How to Quantify and Verify Fire Safety Performance - And Why?

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Preface

This thesis constitutes the final, mandatory assignment for the degree of Master of Science at Western Norway University of Applied Science.

Observing fire safety engineering from outside the discipline, the field may appear limited and narrow. After this first glance, one will have to acknowledge that fire safety is a highly complex and abstract term, which must be regarded in context. For this to happen in a scientific and reliable fashion, regulators and practitioners need an adequate understanding of fire as a phenomenon, but also risk, risk perception, seeing fire as a societal challenge. Thus, social sciences, socio-economic considerations, and questions at a political scale are relevant. The rabbit hole continues into more technical topics like fire chemistry, fire dynamics, human behaviour in fires, modelling of evacuation, group dynamics, and it becomes overwhelming. Similarly, society and the building industry is at an age characterised by enormous technological development, where the rate of change and the potential disruption of the changes are considerable.

Performance-based building regulations were meant to be the answer to much of this, allowing government to pass legislation with goals and requirements agnostic to the technology applied. Practitioners were to apply the best knowledge available, applying science-based methods to find optimal solutions to new risk factors, novel designs, and new technology.

Other jurisdictions have had several iterations, trying to improve and optimise the regulations. Norway has had no significant change to the functional requirements since their introduction in 1997. Thus, it is called for a thorough review of the performance-based building regulations of fire safety, and the framework in which it is placed.

We need fire safety measures in buildings to cope with imperfect fire prevention.

We need verification and performance-based options due to imperfect specification of pre-accepted performance levels and solutions.

We need margins and uncertainty treatment because of imperfect and incomplete models, data, and knowledge.

We need controls and reviews because practitioners are human – imperfect.

A Special Note on Chapter 11

In an attempt to ensure the relevance of this thesis, numerous attempts have been made to gain insight into the candidate strategies for future building regulations – unsuccessfully. With the intention to find updated data for the number of technical questions raised to the national building authority, the author reviewed the national building authority's annual report for 2023, days prior to the submission date of this thesis. Despite following DiBK through newsletters, Twitter, and LinkedIn the annual report revealed new information about a strategy called for the future development of building regulations, which was initiated in 2022. Pivotal to this thesis, the mentioned strategy encompasses the transfer of pre-accepted performance levels from the non-mandatory guide, VTEK, into the mandatory, legally binding Technical Regulations. No more information has been found publicly about the strategy.

The status of pre-accepted performance levels is central to this thesis, although knowledge of the strategy at an earlier stage would have allowed for a more direct evaluation of the expected consequences. As seen in chapter 11, an appeal is made for an increase in transparency and user involvement.

Wherever this thesis gives direct commentary to the proposed strategy, beyond the contents of chapter 11, a grey highlight is used for clarity.

Acknowledgements

In the process of writing this thesis I have relied on the advice, discussions, support, and inspiration by many:

Stefan Andersson with Western Norway University of Applied Science/ Norconsult has generously shared of his wisdom and experience, with equal amounts of enthusiasm and curiosity, in a seemingly 24/7 service. Thank you!

Dagfinn Kalheim with DiBK, the Norwegian Building Authority has been my external tutor, taking time to being my sparring partner in the early stages of the thesis.

COWI AS, my employer has supported me in this endeavour financially, but also by encouraging and facilitating. I would further like to thank my colleagues Kristian Hox, Jon Arild Westlund-Storm, and Jan-Erik Bauge, who provided support and

Greg Baker graciously spent several hours (with inconvenient time differences) on Teams with me discussing potential topics for the thesis and fire safety engineering at large.

The entire fire safety engineering community seem to exclusively consist of helpful, generous, humble, and wise persons. I have received useful input from Brian Meacham, Henrik Bjelland, Ove Njå, Jake Pauls, Vidar Stenstad, Frode Kirkeli, and many more.

Lastly, I would like to thank my family for tolerating me through this work!

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Abstract

This thesis explores ways to improve the framework for performance-fire safety engineering of buildings.

Performance-based building codes have been widely adopted, as they allow regulators to set the ambitions by policies and functional requirements, thus leaving the choice of technology and solutions to the designers in building projects. Compared to the traditional prescriptive approach, where dimensions, solutions, and performance levels are specified, performance-based design is meant to provide more flexibility – a highly attractive feature considering the rate of change in the building industry and in society as a whole.

Some jurisdictions introduced performance-based building regulations for fire safety in the 1990s, all with a slightly different approach to the mandatory and non-mandatory contents. It is furthermore of utmost importance to consider the accompanying support structures – a term meant to encompass authority involvement or oversight in the building application process. As in Norway, this can also be privatised through accepting public responsibility for design, control, or third-party review, and hence, the qualifications, competencies, and ethics of the practitioners are important components of the support structure. Similarly, accountability and sanctions are components of the same support structure.

The review of the current Norwegian Building Regulations shows that fundamentally different approaches are used to the different chapters, where some chapters are prescriptive, some are regulated by performance criteria, many have functional requirements, supplemented with pre-accepted performance levels, either in the guide to the regulations, or in national or international standards.

The chapter on safety in case of fire has functional requirements, but also includes mandatory provisions (prescriptive). The review has exemplified a bias in the regulation towards a building tradition, which in some cases is obsolete, thus creating barriers for performance-based design. Pre-accepted performance levels are of great importance for interpreting the functional requirements and are often used as benchmark for analytical design.

Verification is the process of demonstrating that the design is in compliance with the functional requirements. Different methods exist, typically categorised by whether they are numerical (quantitative) or non-numerical (qualitative), if they evaluate against absolute criteria or to a reference building known to be compliant (comparative), and finally, whether the uncertainty is treated by conservative single assumptions (deterministic) or if the uncertainty is quantified and treated as random variables (probabilistic).

Various metrics for fire safety performance are assessed. The aim of this exercise is to identify means for regulators to increase regulatory control by expressing explicit values representing acceptable risk – preferably on a global building scale, allowing for full flexibility regarding design choices for technology and strategy.

The inherently stochastic nature of fire science and human interaction results in significant uncertainty embedded in any analysis of fire safety at the design stage for buildings. The identified metrics can therefore not in isolation give adequate certainty of outcome but must be seen in context of the verification method used and the treatment of the uncertainty.

Alternatives to verification are discussed, where emphasis is put on the support structure, to allow for relaxations to the verification. The concepts of socio-technical system for fire safety engineering are

gaining momentum and is identified as a candidate to replace verification. Although scenario analysis and many other established tools and techniques within fire safety engineering can be repurposed in systemic thinking, the concept of verification must be abandoned, in favour of definitions of safety constraints, information loops, capable of keeping the system in a state of safety in a life cycle perspective.

It seems fire safety engineering is at a crossroads, where one road means to further pursue verification by science-based expressions. Here, the challenges are an immense need for data, lack of specific guidance and criteria, and lastly, inadequate methodologies for treating the substantial uncertainty. The alternative is to enforce regulation of the practitioners to a degree where society find confidence in the design adequacy without verification. In this alternative, systemic thinking can fit, when further advanced, but also established concepts like risk assessment and ALARP could be applied.

Calls for more holistic fire safety design are discussed, where barriers are identified, and remedies are proposed. For the Norwegian regulatory framework, the main barrier is the regulatory segregation between the Planning and Building Act, governing design and construction, and the Fire and Explosion Prevention Act, governing the operation of (existing) buildings, fire prevention, and the fire and rescue service. The thesis proposes to initiate the considerable task of merging the legislations, but also points to several short-term improvements to mitigate the identified challenges.

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Sammendrag

Denne rapporten utforsker mulige forbedringer av rammeverket for funksjonsbasert prosjektering av bygninger.

