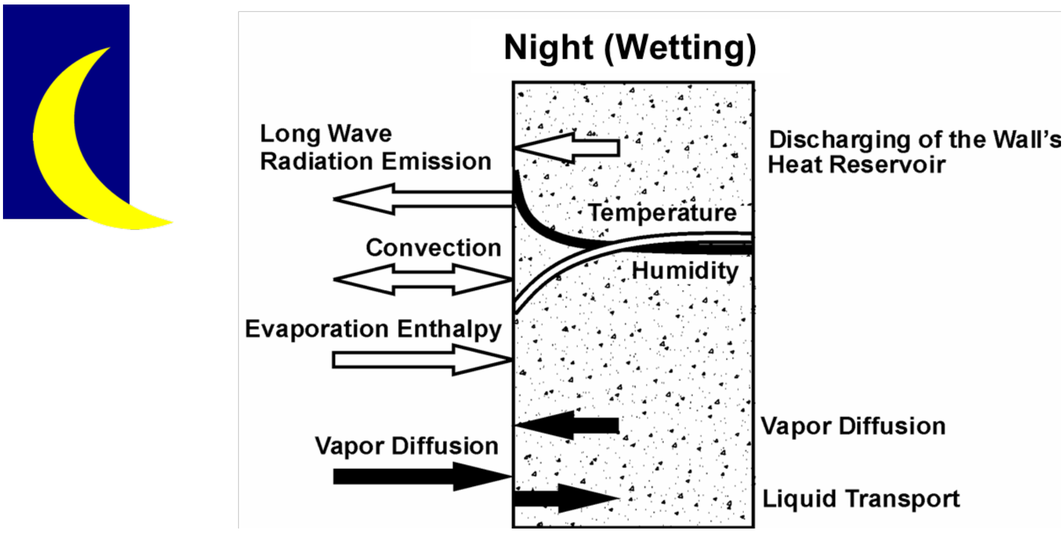

Figure 27 Physical processes of water transport during night conditions (Picture Petter Wallentén)

Possible sources for water are:

- Rain (Wind driven)
- Vapour diffusion/convection from inside
- Vapour diffusion/convection from outside
- Wet materials enclosed in during construction
- Condensation on inside surfaces (e.g. from air conditioning)

Possible damages due to humidity problems are:

- Mould/algae on exterior surfaces (see Figure 28)
- Frost damages

- Mould inside construction
- Corrosion on metals
- Mould on inside surfaces
- Rot

Figure 28 gives an example of algae on an ETIC system while Figure 29 gives examples of possible leakage sources for ETICS.

Figure 28 Example of algae on the outside of an ETIC system (picture Petter Wallentén)

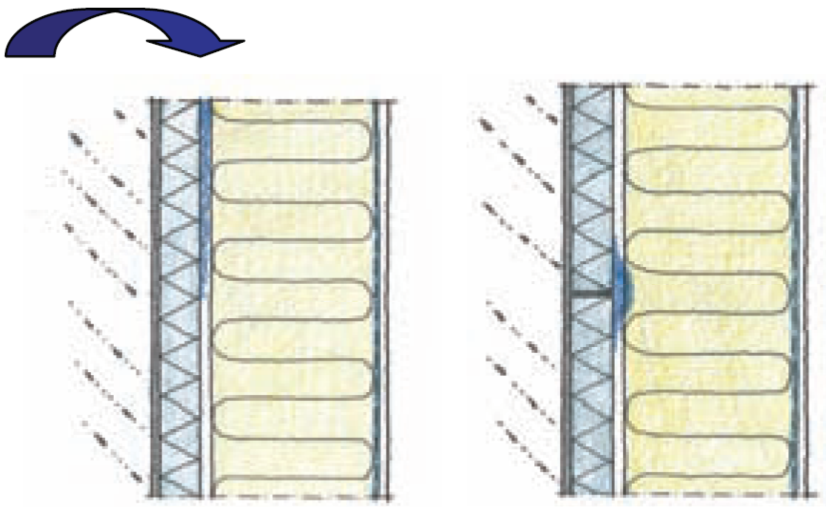

Figure 29 Possible leakage sources for ETICS. To the left leakage due to, cracks in the render and to the right leakage due to capillary plaster (picture Petter Wallentén)

As a summary it can be concluded that in Nordic countries the largest risk is wind driven rain and humidity. For this reason, the best solution is to have a separated wind and rain protection system. Another important aspect is that for all systems the moisture which can cause problems must be mitigated.

4.1.4. Pressure and Wind stability requirements

One of the exposures of the building is due to wind conditions. The wind exposure on a building influences of course the water penetration as was given in the previous chapter 4.1.3 and this will also be taken up with respect to the rainscreen properties in chapter 4.1.6 But it is also important for the air tightness of the building as the wind can influence the permeability of the buildings i.e. the air tightness. Finally, it puts demands on the mechanical stability of the façade system which is explained in the next chapter.

4.1.5. Mechanical stability requirements

Mechanical stability of the facades is related to the fact that the different components of the façade systems should be designed in such a way that it can sustain all mechanical loads from the both the structure itself or from any external loads such as e.g. wind. There is certain overlap with the pressure and wind stability which was described in the previous subparagraph 4.1.4.

4.1.6. Rainscreen properties requirements

In case of rainscreen claddings, the performance of the rainscreen on the outside layer of a façade system is mainly with respect to protect the inner structure from the major exposure of rain but providing a tight skin on the outside of the façade. In high-rise buildings the openings between the panels provide also pressure equalisation so that the risk for large pressure drops over the rain screen causing forces on the panels is prevented. The requirements are therefore focused towards these two properties but quite often a full system overview of the different physical requirements needs to be considered (Falk 2015).

4.1.7. Acoustical performance and requirements

The building façade provides also an acoustic separation between the external and internal environments. In general, a building envelope constructed of more massive elements (e.g. masonry or pre-cast concrete) provides better acoustic separation.

A good acoustic performance is required in most of the buildings in one way or another, but it is particular of importance for residential buildings, schools and hospitals. Quite detailed description and requirements can be found in the building regulations of the specific country. In Sweden this is the regulation from Boverket (Boverket 2019b). Technical solution can be very detailed and require complex calculations as can be seen in the guidance for e.g. steel constructions (Steel construction 2019) and for wooden construction (Träguiden 2019).

4.1.8. Fire Safety Requirements

Fire requirements are important as the spread of fire can happen when the façade system is not well designed. In the introductory chapter the different ways of possible fire spread routes were given. They can be summarised in the picture as given in the requirement given in BR135 (BRE 2003) and demonstrated in Figure 30 (Colwell and Baker 2013). For each of the risk of fire spread an appropriate solution is necessary for each of the type of façade systems.

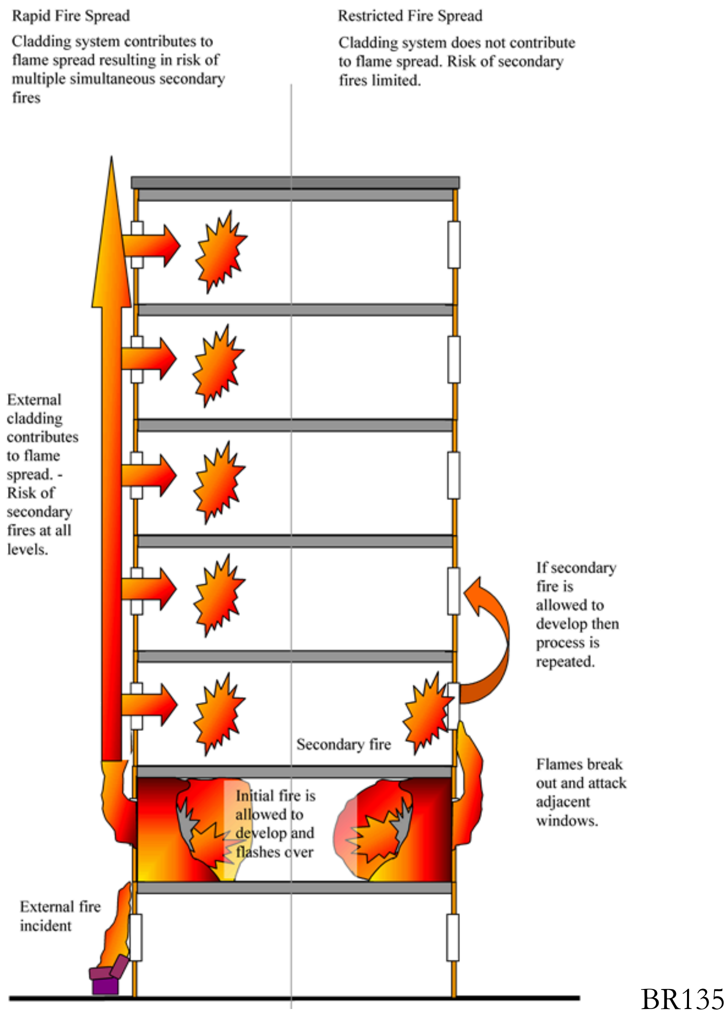

Figure 30 Fire spread possibilities according to BR135 (picture courtesy BRE).

While the figure includes most of the risks for fire spread it is important to note that specific location of the fire can lead to unforeseen fire spread if no appropriate risk analysis or measure have been done. An example is the fire in a residential area in Rotebro, Sweden (Törnblom 2003) where the attic of the building caught fire and where fire spread occurred through the ETIC system from the attic into the façade construction leading to fire spread over large parts of the façade as can be seen on the left part of the picture from Figure 31. The process of determining the fire properties and designing a fire safety solution for the façade system will be further given in chapter 4.2.