Mange land har implementert funksjonsbaserte byggeregler, siden de gir myndighetene anledning til å sette ambisjonsnivået via mål og funksjonskrav, og dermed overlate til ansvarlige foretak å velge løsninger og strategier. Sammenliknet med tradisjonelle, preskriptive byggeregler, hvor dimensjoner, løsninger og ytelser er gitt, er funksjonsbaserte byggeregler ment å gi større fleksibilitet – en attraktiv egenskap tatt i betraktning den høye endringstakten en ser i byggeindustrien og samfunnet for øvrig.

Enkelte land innførte funksjonsbaserte regelverk for brannsikkerhet i bygninger på 1990-tallet, riktig nok med noe variasjon hvilke deler av regelverket som var obligatorisk og ikke. Det er videre avgjørende å se regelverket i sammenheng med rammeverket rundt, hvilket innebærer myndighetsinvolvering og tilsyn i søknadsprosessen. For Norge ble også dette aspektet privatisert igjennom byggesaksreformen, når man innførte ansvarsrett, egenkontroll og uavhengig kontroll – dermed ble det også avgjørende å kunne sikre at aktørene hadde tilstrekkelig kvalifikasjoner, kompetanse og integritet. Tilsvarende, utgjør ansvar og sanksjonsmidler komponenter i rammeverket rundt de mer tekniske delene av regelverket.

Gjennomgangen av de norske byggereglene viser at de ulike kapitlene er håndtert fundamentalt ulikt, hvor enkelte kapitler er preskriptive (ytelsesbasert), enkelte har kvantifiserte resultatmål, mange har funksjonskrav supplert med preaksepterte ytelser – enten i veiledning til forskriften eller i nasjonale eller internasjonale standarder.

Kapittel 11 om sikkerhet ved brann er basert på funksjonskrav, men har og ytelser og krav til bestemte brannsikkerhetstiltak. I gjennomgangen er det vist eksempler på at funksjonskravene forutinntatt legger til grunn en byggeskikk som i enkelte tilfeller er foreldet, hvilket utgjør en hindring for å kunne dra nytte av funksjonsbaserte byggeregler. Preaksepterte ytelser er av stor betydning for å kunne tolke funksjonskravene, og er ofte benyttet som referansenivå der en fraviker preaksepterte ytelser.

Verifikasjon er prosessen med å dokumentere samsvar med funksjonskravene. Det finnes en rekke verifikasjonsmetoder, som typisk kategoriseres av om de tallfestes (kvantitativ analyse) eller ikke (kvalitativ analyse), om sikkerhetsmålene er absolutte eller om en sammenlikner med en akseptabel utførelse (komparativ analyse), og om en håndterer usikkerhet ved å gjøre konservative antakelser på enkeltverdier (deterministisk analyse) eller om usikkerheten tallfestes og håndteres som stokastiske variabler (probabilistisk analyse).

Rapporten har undersøkt ulike tilnærminger til å tallfeste brannsikkerhet (enheter). Målet med øvelsen er å identifisere muligheter for å oppnå bedre regulering av sikkerhetsnivået gjennom å eksplisitt angi akseptabel risiko – fortrinnsvis for hele byggverket, slik at prosjekterende står fritt til å velge strategi og løsninger.

Brannteknikk og menneskelig adferd ved brann er befestet med en betydelig usikkerhet, som dermed ikke kan adskilles fra analytisk brannteknisk prosjektering. De identifiserte enhetene for brannsikkerhet kan derfor ikke alene gi tilstrekkelig trygghet for brannsikkerheten, men enhetene må ses i direkte sammenheng med analysemetoden og usikkerhetshåndteringen.

Rapporten diskuterer også alternativer til verifikasjon, hvor en må innrette rammeverket rundt slik at en kan tolerere mildere krav til verifikasjon. Sosiotekniske systemer (systemtekning) for brannteknisk

prosjektering er et konsept som stadig får mer støtte, og det anses som en sterk kandidat for å erstatte verifikasjon. Selv om scenarioanalyse og mange andre analyseverktøy kan gjenbrukes innen systemtenking, må en forkaste ideen om at det er mulig å fremlegge objektive bevis for at et funksjonskrav er oppfylt, til fordel for en helhetlig tilnærming til samspillet mellom byggverket, mennesker og organisasjoner i et livsløpsperspektiv.

Det ser ut til at fagområdet står ved et veiskille, hvor den ene veien innebærer å fortsatt forfølge en tanke om verifikasjon basert på vitenskapelige uttrykk. Utfordringen her ligger i et betydelig behov for data, manglende veiledning og kriterier, samt fravær av tilfredsstillende metoder for å håndtere den store usikkerheten på en tilfredsstillende måte. Alternativet er å innføre andre tiltak, til det punktet hvor samfunnet kan være trygge på at tilfredsstillende sikkerhet ved brann oppnås, selv om det ikke er bevist ved beregning. Systemtenking passer godt inn i dette alternativet når det er videreutviklet og modnet, men også mer etablerte konsepter som ALARP og risikovurdering kan anvendes.

Rapporten diskuterer også en mer helhetlig tilnærming til brannteknisk prosjektering, hvor det pekes på hinder for slik helhetlig håndtering og avbøtende tiltak foreslås. I Norge er den primære hindringen det juridiske skillet mellom plan- og bygningsloven, som regulerer prosjektering og byggefasen, mens brann- og eksplosjonsvernloven regulerer driftsfasen, brannforebygging og brann- og redningstjenesten. Rapporten foreslår å igangsette det omfattende arbeidet med å forene disse regelverkene, men peker også på tiltak som kan forbedre situasjonen betydelig på kortere sikt.

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Definitions

Term	Definition	Source
Performance-based regulation	A document that expresses requirements for a building or building system, in terms of societal goals, functional objectives and performance requirements, without specifying a single means for complying with the requirements.	[1]
Prescriptive regulation	Regulation in which the means and approach for compliance are completely or mostly specified	[2]
Performance-based fire safety design	Deign that is engineered to achieve specified fire safety design objectives based on performance criteria.	[3]
Functional requirements	general purpose or task that will be fulfilled in the completed construction work	[4]
Performance criteria	Quantitative engineering specifications, which form an agreed basis for assessing the safety of a built environment design.	[5]
Performance level	Technical, functional, or environmental quality, capacity or property of a construction work, building component, installation or outside area. A performance level is an interpretation and specification of a functional requirement and may be specified quantitatively or qualitatively.	[4]
Fire concept	Also referred to as fire safety strategy report or fire safety design. Collation of requirements and performance levels for a specific construction work, forming basis for detailed design.	[6]
Verification	Process of determining that a fire safety design complies with the fire safety requirements by examining the design in the light of safety criteria. Also used to refer to the outcome of this process.	[5]
Deviation	An alternative to pre-accepted performance level found adequate, either by comparison to a pre-accepted reference building or by verifying compliance with the functional requirement. Can also be called alternative solution.	
Pre-accepted performance level	Performance level specified by the relevant authority as deemed to satisfy or helping to ensure compliance with one or more functional requirements in the regulations. May also be called deemed-to-satisfy, acceptable solutions, example of acceptable design.	[4]

Term	Definition	Source
Managerial procedures	Procedures for operation, maintenance and emergency preparedness and response, with the intention to provide adequate fire safety. Internal or external fire safety measures to be initiated by persons or organisations. Also referred to as organisational measures.	
STS	Sochio-technical systems	
QDR	Qualitative design review	[7]
TEK	Technical Regulations to the Norwegian Planning and Building Act. TEK'97 and TEK10 refer to the versions of the regulations of 1997 and 2010 respectively.	
PBL	Planning and Building Act	
SAK	Building Application Regulations SAK10 refers specifically to the 2010 version	
GOF	Regulations of Responsible Enterprises (withdrawn in 2010 and replaced by SAK10)	
VTEK	Guidance document to the Technical Regulations. The guide is authored by the National Building Authority. VTEK10 and VTEK17 refer to the guides to TEK10 and TEK17 respectively	
REN	Guidance document to the Technical Regulations of 1997. The guide is authored by the National Building Authority. Since 2007, the term VTEK is used.	
BF'87	Building Regulations of 1987	
NS	Norwegian Standard	
INSTA	Inter-Nordic standard	
EN	European standard	
ISO	International standard	
ICC	International Code Council	
DiBK	Direktoratet for Byggkvalitet, the Norwegian Building Authority. Before 2012 called Statens bygningstekniske etat (BE).	
DSB	The Norwegian Directorate for Civil Protection	
IAFSS	International Association for Fire Safety Science	