Figure 31 Example of fire spread from the attics into a rendered façade system (picture courtesy RISE)

Another important aspect is the use and effectiveness of fire barriers or fire stoppers in the risk reduction for the vertical fire spread in the façade system. It is important that the designer investigate in detail how much the risk is reduced when using a fire stopper. The fire stopper should go all the way to the external part of the façade (in case the external face is combustible) or a least until the inner side of the external part (in case of a non-combustible façade) as seen in Figure 32. In this example it is not sure if the fire stopper made of stone wool is really touching the brick facades as there is an air gap between insulation and the brick wall. There would in this case still be a risk for fire spread through the air gap. Solutions with intumescing products are possible in this case.

Figure 32 Example of the introduction of fire stopper in a combustible insulation of a façade system where the external layer is non-combustible (picture Patrick van Hees)

In the same example (see Figure 33) it can also be seen that there are only fire stoppers between the different floor levels in a horizontal way where the different apartments are located. There is no vertical fire stopper between the levels and the staircase which could lead to fire spread to the next floor level through a fire spreading and bypassing the fire stoppers in the insulation from the staircase.

Figure 33 Example of the introduction of fire stopper in a combustible insulation of a façade and where no vertical fire stoppers are placed (picture Patrick van Hees)

Finally, it is important to ensure the quality of possible interface layers which might help to protect the insulation material from ignition e.g. by glass fleece layers as can be seen in Figure 34. In this case the layers have loosened during mounting or due to weather conditions. It is therefore of high importance that these loose parts are fixed again before the façade systems is closed. This can also be important for humidity problems of course.

Figure 34 Example of need for detailed finished of possible protection layers of the insulation material (picture Patrick van Hees)

4.2. Detailed Fire requirements

This subchapter will give an overview on how fire requirements can be achieved for the different risks indicated in the previous chapters (Introduction and chapter 4.1.8)

4.2.1. Prescriptive requirements

4.2.1.1. Building regulations

The rules and requirements in the prescriptive building regulations are quite often grown historically during the major incidents where adaption of regulation or introduction of new rules were necessary. While Sweden has mainly a performance-based regulation, detailed accepted prescriptive solutions are given in the building regulation in order to fulfil the functional requirement of the performance-based solution. (Boverket 2019a). While general rules and requirements are given in the main regulations, Boverket established specific additional guidance for façades. (Boverket 2019c).

The guidance is corresponding to the same type of risks described earlier in this report and is depending on the type or class of building (Br0-Br1-Br2-Br3). Br0 are buildings with very high need for protection (highest level).

The guidance results in the following requirements (see Figure 35) (translation Boverket 2019c) for Br1 buildings (buildings with a high need for protection) connected to 4 risks:

1. Separation between different fire compartments shall be guaranteed.
2. The fire spread in the wall shall be limited
3. Risk for fire spread on the façade surface shall be limited.
4. Risk for damage to people by falling parts of the façade shall be limited.

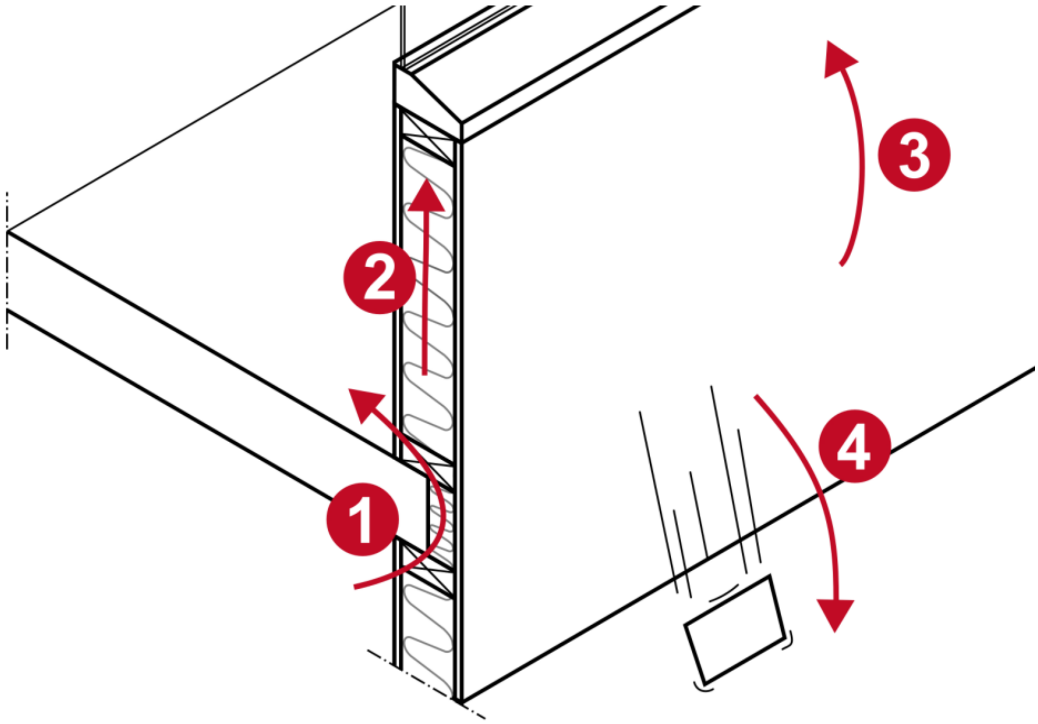

Figure 35 Overview of the different fire risk for façade system as given by Boverket (picture courtesy Boverket, Fabian Ardin)

As it is difficult to refer to one single fire test method in order to fulfil these 4 requirements, a combination of different test methods and their requirement is given in the guidance rules. The reader is referred to the detailed text in the guidance rules. (Boverket 2019c) in order to obtain the information.

A summary of the requirements for Br1 building of more than 8 floors can be given as follows:

- The facade cladding may be either a non-combustible material in class A2-s1, d0 or with certain exceptions in combustible materials of class D-s2, d2, for example if the building is sprinkled.
- Even though the exterior wall construction is of non-combustible material, risks 1 and 4 above must be considered in fire protection design, that is, fire compartments boundaries are maintained and the risk of falling parts is considered.
- For combustible facades in addition to the exemptions that exist in the general guidance, testing according to SP-FIRE 105 applies. However, risk number 1 should be considered since the SP-FIRE 105 test only can be used in order to be able to verify of criteria 2, 3 and 4.

For Br0 buildings which need a higher protection level (very high need of protection) the requirements a performance-based design is required. Examples of such buildings are buildings with more than 16 floors. No specific prescriptive requirements are given but it is considered that the requirements for Br1 are the minimum requirements although that additional requirement might be necessary as a result of the performance-based design.

For Br2 and Br3 buildings (respectively medium and lower need for protection) the façade covering shall fulfil class D-s2,d2 for wall and ceiling linings. These buildings are often one or two storey buildings. More detailed information can be found in Boverkets guidelines (Boverket 2019c).

As can be observed above the requirement of a full-scale test (SP-FIRE 105) is present in the Swedish building regulations but also other options are available. The SP-FIRE 105 test might be replaced by the future European full-scale tests which are under development and which are mentioned in chapter 4.2.1.2. In view of the different options which are given in the regulation to obtain a prescriptive solution it would be good to be able to investigate a number of practical examples to see how the requirements are met for the different façade systems especially those with very complex compositions and constructions.

This report is focused on the Swedish situation but since the Grenfell fire more European countries have established guidance and requirement for façades. As a complement to this study the reader can use the extended and detailed report of the harmonisation work performed an international consortium. In that report which is Annex G to this report, different test methods and additional requirements are given for many of the EU countries (Boström et al. 2018). Specific guidance has been found for a number of countries such as BR135 (Colwell and Baker 2013) for the UK and the guidance documents issued by BBRI for Belgium (Martin et al. 2017). Important to note is that curtain wall claddings are evaluated in most countries solely by means of a fire resistance tests and not evaluated for other risk. This should be considered in the future.

4.2.1.2. Large scale tests for determination of fire risks

One of the major requirements in the Swedish regulation for facades is given in the full-scale test described SP-FIRE 105. The scope of the test is the following:

> *This SP method specifies a procedure to determine the reaction to fire of materials and construction of external wall assemblies or façade claddings, when exposed to fire from a simulated apartment fire with flames emerging out through a window opening. The behaviour of the construction and material and the fire spread (flame spread) in the wall/cladding can be studied. (SP-FIRE 105)*

Figure 36 Front view of the SP-FIRE 105 test (picture courtesy RISE)

The field of application of this test method according to the harmonisation report (Boström et al. 2018) is the following:

> *The test method described is applicable to:*
> *-external wall assemblies*
> *-and façade claddings added to an existing external wall.*
> *The test method is only applicable to vertical constructions.*
> *The method is not applicable for determination of the structural strength of an external wall assembly or façade cladding construction when exposed to fire. (citation Boström et al. 2018)*

The test method itself represents a fully developed fire in a room represented by 60 liters of heptane. The fire exits the fire room through a window with dimensions of 3000 x 710 mm (width x height. The fire room is built by light weight concrete with dimensions of 3000 x 1600 x 1300 mm (width x depth x height). An additional opening through the floor in the back of the fire room with dimension of 3140 x 300mm provides the fire with air. The fire duration is approximately 16-18 minutes. The specimen (4000x6000 mm, width x height) is placed above the fire room and consists of a vertical wall with 2 fictive windows. Temperature and heat flux measurement are performed as well as observation of falling parts.