Term	Definition	Source
SFPE	Society of Fire Protection Engineers	
NFPA	National Fire Protection Association (US)	
NBK	Nordic Commitee on Building Regulations	
RIF	The Norwegian Association for Consulting Engineers – Rådgivende Ingeniørers Forening	
NOU	Norwegian Official Reports (Norske offentlige utredninger)	
STM	White paper (Stortingsmelding)	
AHJ	Authority Having Jurisdiction – An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.	[8]

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1. Introduction

1.1. Background

By 2023, the fire safety section of the Norwegian building regulations has been performance-based for 25 years. The use of performance-based building regulations has been widely adopted throughout the western civilization, but many different approaches are taken, which all have their strengths and weaknesses.

The 1980s saw a movement globally towards deregulation. The increased knowledge and attention to risk and risk assessments, paved the ground for regulations with functional requirements, rather than detailed descriptions of means. The performance-based building regulations in Norway were introduced after an inter-Nordic collaboration, where structure and terminology were proposed, with the intention to

- Allow for innovative technology and solutions,
- Increase efficiency and reduce bureaucracy, and
- Reduce barriers to trade.

Within fire safety this change was made possible by the availability of engineering tools and textbooks, which gave rise to fire safety engineering as a discipline in the 1980s and 1990s. Norway established specialised fire safety engineering educational programmes in the early 1990s, supplementing existing programmes in Sweden, Scotland, and the US.

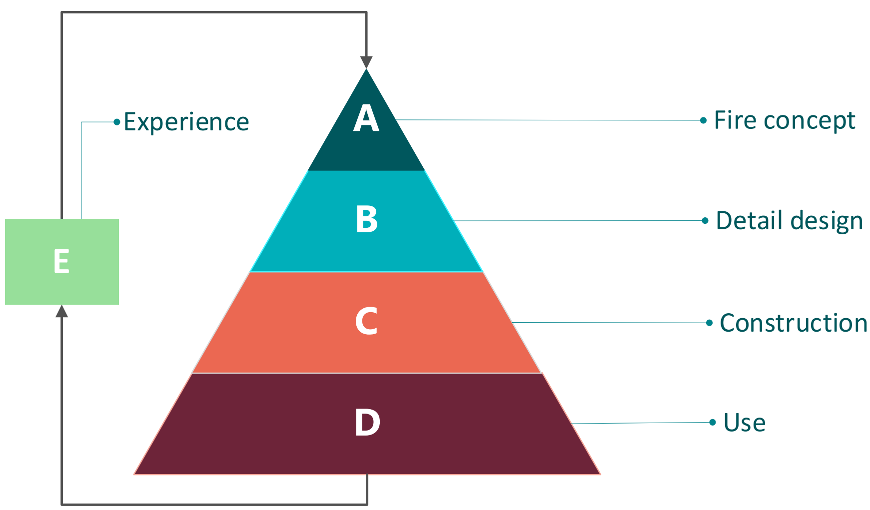


Figure 1 Fire safety from concept, through detailed design and construction. Use and experience feeds back to coming building projects. Adopted from [9]

Where the basis for detailed design previously was found in prescriptive regulations, the new regulations gave rise to a new role and profession in projects: Fire safety engineers, responsible for a fire concept (also called fire safety strategy).

On level A (ref Figure 1) functional requirements from the building regulation are translated into performance requirements. On level B performance requirements are refined to solutions, choice of products and construction drawings. Level C materialise the design and prepare basis for operation and maintenance. Level D use and maintain the building as intended, until a need for alteration occurs, in which experience from previous levels should be fed back into the new project.

With the new performance-based building regulations, the designers were given a choice. Either

1. Design according to a set of examples, deemed to satisfy the functional requirements (pre-accepted performance levels) – performance levels and solutions previously found on a legally bounding level, or
2. Deviate from the pre-accepted performance level if this could be justified by an analysis showing that the functional requirements were fulfilled.

Initially, these analyses were assumed to be used only for novel buildings, not covered by the pre-accepted solutions. Experience showed however that analytical design, or fire safety engineering, also was used for optimizing purposes in more conventional building projects. For these projects, most of the design was based on pre-accepted performance levels, but minor trade-offs were done, and the analysis was most often made to verify compliance by comparison to a reference building, complying fully to the pre-accepted performance levels of the guide.

1.2. Current Development

At the time of writing this thesis, there are many wheels in motion with relevance to the topic of fire safety engineering under a performance-based building regulation in Norway.

- The Norwegian standard NS 3901, which is referred as an acceptable verification methodology in the guide to the building regulations, is under review.
- The National building authority is tasked to do a review of the building regulations. A project was initiated in 2022 for a long-term new structure for the building regulations.
- The current regime for qualifications, review and liability in Norwegian building projects is being revised.

Similarly, there are several activities internationally with a potential to affect the development of fire safety engineering generally.

- The European standardization committee CEN TC 127 has tasked the working group on fire safety engineering WG8 to produce a model code for ease of implementation of performance-based design.
- A process of "reimagining" the ICC PC (International Code Council Performance Code) is ongoing.
- SFPE (the Society of Fire Protection Engineers) are developing a standard for performance-based fire safety design.

Many jurisdictions have introduced performance-based building regulations and have had several iterations to correct unintended development or to address new challenges. The ongoing process of updating the building legislation in Sweden and Australia may serve as inspiration to the coming changes in Norway.

1.3. Problem

Uninterrupted of the above-mentioned processes, the building industry is progressing at high pace. There is a significant focus on sustainability, which challenges the traditional fire safety strategies by adopting new materials, new technology and new construction methods. The increasing focus on sustainability is also expected to require more re-use of existing buildings and building materials – further making performance-based fire safety engineering crucial for meeting all objectives in the project.

Since the introduction of the Norwegian performance-based building regulations, with legally binding functional requirements in 1997, the guide to the building regulations has played a central role, with three intended tasks:

- Elaborate and explain on what is required in the regulations,
- Provide guidance when an analytical approach is taken to demonstrate compliance with the functional requirements of the regulations, and
- Give examples of acceptable solutions, deemed to comply with the functional requirements of the regulations (pre-accepted performance levels).

Over the years, the status of the pre-accepted performance levels has been discussed. What initially was presented as acceptable examples, is now presented as minimum requirements. Legally, this is challenging, as the limitations of citizens' liberties shall have a warrant in law or regulation, and procedures are set to regulate the processes where laws and regulations are made, amended og changed. The status of the guide has now been raised to a point where the ministry requires changes to the guide to be treated as regulation.

The intention when introducing the building regulations in 1997 based on functional requirements was to decouple the building regulations from technical solutions – allowing for more innovation. Furthermore, one envisioned a reduced need to update regulations, as the technical guidance on a lower legal level was easier to adapt to new knowledge, experience, and technology.

The verification against functional requirements has not been widely used, and the majority of verification is done comparatively – demonstrating equivalency with the pre-accepted performance levels. Although this provides some flexibility, it does not fully meet the intended purpose of the performance-based building regulations. For buildings with potential very high consequences, novel buildings, or other cases where the guide does not give adequate guidance, the functional requirements serve as means of regulation to achieve the safety against fire demanded by society.