The test method is referred to in the Swedish building regulations (Boverket 2019a). With the oncoming harmonization of a large-scale test for Europe the Swedish tests will in the long run be replaced by this European harmonized test standard. The harmonization was needed since there exist at the moment a myriad of full-scale tests and requirements in Europe as was indicated in the introduction chapter. A first preliminary study was conducted and is given in Annex G. The outcome of the project is number of proposals for classification and testing and uses the BS 8184 series (BS 2015) and DIN 4102 part 20 (DIN 2016) test or a combination of them to determine the criteria necessary for the fire safety of façades defined by the European members states by adding optional measurements for characteristics that are regulated but not covered by the methods. In addition, an alternative method was included in the report, which tries to merge the two methods into one test method. This option would give one test method and a simple classification system. (Boström et al. 2018). Details of the proposal and the way how this solution was obtained are given in the report in Annex G. The report also indicates a number of future actions of which the following summary is given:

- Countries should check their requirements with the proposed method
- Investigate the field of application
- Investigate which type of façade systems are applicable for the test method and to follow up new façade systems
- Further studies to ensure that the selected method has acceptable repeatability and reproducibility levels.

An Invitation to Tender was launched during the fall 2019 to continue the work and it has been decided to continue with the "alternative" method in Annex G.

4.2.2. Performance based solutions

In case the prescriptive rules are not applicable (e.g. for Br0 buildings) a performance-based solution can be applied (Boverket 2019e). This has resulted in several advices given in BBRAD (Boverket 2019f). BBRAD gives examples and guidance for applying performance-based solutions. While it is not the intention to explain the whole procedure and guidance given in these documents a number of typical assessment methods are given here which are currently used or can be used in the future as part of the research in the project. Parts of this chapter contain namely also pieces of work performed by the project group or international researchers during the duration of project with respect to novel techniques on modelling and risk-based approaches

4.2.2.1. General principle.

The general principle of performance-based design of building is explained in documents such as ISO 23932-1 (ISO 2018) and the SFPE Guide for performance-based design (SFPE 2007). The principle is based on a full analysis of the design process and a summary is given in Figure 37.

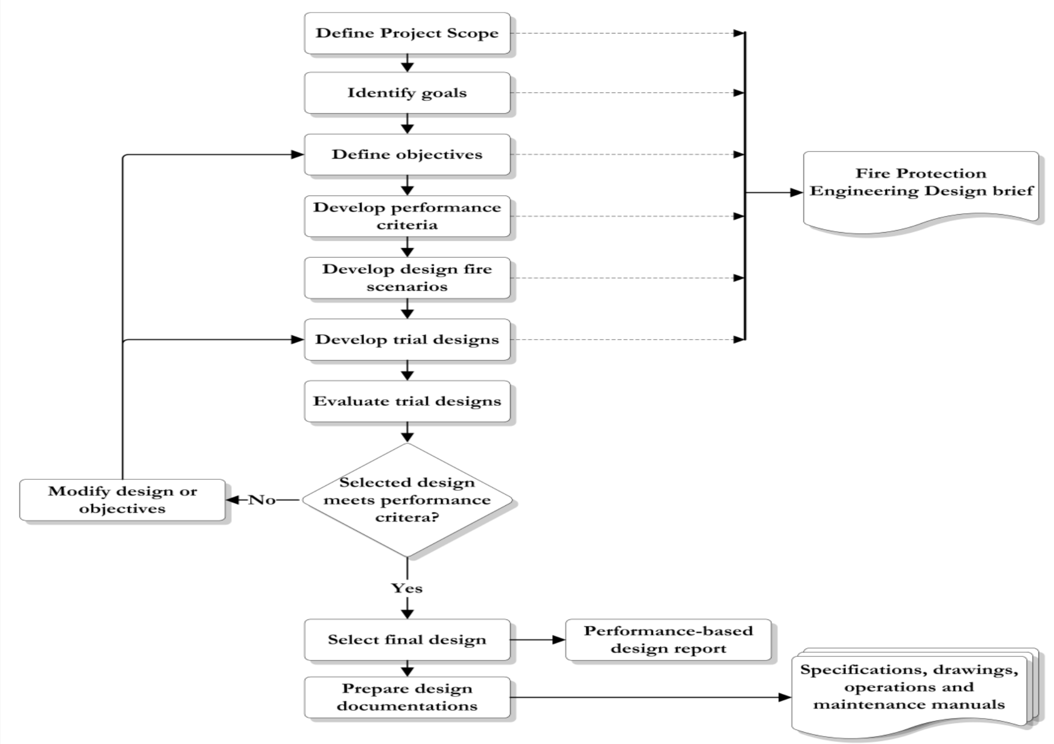

Figure 37 Overview of the performance-based design process (picture adapted from SFPE 2007)

4.2.2.2. Evaluation by experts

During the assessment of the fire safety of a façade system the consultant or the consultant team are often using an expert evaluation of the system. This happens often when the proposed system has not been tested or tested according to other test methods than those proposed in the regulations. While this is allowed in the scope of a performance-based design it would be of high value to screen these types of expert evaluations and to see how they differ e.g. in quality, methodology and final reporting. This is important as it is shown in this study that the façade system(s) can be very complex and final overall fire behaviour can change considerably even if small items are changed in a system.

4.2.2.3. Modelling (Annex B, E and F)

Modelling of fires is part of a continuous effort to be able to predict the fire and smoke spread in building. With respect to facades it would be of value that the actual spread can be predicted either by empirical or by advanced models such as CFD. Internationally several publications are available which show attempts to simulate façade fire by means of modelling. These models are all based on obtaining data from smaller or intermediate scale tests and have different grades of success in prediction the full-scale test results (Carlsson and Karlsson 2001, Drean et al. 2019a, Drean et al. 2019b, Guillaume et al. 2018, Guillaume et al. 2019a , Guillaume et al. 2019b, Anderson and Jansson 2013, Hostikka 2016). The list is certainly not exhaustive but the results show that considerable knowledge and expertise is necessary to perform this type of modelling and that it might not be possible to apply such modelling in daily assessment of facade systems for performance-based design.

During the project a number of initiatives were taken to try to investigate how one could predict the fire spread on a façade system. Two approaches were investigated in this project.

The first one was to investigate the prediction on an ETICS system and the determination of model parameter for three type of different EPS insulation materials. The work was performed within a master thesis of the international master of fire safety engineering (IMFSE) and gives a good indication on how difficult it is to obtain all the material parameters of three rather similar insulation materials and to simulate the large-scale behaviour in the BS 8414 (Branisteanu-Albulescu 2019). It could be seen that differences in the different fire properties of the insulation could be detected for the different small-scale tests (microcalorimeter, TPS, bomb calorimeter, TGA and cone calorimeter) but that it was very difficult to simulate the initial conditions of the large-scale test of BS8414 and the final application of the insulation. The report can be found in Annex B.

A similar work was done within a post doc work as a cooperation between DBI and LTH Fire Safety Engineering. In this work, the insulation component of an EPS ETICS façade was tested using micro- to small-scale methodologies. The objective of this is to characterize some of the fundamental thermal material properties, ignitability, heat release, and flame spread of the specific components. The aim was to extend later these results to a larger-scale methodology for assessing of complete systems. The testing can than later also be complemented by numerical modelling to enable more scaling. The result of this study was a method for extracting apparent flame spread properties from flame retarded polystyrenes. (McLaggan et al. 2018).

The second approach was to investigate how it could be possible to study the flames in the void of the façade system. A medium scale test set-up was in order to study the flame increase in a void of a façade system. In Figure 38 pictures are showing the considerable extent of the flame when the cavity becomes smaller and smaller. The experiments showed also up to 50% higher flames than those reported in previous research by Karlsson et al. (Karlsson et al.). This inconsistency could be explained by the fact that Karlsson et al. used a burner in the middle of the cavity, while in this study, it was placed next to the near wall. The performed study provide data for investigating fire induced flows, heat transfer and flame spread modelling in vertically oriented air cavities and showed how complex and different the fire dynamics are in a cavity in comparison to a flame in a wall configuration. The work should however be complemented by further analysis on how ventilation and ventilation restriction can affect the flame. This modelling was further explored in a paper dealing with the modelling of the flames in FDS. (Livkiss et al. 2019). The modelling of these types of fire induced flow in narrow cavities is creating challenges as it is related to the need to use very fine mesh, because of geometrical characteristics of the computational domain (Livkiss et al. 2019).

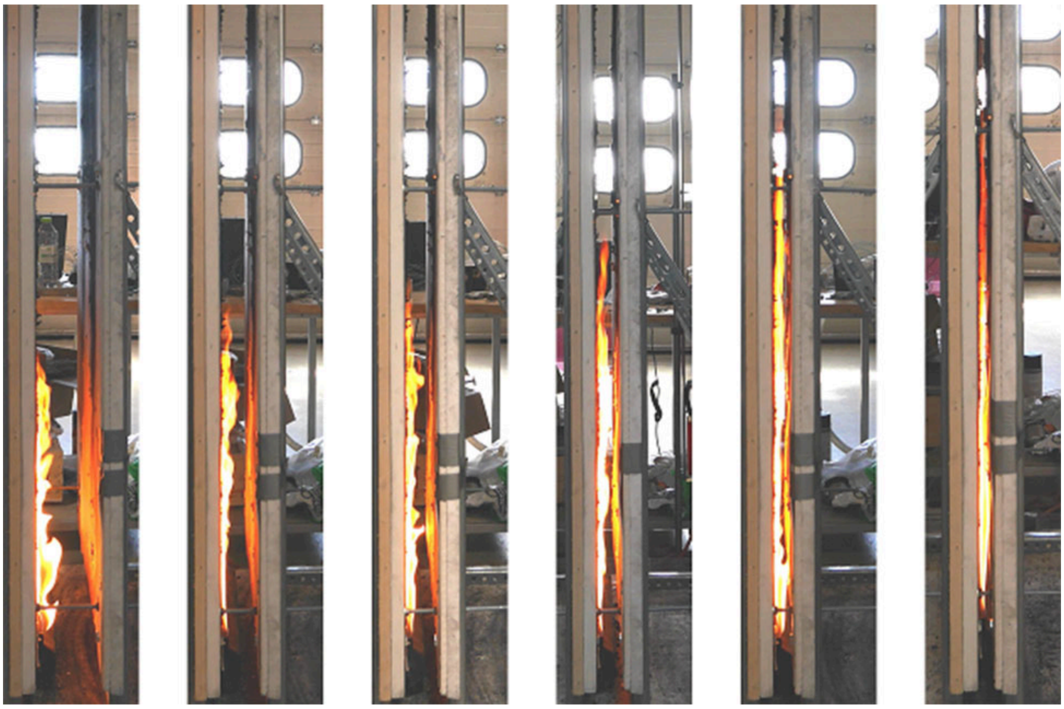

Figure 38 Photos of the experimental series II. Width of the cavity from left to right: W = 10, 6, 5, 4, 3 and 2. (picture courtesy Karlis Livkiss, Livkiss et al. 2018) Pictures taken during steady state conditions.

Both papers are annexes to this report and can be provided by the authors on request.

4.2.2.4. Risk based approaches

After the Grenfell fire a number of initiatives were taken to establish methods to have a risk-based tool to screen the fire behaviour of a façade system in order to exclude certain solutions or to require more testing for certain systems. Two different tools were found in the literature and through discussion with experts.

The first was an Excel based tool developed by van Mierlo at DGMR in the Netherlands (Van Mierlo 2018). The Excel sheet includes 4 facade features and 5 building (usage) features. For each of these characteristics, a value must be given from a short list of options. Based on this input, a building is classified into one of the four possible categories of red, orange, yellow or green and allows then further assessment according to the Dutch Building regulations.

The second one is an internet-based tool developed by Arup and published as an NFPA report (Lamon and Ingolfsson 2018, Messerschmidt and Lamon 2019) and is a fire risk assessment tool for High Rise buildings with combustible exterior wall assemblies and is called NFPA's EFFECT ® Tool. The methodology is more qualitative than quantitative and follows internationally recognized risk assessment approaches and results two tier approach to the risk assessment tool. Tier 1 is a prioritization stage based on a qualitative assessment based on PAS 79 (BSI 2012) to be used where a regulation has a large number of buildings to review and needs to prioritize those at highest risk. Tier 2 is a more detailed fire risk assessment, also based on PAS 79 (BSI 2102), on a building by building basis looking at those of highest priority first (Lamon and Ingolfsson 2018). The report results also in a number of recommendations for future which are useful to see how research can help future development of the method. Amongst the recommendation is the use of small destructive testing, further fire testing to validate the tool, further determination of ignition properties, investigate to introduce a smoke toxicity parameter and introduction of a tier 3 level. The Fire Risk Assessment Tool can be found at: www.nfpa.org/exteriorwalls.

Both tools are very interesting to look into further in order to implement or adapt them for a number of applications in Sweden in order to assist the designer to make the appropriate choices.

4.3. Summary

In this chapter an overview was given of all different technical properties and requirements which relate to different façade systems. The study resulted in the following technical requirements:

- Esthetical aspect
- Insulation properties
- Humidity aspects
- Pressure and wind stability
- Mechanical stability
- Rainscreen properties
- Acoustical performance
- Fire requirement.

Many of these aspects are overlapping and influence each other and the importance of them depend a lot on the type of façade systems and its complexity. For this reason, a case study is necessary to go into depth how these interaction works and to give for detailed guidance to user and designer of façade systems

With respect to the fire requirements more detailed information was given showing that also here more in depth knowledge is needed on all levels of assessments: prescriptive rules and different type of performance-based design such as expert level assessment, full scale testing and modelling.

5. Socio- technical system considerations and regulatory system comparisons

This chapter gives a short overview of outcome of the socio – technical systems considerations and regulatory systems. It is a summary of the report issues by BRIAB as part of WP 3 (Meacham, Strömgren, 2019).

5.1. Introduction

The HOLIFAS project aims to identify and address challenges with fire safety of facades from a technical and regulatory perspective. While the other work packages mainly deal with the technical challenges, this chapter (WP3) focuses on the regulatory challenges, as viewed through a socio-technical systems (STS) lens. Here, the regulatory regime is considered as a socio-technical system with complex interactions between institutions, actors (stakeholders) and technology. The structuring of the socio-technical building regulatory system assessment methodology (STBRAM), including diagnostic questions and answers, can be found in the separately published WP3 report (Meacham, Strömgren, 2019).

The starting point for this project is the aftermath of the Grenfell Tower fire in London in June 2017. As the picture of what happened started to become clear, government and industry stakeholders in many countries sought to understand whether similar accidents could happen in their respective countries, and the roles that regulations, practitioners and technology played. The Hackitt review in England (Min. of Housing 2017c, Min. of Housing 2018a and b), the Shergold and Weir review in Australia, (Shergold and Weir 2018) and the Ministerial Review on Building Standards (Fire Safety) in Scotland (Stollard 2018) are just a few examples.

From the very beginning, attention was focused on the fact England operated under a functional-based building regulatory scheme, and questions were raised as to how this might have contributed to the significance of the fire. Arguably, Australia and Scotland began reviews for similar reasons, as the Australian system is performance-based and the Scottish is functional-based (although different from England). In addition, Australia also had by some accounts narrowly avoided a 'Grenfell-type disaster' when the exterior cladding of the Lacrosse Building in Melbourne caught fire and burned up the side of the building, and post-incident investigations surrounding that event highlighted numerous building regulatory system concerns. (Metropolitan Fire and Emergency Services Board 2014).

Since Sweden was an early adopter of performance-based building and fire safety regulations, it shares common denominators with the Australian, English and Scottish regulatory systems. Therefore, even though Sweden had not suffered a Grenfell-type façade fire, it was deemed important to review the interactions of the regulations, actors and technologies used for façade systems in the Swedish context as well. This view was informed in part by recent studies into how the system is working for fire safety engineering in Sweden (Meacham 2017, Strömgren 2017, McNamee et al. 2019).

The recent studies and the Grenfell event suggest that the current regulatory regime for structural fire safety in Sweden should undergo re-evaluation. While the Swedish building regulatory system is currently under review with respect to becoming more modern, Näringsdepartementet 2017) that review is not specifically focused on building fire safety and associated infrastructure. Considering the situation in England with the Grenfell fire, it is clear that there are challenges and risks inherent in the regulatory regime which require attention to ensure that they continually lead to the desired safety outcomes. Since there is often a long-time lag for fire events as compared to other hazard events (e.g., wind or snow events), fire rarely stress a building's fire safety system, so it is challenging to evaluate the performance accordingly. Holistic approaches are needed to anticipate systemic problems and to capture and address them early on. Systemic problems may affect building owners, insurance industry, tenants and many other stakeholders in the built environment.

Fire safety provisions in building regulation are about managing risk. In order to appropriately characterize and incorporate risk measures into building regulation, it is helpful to view building regulatory systems as complex socio-technical systems (STS) (Meacham and Van Straalen 2017). STS theory and concepts emerged from studies of organizations and the roles of social and technological components, and the realization that they are integrally linked (Cherns 1976 and Emery 1993). The initial structuring of the social-technical building regulatory system (STBRSAM) laid out some fundamental parameters and suggested how components of the building regulatory system need to interact with other institutions and actors, operating between the public and private sectors (Näringsdepartementet 2017). In this study, the STBRS methodology is further refined for use as a tool for analysing building regulatory systems. The outcome is the STBRS Assessment Method (STBRSAM). As a means to assess the STBRSAM reactively and proactively, it is applied to both the English and Swedish regulatory systems. In both cases, data used to underpin the assessments come largely from published reports and literature.

5.2. The STBRSAM

Starting with the construct of building regulatory systems as complex socio-technical systems (STS), and building from the socio-technical building regulatory systems framework, (Näringsdepartementet 2017) a first order socio-technical building regulatory system assessment model (STBRSAM) has been developed (Meacham 2019). The STBRSAM considers primarily the building-actors-institutions interactions associated with building design, construction and management, including government and private sector. The current version of the STBRAM is focused around the fire and life safety aspects of building regulation, and does not currently explicitly consider structural systems, mechanical systems, etc., except in relation to fire performance. In addition, land use planning, zoning, and related regulatory influences are not considered. The STBRSAM is illustrated in Figure 4.