Thus, it can be seen as a sign of mistrust towards the performance-based fire safety design to raise the status of the pre-accepted performance levels: Is fire safety sufficiently regulated by functional requirements only? The level of safety obtained implicitly by the pre-accepted performance levels is assumed to be adequate - it is not translated into metrics as measures of acceptable risk. The international guides and standards for performance-based fire safety design are general and non-specific in terms of design fire scenarios, criteria, safety margins and other components of an analytical design. The result is considerable variance between different practitioners, and no formal benchmark exists for regulators nor practitioners apart from the pre-accepted performance levels.

Another disruptive force of Today's building industry is digitalization. The Norwegian building authority is instructed by the ministry to make due changes to the building legislation to prepare it for automated rule-checking, and making the building legislation readable to machines. Functional requirements do not seem to fit well with the needs for machine-readable legislation.

Considering the pace of change and technology, the building regulations need, more than ever, to be flexible and decoupled from technology. Nonetheless, performance-based fire safety regulation as it has been practiced in Norway for soon 25 years is being challenged. In the name of digitalization, to respect the principle of legality, and to ensure regulatory control over the minimum fire safety level. These three forces align towards a more prescriptive regulation, where the means to achieve adequate safety are stipulated in legally binding documents. A regulatory framework most of Europe and the western civilization deliberately have left the last 20-30 years.

Although many signs point towards a more prescriptive regulatory framework, more and more researchers are advocating for a more holistic approach to fire safety, where safety is not treated as a static property of the building, but a dynamic, socio-technical system. This would require a shift in paradigm, moving away from verification and demonstration of compliance, towards systems thinking, where the interplay between humans or the organization and the building is at the focal point.

1.4. Research Needs

The rate of innovation and disruption, much of which is driven by the pursuit of a more sustainable built environment, renders prescriptive building regulations a non-viable option. Thus, well-functioning performance-based fire safety engineering can be seen as a prerequisite for advances in sustainability [10]. This development is seen worldwide and is reflected in the research needs identified in the fire safety engineering community.

The following research topics identified by the Society of Fire Protection Engineers in the SFPE Research Road Map [11] are considered to have relevance to this thesis:

- Standardisation of design fires and analysis approaches (Design Tools; Building Fires)
- Quantify level of "life safety" in a building (Risk/ Probabilistic Approaches; Human Behaviour)
- Quantification of building code performance criteria (Data; Building Fires)
- Quantification of structural fire resilience (Data; Resilience/ Sustainability)

Also the International Association for Fire Safety Science, IAFSS have in their agenda 2030 [12] addressed research needs relevant to the problem described above:

- Risk-based fire safety engineering (Climate Change, Resilience and Sustainability; Fire Safety and Sustainability)
- Global consistency (Population growth, urbanisation and globalisation; Globally-Consistent Regulations, Standards, and Guidelines)
- Internally-consistent regulations (Population growth, urbanisation and globalisation; Globally-Consistent Regulations, Standards, and Guidelines)

Nationally, the Norwegian building authority is tasked by the ministry to:

- Increase knowledge about the effect of and compliance with the legislation,

- Reconsider the level of safety in case of fire required by current legislation, generally, but also specifically in relation to external walls with wooden cladding.

1.5. Research Questions

With the intention to prevent a relapse to prescriptive building regulations, the problems outlined in the previous section must be resolved. The extent of this problems is beyond the scope of one master's thesis, so emphasis will be set on verification. This is because:

- If compliance with functional requirements is feasible, the status of the pre-accepted performance levels can be returned to the original intention – examples of acceptable design, not minimum requirements. Thus, the legal issues of the status quo can be remedied.
- If metrics can be developed, as a representative measure for the obtained fire safety level, the reliance on pre-accepted performance levels can be further reduced, and the fire safety engineering community will be equipped with the necessary tools to assess the sustainable and innovative built environment of the future, with a fire safety demonstrated to be acceptable to society.

Thus, this thesis will study the following questions:

1. How can the fire safety performance of a design be measured?
2. How can compliance with performance-based building regulations be verified?
3. Is verification of compliance even the right way to go?

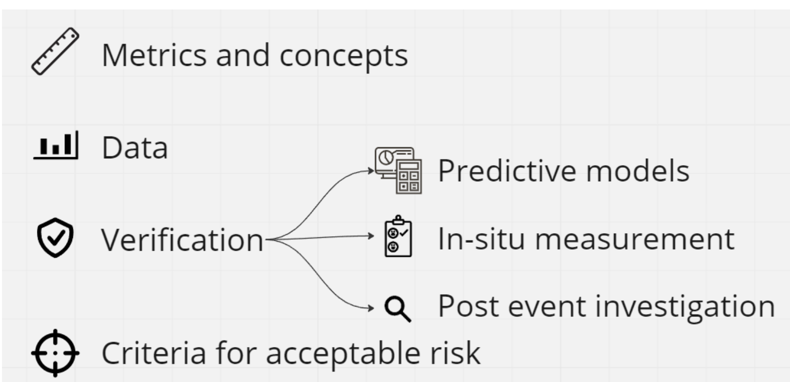


Figure 2 Illustration of components involved in verification of fire safety

Ideally, metrics and concepts were established for all phenomena involved in fire safety, by which data could be collated and systemized. Thus, verification should be an objective assessment against agreed-upon criteria for acceptable fire risk, by either predictive models, in-situ measurements, or post-fire investigations.

This thesis will have emphasis on design and will therefore not go into detail on in-situ measurements and post event investigations, although ideally, all these three approaches should come to the same conclusions given the same input.

1.6. Report Structure

Figure 3 illustrates the structure of this thesis, where chapters 1, 2, and 0 are used to create a common ground, by describing the problem, its context, and introducing the basic concepts needed for subsequent chapters.

An evaluation of the current building regulations are given in chapter 4, before the a study of different means of quantifying and verifying fire safety performance is presented in chapters 5 and 6, including brief discussions. Chapter 7 discusses the need for verification and explores possible alternatives. Chapter 8 gives a wider discussion of the implications of the findings for performance-based design and regulations. Chapter 9 summarises the findings and conclusions, including recommendations. Suggestions for further research are given in chapter 10.