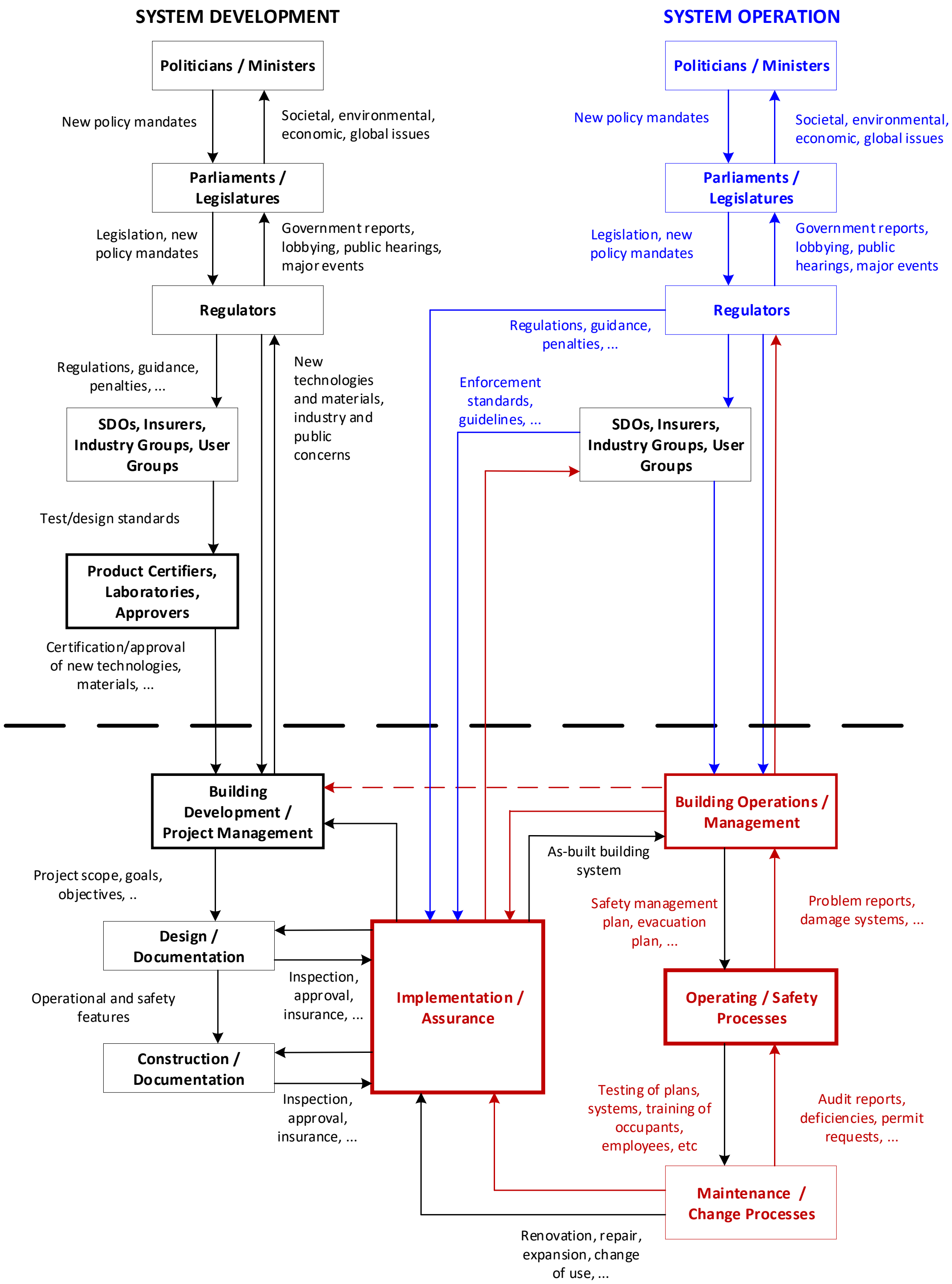

Figure 39 Socio-technical building regulatory system assessment model (STBRSAM).

The STBRSAM is characterized by seven major 'levels' of actors that intersect across two primary 'operating' system regimes – system development (building design and construction) and system operation (buildings in use). The considered components of, and interactions between, the seven levels are as follows:

1. Politicians / Ministers (i.e., policy setters)
2. Government / Legislation (i.e., policy implementers – members of parliament, legislature, etc., and governing legislation, Acts, and the like)

3. Regulators / Regulations (i.e., government entities with responsibilities for development and promulgation of regulations and guidance, and the regulations that they develop)
4. Standards Development Organizations / Standards (i.e., private sector organizations who develop standards referenced in regulation, and the standards that they develop)
5. Certifiers / Enforcers (i.e., government or private sector entities with enforcement authority)
6. Developers / Owners / Operators
7. Development side (i.e., those that contract works to be done)
8. Operations side (i.e., owners, operators, managers)
9. Implementation / Assurance (i.e., the inspection, enforcement, control aspects)

As its diagnostic base, the STBRSAM utilizes questions related to the following fundamental factors. Note that while these have been tailored to fire as a hazard, the STBRSAM is easily modifiable to other hazards (e.g., wind, snow, earthquake, moisture, flood, etc.) simply by changing the focus around factor 3:

1. Policy objectives unclear, ambiguous, or in conflict with respect to constraints
    a. Understanding, characterization and treatment of risk / mitigation lacking
    b. Understanding of communication flows, responsibilities and accountabilities lacking
2. Inadequate implementation or enforcement of constraints
    a. Regulatory structure lacking, misinterpreted or not properly followed
    b. Regulations lacking, misinterpreted or not properly followed
    c. Standards lacking, misinterpreted or not properly followed
    d. Certifications / approvals lacking, misinterpreted or not properly followed
    e. Non-mandatory guidance lacking, misinterpreted or not properly followed
    f. Design and analysis processes lacking, misinterpreted or not properly followed
    g. Construction acceptance / approval processes lacking, misinterpreted or not properly followed
    h. Design, construction, inspection, test, maintenance, safety management documents missing or lacking
3. Inadequate execution of control actions
    a. Fire safety systems inspection, test, maintenance documents lacking, misinterpreted or not properly followed
    b. Fire safety management plans lacking, misinterpreted or not properly followed

   c. Evacuation plans lacking, misinterpreted or not properly followed
   d. Fire risk assessment plans lacking, misinterpreted or not properly followed
   e. Safety management / occupant training processes and procedures lacking, misinterpreted or not properly followed

4. Inadequate or missing feedback through the system to pertinent actors
   a. Building / system modifications, updates, replacement, exchange, expansion not properly communicated through the system
   b. Building management / operations information not properly communicated through the system
   c. Information / concerns from management to occupants not properly communicated through the system
   d. Information / concerns from occupants to management not properly communicated through the system

Based on this classification scheme and associated factors, a set of targeted questions is developed regarding the completeness and quality of information flow in the system which are used to help identify gaps and risks in the regulatory system.

The STBRSAM was applied to the building regulatory systems in England and Sweden, with the intent to be relatively wide-ranging, yet with particular attention given to high-rise, high-risk, and complex buildings. For both England and Sweden, the majority of factors considered by the STBRSAM resulted in 'inadequate' ratings.

For England, this is arguably biased by the Hackitt review and associated findings following the Grenfell Tower fire. However, several of the identified inadequacies have been identified in other studies of building regulatory systems and are not unique to England. For Sweden, other reviews and finding supports similar conclusions. For information about the actual analysis, as well as for more comprehensive results, the reader is referred to the the full WP 3 report (Meacham and Strömgren 2019).

5.3. Key Issues – English Building Regulatory System

A majority of factors considered by the STBRSAM for England resulted in 'inadequate' ratings. This is biased by the Hackitt review and associated findings following the Grenfell Tower fire. However, several of the identified inadequacies have been identified in other studies of building regulatory systems and are not unique to England. These include:

- Inadequate clarity regarding roles and responsibilities
- Inadequate understanding of expected performance (i.e., lack of criteria)
- Inadequate competency and qualifications structures
- Inadequate control and enforcement, in this case driven by uncertainty regarding the responsible entity
- Inadequate communication between actors and actor levels

The extent of these shortcomings overwhelmed the positives, which include:

- Adequate policy objectives as related to fire performance expectations

- Largely adequate system of standards (which were not always used appropriately)
- The availability of adequate guidance
- The availability of adequate tools of assessments (tests and computer models)

Arguably, the most important outcomes are:

- Widespread lack of clarity in roles and responsibilities,
- Lack of clear competency and accountability structures, and
- Ethically questionable practices, leading to low bids, incomplete analysis, poor execution, and little to no follow through

Much of the support infrastructure exist and should have (and arguably would have) sufficed had better mechanisms for the above been in place.

5.4. Key Issues – Swedish Building Regulatory System

There are large similarities between the Swedish and the English Regulatory System. Both countries were early adopters of performance-based design and have deregulated large parts of the building control. Both countries allow complex buildings and fail-sensitive solutions e.g. tall buildings with a single means of escape, combustible material in external walls and optimized designs with small safety margins. Desktop studies, i.e. allowing verification of fire performance of products and systems in lieu of testing, is also allowed in both countries.

As noted for England, Sweden shares the following inadequacies:

- Inadequate clarity regarding roles and responsibilities
- Inadequate understanding of expected performance (i.e., lack of criteria)
- Inadequate competency and qualifications structures
- Inadequate control and enforcement, in this case driven by uncertainty regarding the responsible entity
- Insufficient transparency, i.e. lack of audit trails and information requirements
- Inadequate communication between actors and actor levels

The extent of these shortcomings overwhelmed the positives, which include:

- Adequate policy objectives as related to fire performance expectations
- Clear regulatory structure
- The availability of adequate tools of assessments (tests and computer models)

Arguably, the most important outcomes are:

- Widespread lack of clarity in roles and responsibilities,
- Lack of clear competency and accountability structures

The Swedish regulatory system is currently under review and while there's certainly some infrastructure in place there are several critical areas that need to be addressed.

5.5. Summary

The STBRSAM was developed and applied to building regulatory systems in England and Sweden, with a focus on fire as the hazard of concern. The application of the STBRSAM to England raised issues identified in the Hackitt review. In doing so, it demonstrates proof of concept for the applicability of the STBRSAM. The application of the STBRSAM to Sweden raises similar issues as identified in England. Both systems show inadequacies that may lead to unsafe buildings.

5.6. Future Research

As a first order tool, the STBRSAM was applied only to fire safety related aspects of the subject building regulatory systems and was applied independently by two researchers. In the future, it is hoped that:

- The STBRSAM will be tested for different safety concerns within building regulatory systems (i.e., against different hazards) as well as for applicability to non-safety aspects as well (e.g., accessibility). It is assumed that some aspects will need to be modified, but that the structure will suit.
- A more robust ranking system will be explored, ideally establishing weightings for the four fundamental factors. As part of this, it would be helpful to form a group of experts to provide their views within a structured weighting process, such as the analytical hierarchy process (AHP) or other.
- Importance analysis is applied to perhaps simplify the model to a smaller set of subfactors and associated questions.

6. Dissemination

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6.1. Publications

Following publications were obtained during the project as part of the project or as co-funding of the project.

- Karlis Livkiss, Bjarne P. Husted, Tarek Beji, Patrick van Hees, **Numerical study of a fire-driven flow in a narrow cavity**, Fire Safety Journal https://doi.org/10.1016/j.firesaf.2019.102834, 2019.
- Branisteanu-Albulescu Bogdan-Grigore, **Fire safety of facades**, Master Thesis Lund University, Report nr. 2019.
- Karlis Livkiss, Stefan Svensson, Patrick van Hees, **Flame Heights and Heat Transfer in Facade System Ventilation Cavities**, https://doi.org/10.1007/s10694-018-0706-2 Fire Technology, 54, 689–713, 2018.
- Michael Strömgren, Brian Meacham, **HOLIFAS Project – WP 3: Socio-Technical System (STS) Considerations**, BRIAB report, 2019.
- Patrick van Hees, Michael Strömgren, Brian Meacham, **An Holistic approach for fire safety requirements and desing of façade systems**. Interflam 2019 proceedings, Interscience Communications, 2019.
- Patrick van Hees och Michael Strömgren, **Brandskydd i fasader kräver ett helhetsperspektiv**, Bygg och teknik, 2., 6/18 sid 73, 2018.
- Karlis Livkiss, **Fires in Narrow Construction Cavities - Fire Dynamics and Material Fire Performance**, PhD thesis, Lund Report LUTVDG/TVBB--1061—SE, ISBN 978-91-7895-394-3. Lund University, 2020.
- Brian Meacham, Michael Strömgren, Parick Van Hees P., **An Holistic Framework for Development and Assessment of Risk-Informed Performance-Based Building Regulation**, Fire and Materials Journal in printing, 2020.
- Martyn McLaggan, Konrad Wilkens Flecknoe-Brown, Anders Dragsted, Patrick Van Hees, **Heat release and flame spread assessment of insulation in External Thermal Insulation Composite System (ETICS) facades,** 3rd European Symposium on Fire Safety Science 12–14 September 2018, Nancy, France. 2018.

Additionally, the project was presented at the following conferences:

Fire Seminar Antwerp by Patrick van Hees, June 20th 2019

Interflam 2019 conference by Patrick van Hees, July 1st- July 3rd 2019.

Finally, the project has been supported the discussion and quality assessment of the PhD project of Karlis Livkiss resulting in a PhD during 2020 (Livkiss 2020).

6.2. PhD course during the project

At the beginning of the project a PhD course was organized by Lund University and supported by the PhD research school from Chalmers University. This is the summary of the program of the PhD course. The PhD course was also used as input on the other non-fire requirements from façades and as part of the expert discussions between the teachers before the course.

7. Conclusions and future work

This report has been looking through a holistic approach into the different technical aspects related to façade systems and has reached the following conclusions:

- It is important to define very detailed what is understood in the term façade in order to be able to determine correctly the different technical properties.
- The project categorised different specific type of façades but also detected that a simple categorisation is not easy and that new and innovative façade system are developed which are very difficult to be assessed in a similar way as one of the simple categories.
- Façade systems are very complex and should be considered as systems when considering most of the technical properties of a façade. F
- The different technical properties and their requirements differ depending on the category of façade system and should almost be looked to case by case if the building is more complex. Much more guidance needs to be developed in order to investigate the technical properties of façade systems and what type and level of technical requirements should be required.
- Case studies are needed to look into detail to all technical requirement and how they interact for different type of façade systems.
- A first order socio-technical building regulatory system assessment model (STBRSAM) has been developed and applied for two countries. This model has shown promising results and can be further developed and evaluated.
- With respect to fire safety it is important to study all different components in a façade system and ensure that the overall fire behaviour is sufficient for the risk involved. Case studies are needed to investigate how prescriptive rules consider all aspects of a façade system and certainly how expert evaluation are performed and used. Economical aspects should be included in the choice of systems.
- Modelling of fire spread in façade systems is always improving and promising results are available but there is need for further development with respect e.g. to obtaining input parameters, overall inclusion of all items in a system with respect to the model, understanding of the fire spread inside cavities, validation of the models etc. Full scale tests and screening tests are however necessary in final evaluation of the façade system.
- Risk analysis tools are very promising for screening the complex behaviour of façade system. Good examples are developed and it is worth investigation how they can be used in Sweden or further developed.

The project indicates the following areas for further future work:

- Work with respect to definition, constructional types and requirements
    - Further work on defining façade systems in buildings. It is important to know exactly what is considered a façade system in order to examine the different properties.

  - Further work on categorising the façade systems depending on the type of construction and also the technical requirements needed as the different requirement are in fact different for different types of façades systems. No real overview exists at this moment.
  - Study of a number of case studies of real building projects which uses the different façade systems with respect to all technical requirements and also with respect to expert evaluations. It is important to study how the different requirements are fulfilled especially for a performance-based evaluation
- Work with respect to fire behaviour
  - Fire Modelling of façades systems and all aspects connected to it such as input of data for modelling, validation of models and further improved of the models. The project showed that there is need for a lot of further research to model large and full-scale behaviour of complete façade systems.
  - Investigate the possibility for screening methods of façade systems or subsystems to reduce the amount of full-scale testing. As there is a large amount of different materials in a façade system there is a need to have a screening method to evaluate certain parts and to set-up rules how to evaluate the system. The procedure should however guarantee that full scale behaviour is reflected with satisfaction in these screening methods.
  - Investigation of the use of fire risk models for Sweden to have a good picture what is used for the moment.
  - Further studies to develop further the risk models available or to introduce them (if not available).
  - Investigate if the risk models can be combined into an overall risk model for all technical properties, so that the designer of the façade system can use a holistic approach.
- Work with respect to the socio-technical aspects.
  - Testing of the STBRSAM concept for different safety concerns within building regulatory systems (i.e., against different hazards) as well as for applicability to non-safety aspects as well (e.g., accessibility).
  - A more robust ranking system needs to be explored, ideally establishing weightings for the four fundamental factors. As part of this, it would be helpful to form a group of experts to provide their views within a structured weighting process, such as the analytical hierarchy process (AHP) or other.
  - Importance analysis is applied to perhaps simplify the model to a smaller set of subfactors and associated questions.

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Annex A Market Survey BRIAB Different construction types

This annex contains a general description of different construction types for exterior wall assemblies, and challenges regarding fire protection related to each construction type. The scope is limited to construction types containing combustible insulation.

The following six construction types are most common:

- Sandwich walls
- Half sandwich walls
- Cavity wall constructions
- Plaster systems
- Exterior wall with panels, wooden panels, stone or other façade lining.
- Sandwich panels

Sandwich walls

A sandwich wall consists of prefabricated concrete elements with insulation fully enclosed in concrete. Combustible and light insulation materials are often used to obtain good insulation properties. It is common that these constructions contain EPS or corresponding cellular plastics with low cost and acceptable insulation properties. A typical design is that the concrete is divided in connection with window fixings to avoid thermal bridges. In connection with window fixings the cellular plastic is protected with e.g. mineral wool.

The fire protection of the exterior wall construction is mainly that the combustible insulation is fully enclosed in concrete. Fire spread to the combustible insulation is thereby prevented. With regards to this, insulation with poor fire properties (usually Euroclass E or even F) are often used. Depending on the required safety level of the building and other redundancies, other safety barriers are applied within the wall. It is common to place mineral wool insulation or equivalent in floor slab edges and element joints to prevent fire spread within the wall.

The design of exterior walls with sandwich construction is made in accordance with the general recommendation in the Swedish building regulations. The main challenge is to prevent fire spread within the wall, since the insulation usually has poor fire properties. The main principle is to prevent fire from entering the wall construction and then add safety barriers.