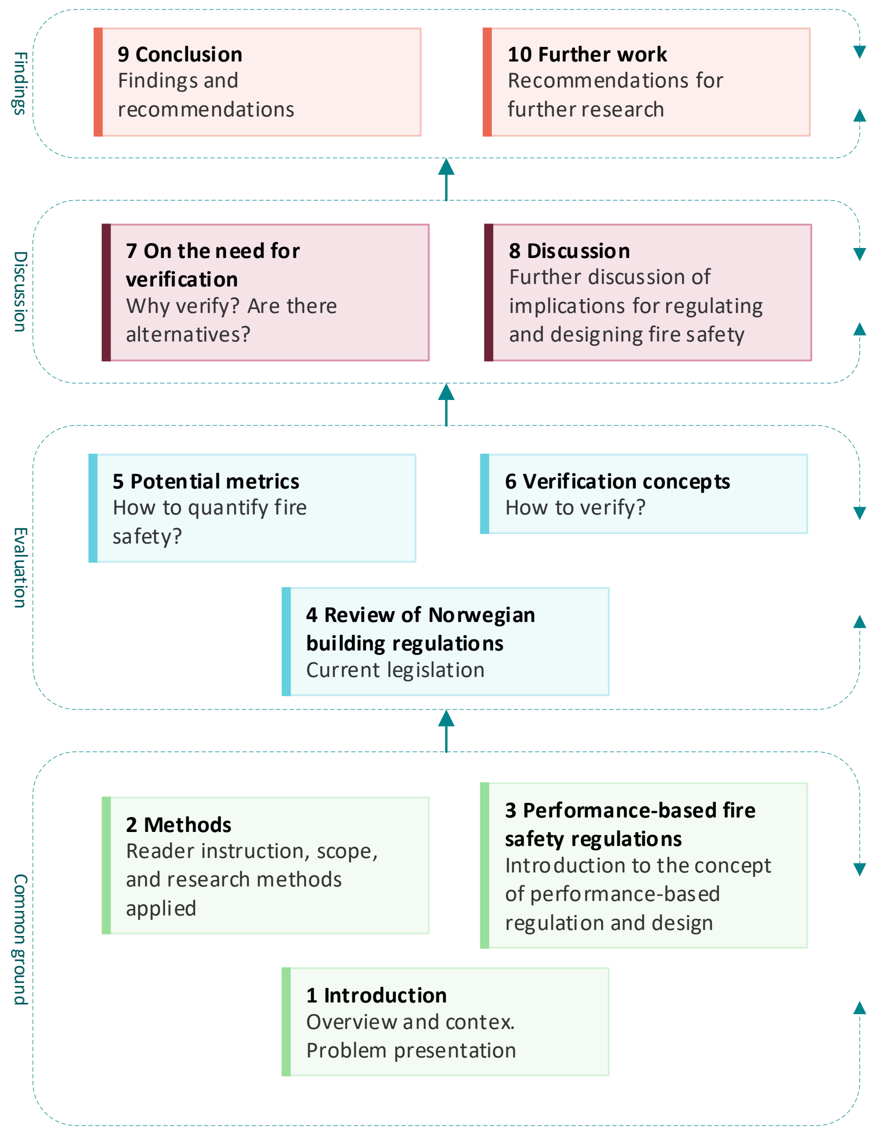


Figure 3 Structure of the report

Chapter 11 was added during the final stages of the thesis, as a preliminary commentary to the strategy for further development of the building regulations. See further clarification in the Preface.

2. Methods

2.1. Scope

This thesis builds upon the efforts made by several researchers over the years and is also highly influenced by the experience of the author as a design practitioner. As highlighted in the research needs described in section 1.4, a considerable research endeavour is called for, well beyond the limits of one master thesis. A shift in paradigm, like treating buildings as socio-technical systems, can take decades to implement, and as a practitioner in the building industry, the need for an improved framework is felt more immediate.

The fire safety of the built environment is a complex interaction between many systems and actors. For this thesis, the main focus will be on design of buildings. Although reference is made to international literature and legislation, emphasis will be on the Norwegian building industry and legislation.

Support structures for competencies and professional ethics, control and review, sanctions and accountability are all seen as vital parts of a framework in which fire safety engineering can be executed safely. The scope of this thesis is limited to acknowledging these factors and that they influence the need for verification. A detailed study of is beyond this thesis.

2.2. Literature Review

An abundance of literature is available on the topics relevant to this thesis. The concepts of risk and performance-based standards and regulations span widely across industries. Similarly, relevant methods for quantifying and verifying performance are explored for other sectors. For fire safety engineering, the abundance also takes a dimension of depth, seeing how performance can be quantified globally, for individual buildings, or for objectives/subsystems and building components.

Historical versions of the building legislation and guidance documents – available through the website of the National Building Authority (www.dibk.no) and https://www.regjeringen.no/no/tema/plan-bygg-og-eiendom/bygningsregelverket-fra-1965--20172. Enquiry documents and evaluations are also made available through these sites.

St.Meld. - White papers are drawn up when the Government wishes to present matters to the Storting that do not require a decision. White papers tend to be in the form of a report to the Storting on the work carried out in a particular field and future policy. These documents, and the subsequent discussion of them in the Storting, often form the basis of a draft resolution or bill at a later stage. https://www.regjeringen.no/en/find-document/white-papers-

NOU - Official Norwegian Reports are reports on different aspects of society, made by a committee or working group constituted by the Government or one or several ministries. https://www.regjeringen.no/en/find-document/norwegian-official-reports/

International, European, Nordic, and Norwegian Standards are reviewed, as provided by www.standard.no and www.eqb.ihs.com. Similarly Byggforskserien has been a vital source for current and previous interpretation of the building regulations, www.byggforsk.no.

Articles and Scientific Publications are primarily found through www.oria.no, which gives access to many peer-reviewed publications. Furthermore, the cited literature in these publications is considered. Tremendous research contributions relevant to this thesis are made by Brian Meacham and Henrik

Bjelland. The author has nothing but respect for this work, but efforts are made to include other sources to provide a wider basis.

Other sources include building regulations from other jurisdictions, master's and PhD theses, handbooks, news articles, presentations, and statistics.

2.3. Problem definition

Contradicting forces are at play involving the foundation for performance-based fire safety design. On one hand, there is a need for improved clarity, reduced variation, and thus more detailed specification. This is to reduce the fear of litigation and lawsuits, facilitate digitalisation, and of course to ensure society's requirements to fire safety are met.

By increasing specification, the key to performance-based fire safety design may be weakened – namely a framework where qualified professionals apply science-based models to solve fire safety challenges with updated knowledge technology. Considering the global attention to the environment, traditional building materials, designs, and techniques are challenged, in the search for more sustainable built environments. Thus, the need for the flexibility and adoptability of a performance-based building regulation may never have been greater than today.

2.4. Outcome statement

In the writing of this thesis, an ambitious statement of the desired outcome has served as a guide of direction.

By clearing up concepts of verification, the thesis will pave the ground for future revisions of performance-based building regulations, where the level of safety is anchored at a legally binding level.

Alternatively, the regulators may choose a route where the practitioners meet so strict requirements to qualifications, ethics, and scrutiny, that society can expect adequate safety in case of fire, even with relaxed verification requirements.

2.5. Bias

Being a practicing fire safety engineer, the author will benefit from a continued flexibility in the Norwegian building industry. Furthermore, by being involved in many projects over the last 15 years, findings representing conflict with solutions, verification or otherwise standpoints in the past may be found more difficult than if this work was done by someone with no ties to the industry. Conversely, first-hand experience of the practice in the Norwegian building industry has been a premise for the research. If similar work had been done by independent parties, surveys and interviews would have been required, which would have given a wider picture of the industry, albeit potentially not with the same depth.

To the best of my abilities, this report reflects my findings.

2.6. The Use of Artificial Intelligence

During the writing of this thesis artificial intelligence (AI) has been made widely available through the launch of ChatGPT [13] December 2022. It is hereby declared that the content of this thesis is solely produced by the author. ChatGPT has been used to provide suggestions for English translations for quotes only found publicly in a Scandinavian language.

3. Performance-Based Fire Safety Regulations

Chapter 3 intends to provide the reader with a basic understanding of the concepts of performance-based design. Even within fire safety engineering, the terms used vary, so another objective is to expand on how the different terms and definitions are applied in the subsequent chapters of this thesis.

This chapter also gives an overview of how fire safety has been and is regulated, with an emphasis on design under the Norwegian Planning and Building Act. For context, international development is mentioned, and other regulations, where they are closely related to fire safety, are described.

The aim is to present different approaches to regulation, but also to demonstrate how regulators have assessed the fire risk and mitigation need over time.

- Section 3.1 serves as a brief introduction and summarises the key concepts of performance-based design.
- Sections 3.2 - 3.3 gives a broad overview of how building regulation has evolved over time, before a presentation of different approaches to performance-based regulations is given in section 3.4.
- In sections 3.5 - 3.8 the implementation of performance-based building regulations in Norway is described, including the subsequent revision.
- Section 3.9 presents formal requirements to verification
- Section 3.10 describes how fire safety is regulated by one legislation during operation, and another in the design and construction stage.
- Section 3.11 presents the mechanism used further improve quality and assure compliance.
- Section 3.12 summarise the legal concerns, particularly for pre-accepted performance levels in non-legally binding documents.
- Sections 3.13 and 3.14 present the expected benefits and known challenges of performance-based building regulation and design.
- In section 3.15 a brief introduction is given to systemic thinking, an emerging school of thought.
- Chapter 3 is summarised in section 3.16.

3.1. Introduction

Performance-based regulations come in many variations, as will be further described in this chapter. In fire safety engineering literature, and thus throughout this thesis, the term performance-based is used as the counterpart to prescription-based, meaning the regulator leave flexibility in terms of means to meet the requirement. The required qualities are typically formulated qualitatively as a description of the desired outcome or function, and does not mandate a specific material, solution, dimension etc.

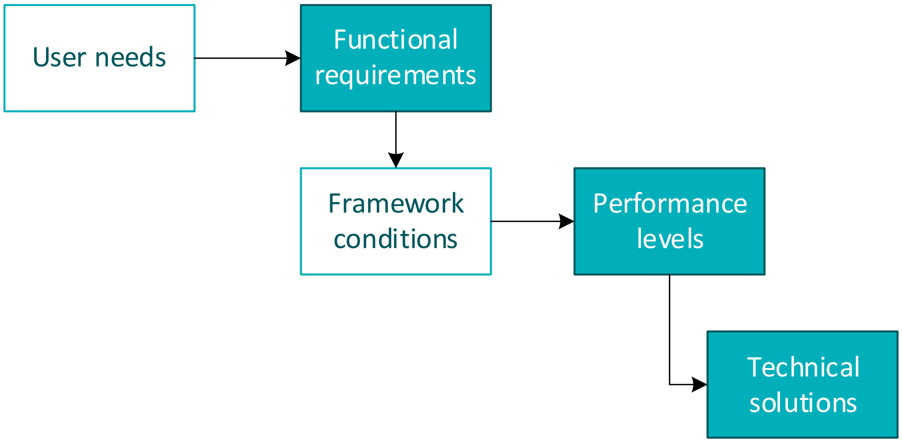


Figure 4 Relation between functional requirements, performance levels and technical solutions, based on [14]

The above figure is meant to illustrate how a project can evolve from its initial phases into technical solutions. The user's needs forms input, which together with the functional requirements of the building regulations constitute the framework conditions for the design. These framework conditions must be substantiated, and for fire safety design, this is done in the fire safety strategy report (fire concept), where performance levels are set, for the other disciplines to adhere to. This can be exemplified by load-bearing structures:

Functional requirement:	Main load-bearing systems in construction works in fire classes 3 and 4 shall be designed to maintain adequate load-bearing capacity and stability for the complete duration of a fire, insofar as this can be modelled.
Performance level:	Main load-bearing system: R 90 A2-s1,d0
Technical solution:	40 mm high density stone wool fire protection boards applied to the steel main frame.

Here, the fire safety engineer may choose between different approaches to complying with the functional requirement – passive fire protection, as in the example above, or one could introduce fire suppression system, fire load restrictions, compartmentation or any combination of measures, where compliance with the functional requirement can be demonstrated.

In Norwegian building projects most often, other actors than the fire safety engineer will choose the technical solution – in this example a structural engineer, likely in dialogue with the architect and client (builder or contractor). The specified performance of R 90 A2-s1,d0 requires the structural system to be made of non-combustible materials, and maintain criteria for load-bearing capacity for 90 minutes under standardised fire exposure. The degree of freedom regarding choice of materials, design and technical solutions is still considerable.

3.2. Previous Regulations

3.2.1. Codex Hammurabi (circa 1750 BC)

The Codex Hammurabi is a collection of laws, found at display at the Louvre Museum, Paris. They were discovered by French archaeologists at the end of the nineteenth century, in what is now south-western

Iran. The laws date back to circa 1750 BC, when King Hammurabi Babylonian Empire reigned the Babylonian Empire.

The law describes punishments for different wrongdoings, and has a separate section on Houses and Builders [15]:

> *(228) If a builder has built a house for a man and has completed it for him, he shall pay as his fee two shekels of silver for each sar in area.*
>
> *(229) If a builder has built a house for a man and has not made his work strong enough and the house he has made has collapsed and caused the death of the owner of the house, that builder shall be killed.*
>
> *(230) If it has caused the death of the son of the owner of the house, they shall kill that builder's son.*
>
> *(231) If it has caused the death of a slave of the owner of the house, he shall give a slave for the slave to the owner of the house.*
>
> *(232) If he has destroyed possessions, he shall make recompense for whatever he destroyed. Moreover, since the house he had built collapsed because he had not made it strong enough, he shall rebuild the house which collapsed from his own resources.*
>
> *(233) If a builder has made a house for a man and has not made his work solid enough and a wall has toppled, that builder shall strengthen that wall from his own resources.*

The law reflects the *eye-for-an-eye philosophy* of the era, and by today´s standards, the punishments are harsh, unfair, and inhumane. However, with these strict sanctions, the person who acquired a builder´s services would have reason to believe that all necessary measures were made to ensure sufficient load-bearing capacity and stability. Furthermore, the builder was free to choose whatever materials and techniques seen fit for purpose, and as such allowing for innovation.

It may be difficult to draw parallels to regulations on fire safety, as the more binary nature of insufficient load-bearing capacity (collapse) stands in contrast to the continuous and uncertain consequences in case of fire safety.

One could imagine the improbable case of 3 m snowfall in ancient Babylon. Should the builder have foreseen this scenario, and built the house so that the construction would withstand the snow loads? As such, the term “made his work strong enough” can be understood to encompass a degree of uncertainty. This uncertainty is more predominant in fire safety, compared to the basic expectations to structural stability as required by Hammurabi. Furthermore, one could argue that minor deflections, uncomfortable vibrations/ springs, or reckless overloading by the user remain uncovered by the code.

3.2.2. Ancient Cultures, Middle Ages and Renaissance

Ancient Greek, Indian and Chinese cultures had laws regulating their cities. The laws intended to provide a certain structure to the cities, typically based on a rectangular grid, creating blocks. Furthermore, the laws could set forth requirements for placement of temples and other public functions. As a direct opposite of the focus of Hammurabi, these ancient laws did not regulate the quality of individual buildings but had an urban planning perspective.

During the Middle Ages, certain fire safety requirements where retained, but generally, the urban building stock was less regulated, until the Renaissance, when principles of urban planning and ideals of miletistic, regular city centres were renewed.

3.2.3. The First Norwegian Building Laws (950 – 1814)

The first building laws in Norway regulated the relation between tenant farmers and landlords, and the duty to maintain buildings at the farm, and requirements for new buildings.

During the unification of Norway into one kingdom, King Magnus the Lawmender (Magnus VI Håkonsson Lagabøte) collated these regional laws into one land law.

Similarly, a city law was established for more densely populated areas. Separate laws existed for the larger cities, and the building sections mainly aimed to mitigate fire risk – both concerning fire spread between buildings and the use of open flame, fireplaces, and cooking.

After a great fire, Oslo introduced *murtvang* in 1624 – an obligation to build in brick or stone. As the cost was drastically higher compared to timber buildings, nogged bay work was allowed.

Figure 5 UNESCO heritage docks of Bergen, (Unknown photographer, Nasjonalbiblioteket/ Riksantikvaren)

Figure 6 Areal view of the docks in Trondheim, showing Kjøpmannsgata as a fire barrier towards the city to the right (Gule Sider)

Both Bergen and Trondheim have heritage docks, in which the fire risk was a concern. These docks where essential for commerce and storage of goods on which the city depended, but they also posed a considerable fire hazard. In 1689 Trondheim introduced new strict fire preventive requirements, as a response to a great fire eight years earlier. The reconstruction of the city was done according to the plan of General Johan Caspar de Cicignon, who introduced a number of squares and strategically placed wide avenues. Although military and aesthetic interests also were involved, the intention was to reduce the extent of fire spread. As seen in Figure 6, the docks were separated from the rest of the city with an approximately 30 m wide avenue, which also included a slope and planted trees.