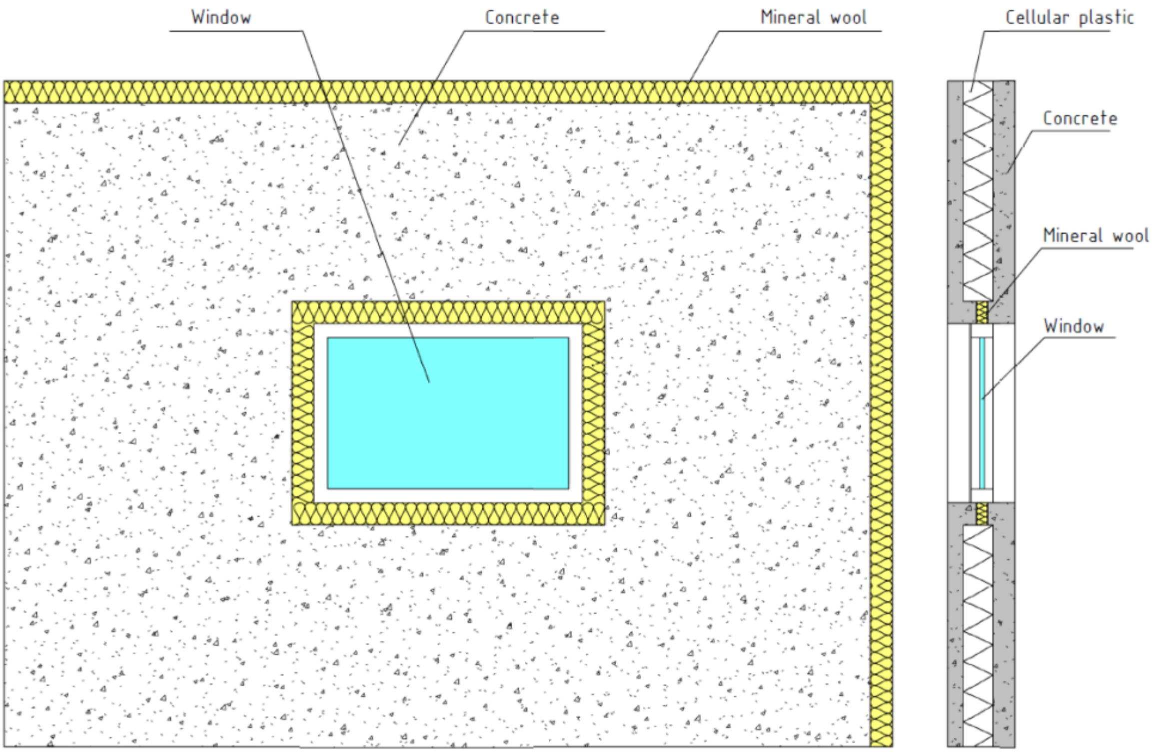

Figure A- 1 Typical design of sandwich walls with safety barriers in connection with windows and element joints.

Half sandwich walls

A half sandwich wall consists of prefabricated elements with an inner concrete slab with external insulation and a plaster bearing façade panel (usually made of mineral wool). The half sandwich element design is similar to sandwich elements, usually with EPS or other cellular plastics with low cost and high insulation properties.

The most significant difference is that the exterior protection consists of a plaster bearing façade panel. With regards to the plaster bearing design, there's a risk that a fire can affect the plaster bearing fixings and that the exterior protection barrier falls down. This means that two performance criteria are not fulfilled; limitation of fire spread within the wall; and protection against falling parts. Hence, the fixing of the plaster bearer is of critical importance, and it should be fixed to the inner concrete slab.

As for sandwich walls, the design is made in accordance with the general recommendations in the Swedish building regulations. The major challenge is to prevent fire spread within the wall, since the insulation usually has poor fire properties. The main principle is to prevent fire from entering the wall construction and then add safety barriers within the wall.

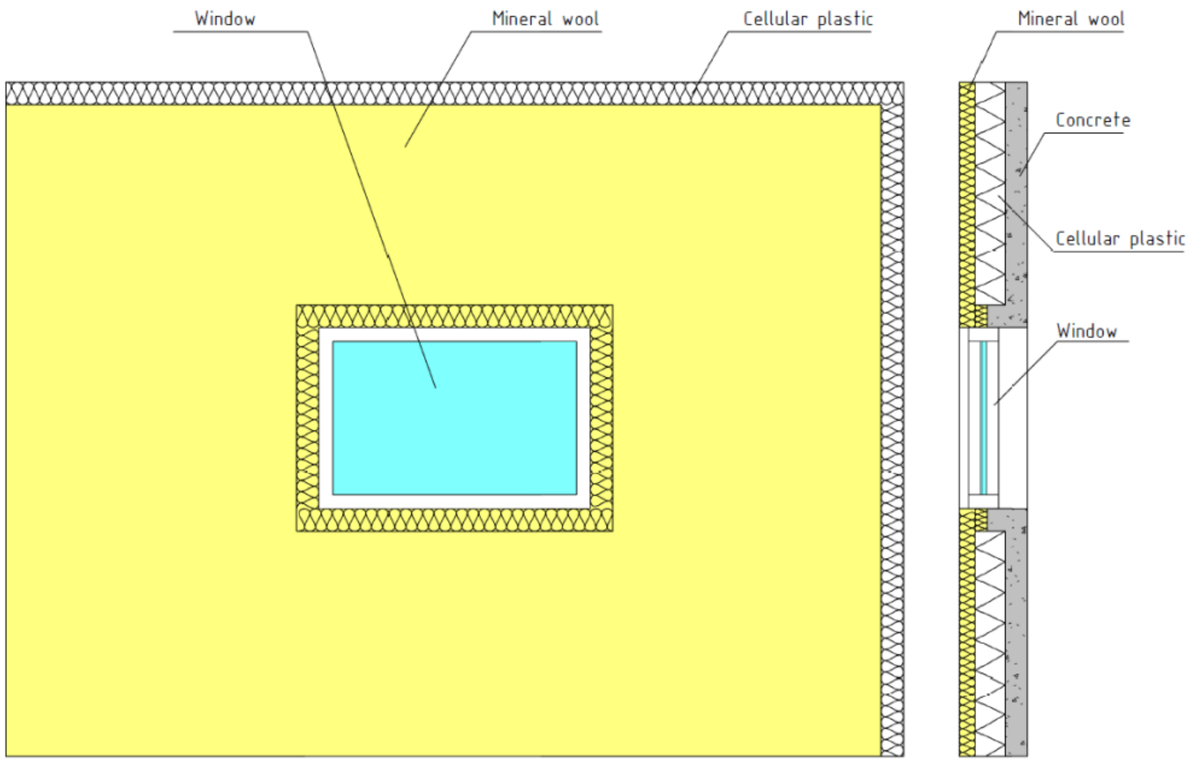

Figure A- 2 Typical design of half sandwich walls with plaster bearers in mineral wool and safety barriers in connection with windows and element joints.

Cavity wall constructions

Cavity wall constructions can either be prefabricated or built on site. A common design is that the wall has an inner concrete slab, insulation, an air gap and the outer wall, e.g. a brick wall. The inner concrete slab could however be made of optional construction that fulfils at least fire resistance class EI 60. Unlike sandwich walls and half sandwich walls, the insulation is not fully enclosed in safety barriers, but freely exposed to an air gap.

It is also difficult to separate the air gap with safety barriers at element joints, since the ventilation is needed for the durability of the construction. Since the insulation is freely exposed, insulation with better fire properties is usually required, e.g. some PIR, PUR or PF insulations.

In this case, it is not possible to follow the general recommendations in the Swedish building regulations to achieve a sufficient safety level, primarily due to the air gap design. The exterior wall construction as a whole must undergo fire testing according to the test method SP-FIRE 105 to show that the performance requirements are fulfilled.

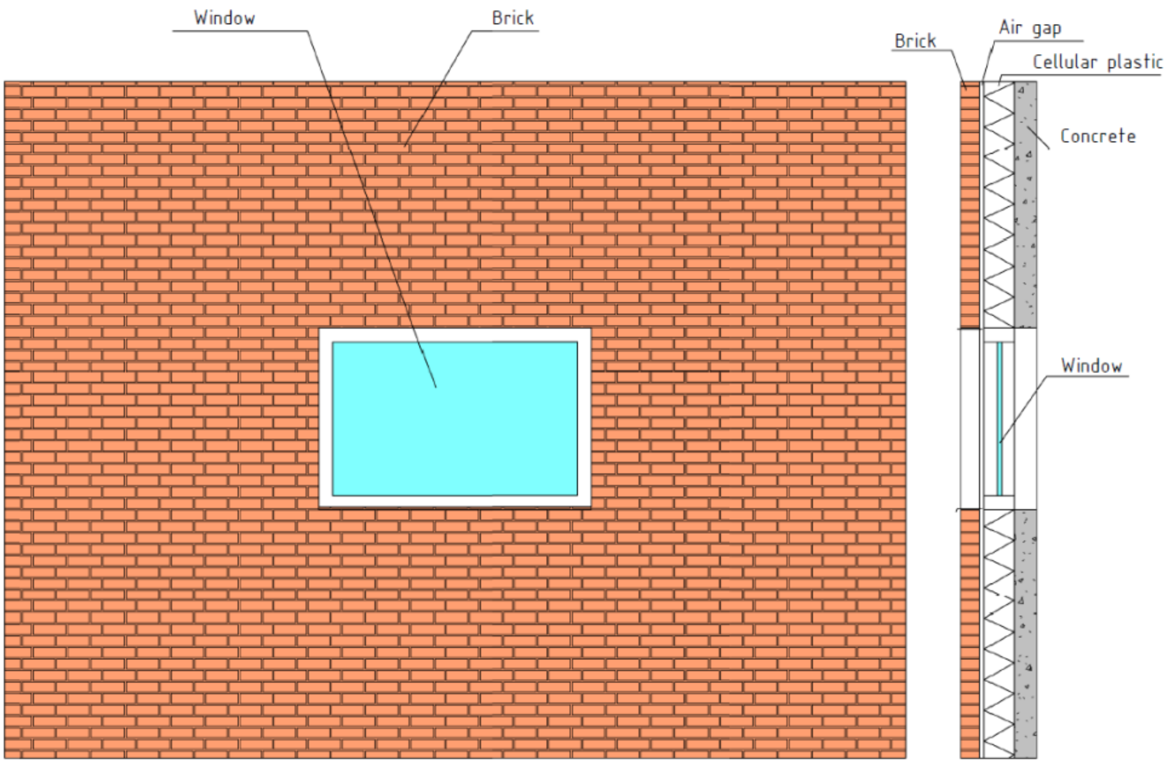

Figure A- 3 Typical design of a cavity wall construction with an inner concrete slab, combustible insulation and a brick wall.