Figure 7 Members of public observing the damage of a fire damaging much of Bergen city centre (Narve Skarpmoen, 1916, Nasjonalbiblioteket)

During the late 1600s and early 1700s improvements were also made to the organization of firefighting efforts and chimney sweeping, although considerable room for improvement remained.

3.2.4. 1814-1965

After the constitution of 1814 a building boom followed in the largest cities, which developed their own building acts. Their main objective was to limit conflagrations, and ensure a certain level accessibility, structural stability, aesthetics, and sanitary conditions. By 1880 4 city acts like these existed, and governed buildings in urban and densely populated areas.

In 1924 an act was passed regulating all cities of the country. The intention was to increase government control of the built environment, regulating urban planning, building heights etc. Special legislation still coexisted with the Planning and Building Act, like the Fire and Explosion Prevention Act.

3.2.5. 1965 - 1997

Until 1965 no acts or regulations were made to regulate building outside towns and cities. The building act of 1965 was thus the first truly national building act of Norway.

In the introduction to the guide to the building regulations of 1969, the building regulations are claimed to be performance-based [16, p. 3]. The building regulation nonetheless had requirements limiting timber buildings of 1 storey to 400 m² or 2 storeys to 200 m² (§ 73), and separation distances between detached buildings of not less than 8 m or half of the two buildings' combined height (§ 70) [17]. Although prescriptive, the use of fire ratings according to national standards replaced the prescription of certain building materials and dimensions.

Hensikten med å formulere forskriftene slik, er å gjøre det mulig for byggevareprodusenter, prosjekterende og ut førende fritt å utvikle nye metoder og produkter innenfor den ramme av egenskapskrav (funksjonskrav) som de nye byggeforskriftene inne holder.

The purpose of formulating the regulations like this is to allow manufacturers, designers, and builders to freely develop new methods and products within the framework of the required properties (functional requirements) that the new building regulations contain.

The guide further acknowledged the challenge of demonstrating compliance, and thus presented a collection of acceptable (but not legally binding) solutions deemed to meet the requirements of the regulations. Referring to the pyramid in Figure 1 (see page 1), level B Detail design is performance-based, and actors on level B and C experience less barriers to innovation. The required performance levels are however given on a legally binding level, and thus no freedom is given on level A Fire concept. Deviations would require a formal application for dispensation, at the discretion of the local fire chief.

A statement from the building act committee referred in an Official Norwegian Report (NOU) describes the difference in view on technical issues compared to aesthetics and urban planning considerations [18, p. 53]:

These relate to more specific problems that are only to a small extent dependent on discretionary assessment, as they are based on exact and measurable results of experience and research. Therefore, the building technical regulations must contain detailed standards for the minimum requirements that must be met.

As will be discussed in this thesis, fire safety can still not, 60 years after, be based on exact and measurable results of experience and research.

3.3. Emergence of Performance-Based Thinking

3.3.1. Initiation

The idea of regulating the building industry through functional requirements were developed in parallel, more or less independently in the mid 1960's, and most likely clearly stated first in 1962 at the International Council for Building Research Studies and Documentation [19]. The contributions of Building Research Station in the UK are deemed instrumental in the early stages of performance-based thinking for the built environment, but also significant contributions were made by the National Bureau of Standards (USA), South-Africa, Japan, and others.

3.3.2. Driving Forces and Enablers

As seen in section 3.2, fire safety requirements have typically been stated as mandatory technical solutions to limit the unwanted consequences of fire. From the 1970s, however, an alternative school of thought for regulating fire safety began to gain traction – Performance-based regulations [20]. Several factors made this possible:

Safety science had emerged as a discipline, and gained foothold, especially within chemical, nuclear, and oil and gas industries [21].

Deregulation as a global trend, favoured the performance-based regulations, allowing better cost-effectiveness and for technical issues to be handled at a lower regulatory (or non-regulatory) level. Thus presidents of both American parties, the World Trade Organization and others proclaimed performance-based regulations to be "generally superior" to other forms of regulation [22].

Fire safety science had progressed from ad hoc experiments of pre-1900 to standardization and repeatable tests by the turn of the century. All of which created increasing understanding of fire dynamics and fire safety, forming a foundation for graduate and post-graduate programs the second half of the 20th century [20]. Technological development also served as a trigger for performance-based design, providing more capable tools for modelling [23].

Harmonisation and removal of barriers to trade was a driving force for the development of performance-based building regulations in the Nordic countries, considering the development of European standards for building products [24].

3.3.3. Performance-Concept for Building Elements

In Norway, the principles of functional requirements for the building industry were presented in 1969 by Norges Byggforskningsinstitutt (NBI, now SINTEF), accompanied with a flow chart as replicated in Figure 8.

The process begins with identifying the needs and desires for the building. This may come from the end users, the building regulations, climatic adaptation or other. The needs and desires are formulated in qualitative terms, describing the required properties of the building element, like wind loads, noise levels, collisions, ease of maintenance or other.

The next proposed step is to find suitable methods of assessing the performance of the building elements under the conditions of interest. This can be done by calculation, by testing or by expert judgement (individual experts or expert panels).

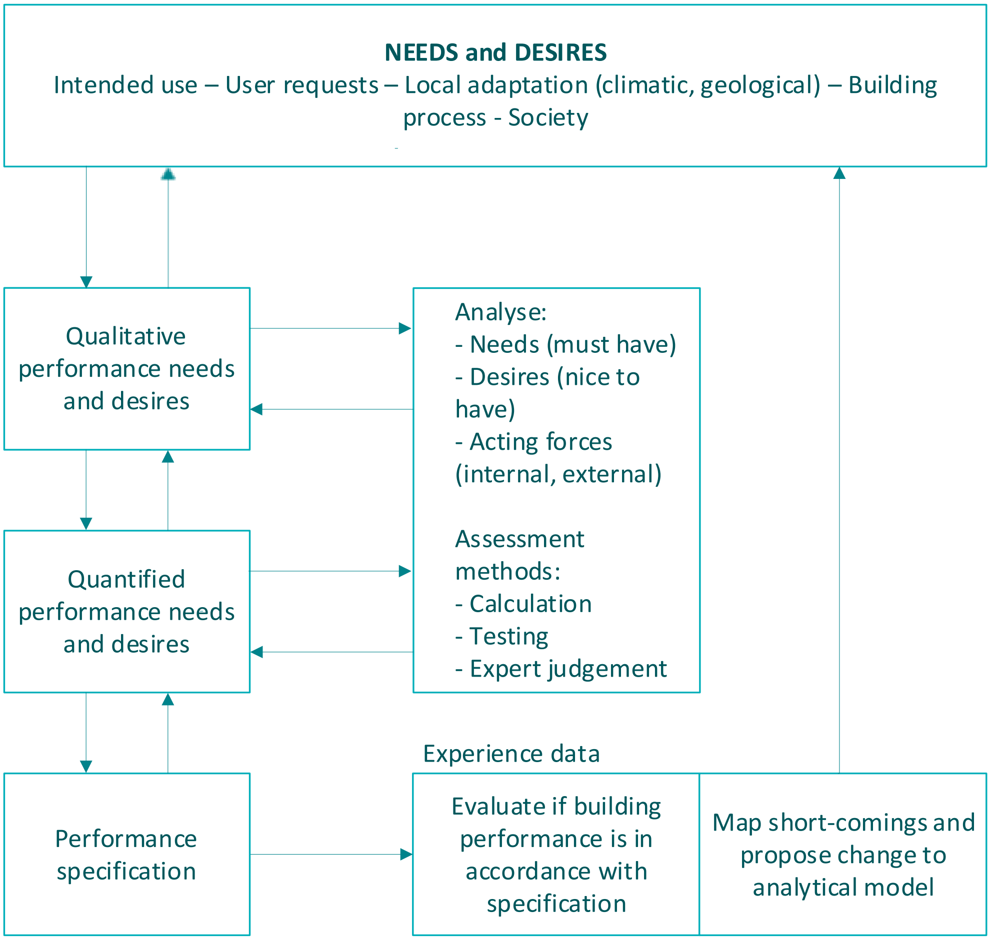


Figure 8 Schematic analytical model of specifying the performance of building elements (translated and reproduced from [11])

When the needs and desires for a building element are mapped and linked to an assessment method which adequately represents the intended property, a performance specification can be created. Currently, this thinking is embedded in standards for many of the relevant properties for fire safety, e.g., smoke leakage through doors, radiative absorption of glazing, measured against standardised fire exposure. This allows the specification of the required properties of building elements without discriminating or giving preferential treatment to any one manufacturer or technology.