Plaster systems

Exterior walls with different kinds of plaster systems usually consist of an inner concrete slab and insulation, often with multiple different layers, on which plaster can be applied directly. The inner concrete slab could however be made of optional construction that fulfils at least fire resistance class EI 60. Unlike half sandwich walls, there is no exterior façade panel of mineral wool that protects from fire from the outside. There are both thin plaster systems (single millimetres in thickness) and thick plaster systems (single centimetres in thickness).

Regardless of the plaster system design, it is difficult to assess the fire properties of the finished plaster. The heat resistance of the plaster and how large pieces of plaster that might be released from the insulation and fall down is not possible to determine in advance. Plaster systems without an outer safety barrier must therefore undergo fire testing according to the test method SP-FIRE 105 to show that the performance requirements are fulfilled

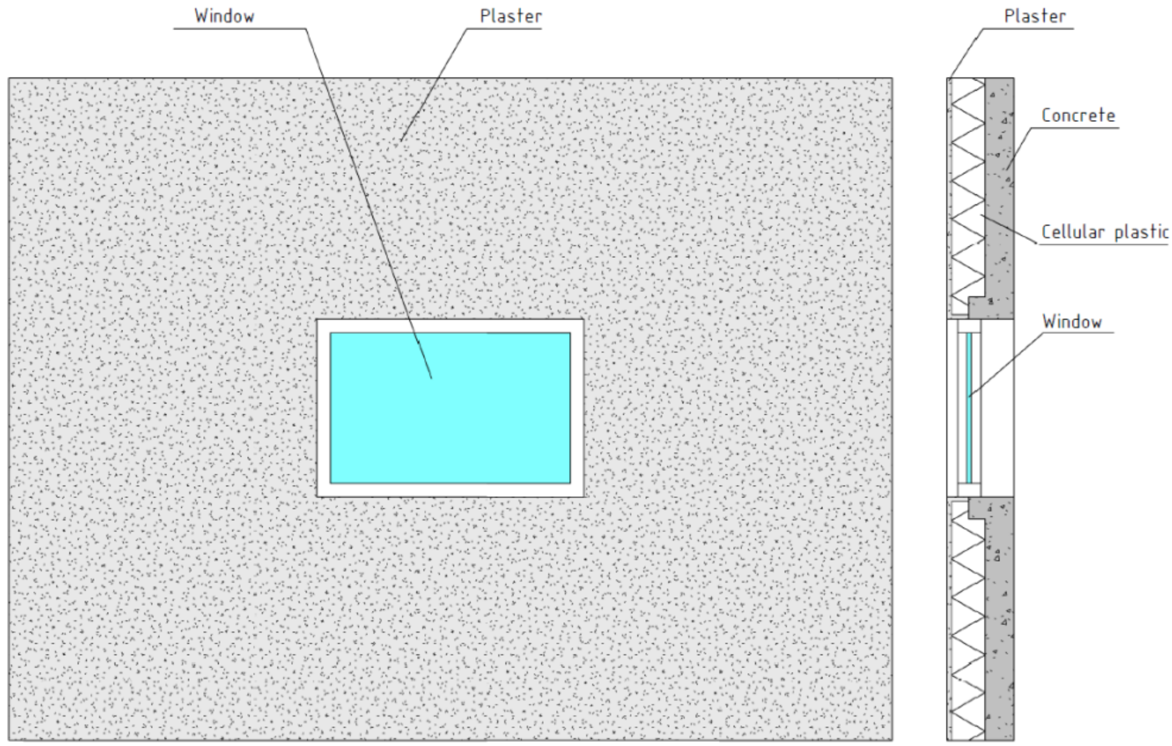

Figure A- 4 Typical design of an exterior wall with combustible insulation with plaster system.

Panels, wood panelling, stone or equivalent

It is becoming more and more common to use other materials than the traditional materials i.e. concrete, plaster or bricks in larger buildings. These are usually built with an inner slab of concrete (or other optional construction that fulfils at least fire resistance class EI 60), insulation and an air gap. The desired façade material is then mounted on laths. The most common materials today are different panel materials (both combustible and incombustible), wood panelling, clinker brick and other types of stone tiles.

Unlike sandwich walls and half sandwich walls, the insulation is not fully enclosed in safety barriers, but freely exposed to an air gap. It is also difficult to separate the air gap with safety barriers at element joints, since the ventilation is needed for the durability of the construction. Since the insulation is freely exposed, insulation with better fire properties is usually required, e.g. some PIR, PUR or PF insulations.

Another challenge with this type of façade construction is falling construction parts. The façade material properties are therefore important for the fire protection. Exterior wall constructions designed completely with incombustible materials might also need to undergo fire testing to show that the performance requirement regarding falling parts is fulfilled.

If the façade material is combustible, another challenge regarding fire protection is added, since the fire can spread across the façade surface. Considering the construction design, there is risk of fire spread within the wall, fire spread across the façade surface, and risk of falling parts. All performance requirements in Swedish building regulations (bullet 2-4) must be verified through fire testing according to the test method SP-FIRE 105.

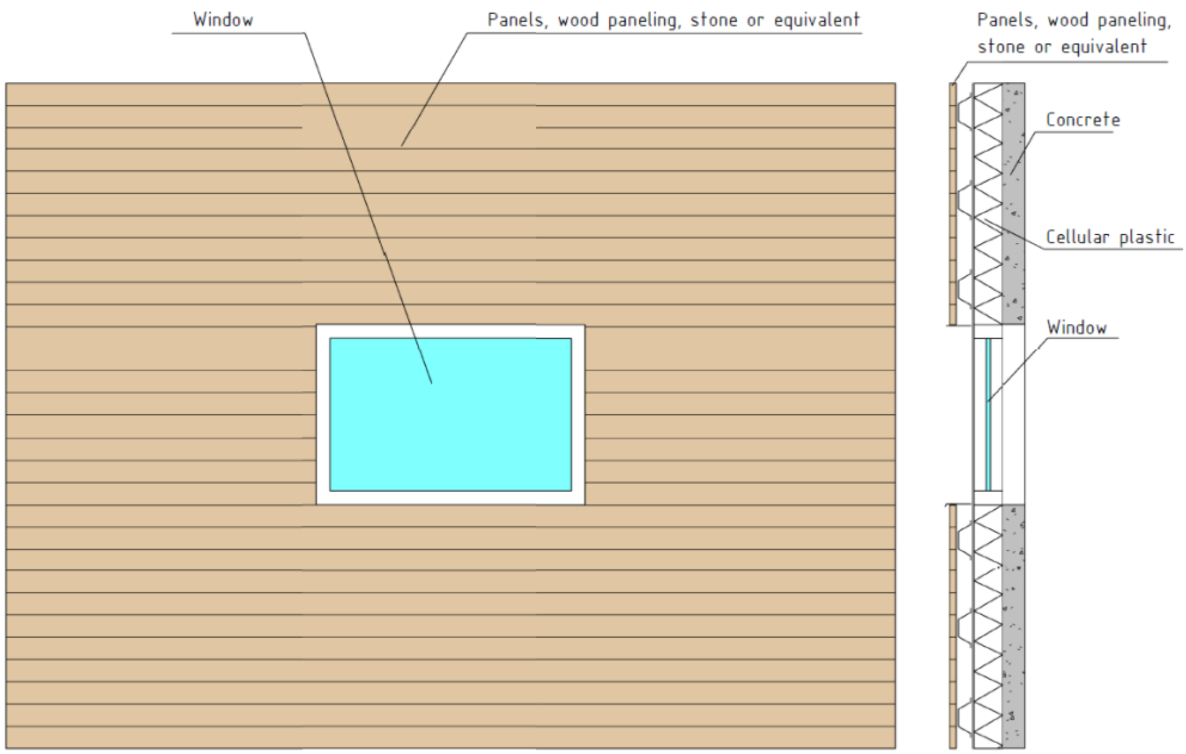

Figure A- 5 Typical design of an exterior wall with combustible insulation and panels, wood panelling, stone or equivalent.

Sandwich panels

A common exterior wall construction in buildings with a lower safety requirement (Br2/Br3) is sandwich panels that form a cantilever wall with a frame of steel pillars. The panels usually consist of steel plate or aluminium that enclose the insulation.

Since the requirements for exterior wall constructions is lower in Br2 and Br3 buildings, this type of panels can often be used without being tested for other fire properties than reaction to fire.

If sandwich panels with combustible insulation is used in Br1 buildings (normally buildings with more than two storeys or buildings that for some reason have a higher safety requirement), the panel must undergo fire testing according to test method SP-FIRE 105.

For this type of construction, bullet 1 in the mandatory provision in the Swedish building regulations must be studied in detail to show that the protection against fire spread between fire compartments is maintained.

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