3.3.4. NKB (1976)

The Nordic countries[1] share many similarities - one of which a modest number of inhabitants, making collaboration reasonable. This also applies to building regulations, where the Nordic countries in 1955 initiated a collaboration for harmonising the building regulations. This was done as an extension of existing collaboration among Ministers of the Nordic countries, in the Nordic Council of Ministers.

[1] Sweden, Denmark, Norway, Finland, and Iceland.

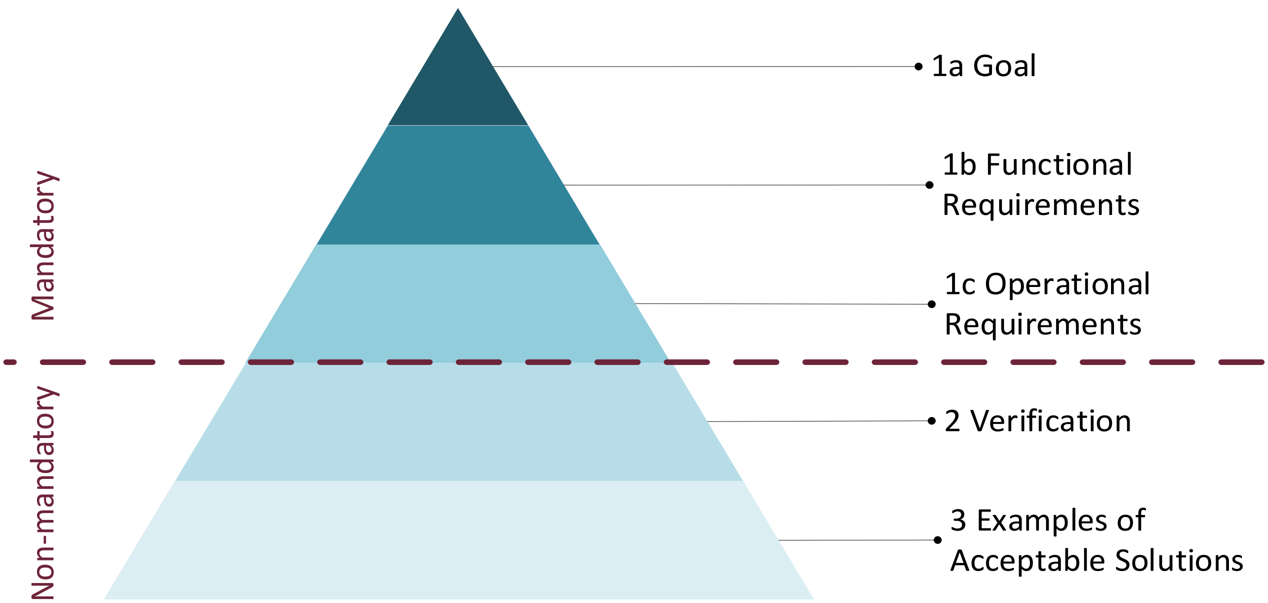


Figure 9 The NKB structure

1a Goal (mandatory) is the highest level of the hierarchy, giving an overall statement of the properties the building must have.

1b Functional requirements (mandatory) are typically qualitative descriptions of the main functions of the building.

1c Operational requirements (mandatory) are formulated to be directly applied to design, and as such may be more specific, and more often quantitative compared to functional requirements.

2 Verification (non-mandatory) means instructions or guidelines regarding how to demonstrate compliance.

3 Examples of acceptable solutions (non-mandatory) are designs, performance levels or other examples which can be applied for design (deemed to satisfy) or as a benchmark (comparative analysis, equivalency).

Table 1 Illustration of how the five levels (rows) can applied to regulate different units of the built environment (columns) [19]

		A Building as a whole			B Building components	C Building materials
		i) All buildings	ii) Building types	iii) Individual buildings		
1. Requirements	a) Overall requirements (principles)					
	b) Interpretation of principles					
	c) Supporting requirements					
2. Methods of verification						
3. Examples of technical solutions						

As illustrated in Table 1, the requirements can apply globally to the building, or to components or materials in the building. Building requirements can be given to specific, individual buildings, types of buildings (e.g., based on building height), or to all buildings. When regulating this buildings or parts thereof, all or some of the levels of the hierarchy shown in Figure 9 can be used.

3.3.5. On the Basis of Function, Objective, or Performance

Acknowledging the complexity of the built environment, metrics and assessment methods for all conceivable properties are not readily available, and the performance of buildings as a whole cannot be described in one value. Thus, there is a need to categorise the properties, and place the different properties and performances in a context. Although different terminology is being used, generally a hierarchy is established, where overarching goals are on top, accompanied with functional requirements. These functional requirements may be supplemented with operational requirements before the required performance-levels are given. The legally binding level of this hierarchy is often used to name the regulatory approach, as presented below [20].

Function-Based Approach

In a function-based approach, the legally binding level will be on functional requirements – primarily qualitative statements dictating acceptable outcomes, properties or states for the end product. The language used is typically at a high, policy-like level, applying to one or more buildings, but can also require a certain function or capacity for building components and systems.

It is up to the responsible designer, the authority having jurisdiction, the contractor, or the builder to determine the optimum way of achieving the required functions, and the functional requirements do not dictate how to meet the requirements. It is not straight-forward to demonstrate compliance with functional requirements [14], so examples of acceptable solutions are important – either by applying solutions that are deemed to satisfy the functional requirements (pre-accepted solutions) or by demonstrating equivalence.

Objective-Based Approach

In an objective-based approach, the legally binding level is in greater detail than functional requirements. Compared to functional requirements, the operational requirements on this level are more detailed and better suited for verification. Although the operational requirements can be quantitative, they do not need to be. Operational requirements are used to gain increased control of the result compared to functional requirements only, but to maintain flexibility in design. Operational requirements may state limit exposures, and as such also be indicative of what verification methods to apply.

Performance-Based Approach

Literarily, a performance-based sets performance-levels at a legally binding level, meaning requirements for fire resistance like EI 60 or R 90 may be given in regulation or code. For fire safety designers, this is seen as a prescriptive approach, not providing the flexibility sought in a modern building regulation. For detail design and contractors, however, this way of regulating fire safety still leaves a substantial flexibility in terms of technology, materials, and building products.

As will be discussed in 5, performance can also be measured in other ways, leaving more flexibility in design, yet providing the regulators with more control of the outcome and reducing variability, compared to the looser forms of regulations mentioned above.

3.3.6. Principles and Good Practice for Performance-Based Regulations

During the 1990s many nations were in transition into performance-based building regulations, and many publications were made to discuss the pros and cons, and to aid implementation. One of these publications came from the International Council for Building Research and Documentation, with a 20-point list of required features of a performance-based code [25].

Figure 10 Required features of a performance-based code [27]

As it is beyond the scope of this thesis to dissect and comment all these features, reference is made to the publication [27].

3.4. Variations in Application of Performance-Based Regulation

Different jurisdictions chose different approaches to performance-based building regulations. Figure 11 gives an indication of the status per 1997.

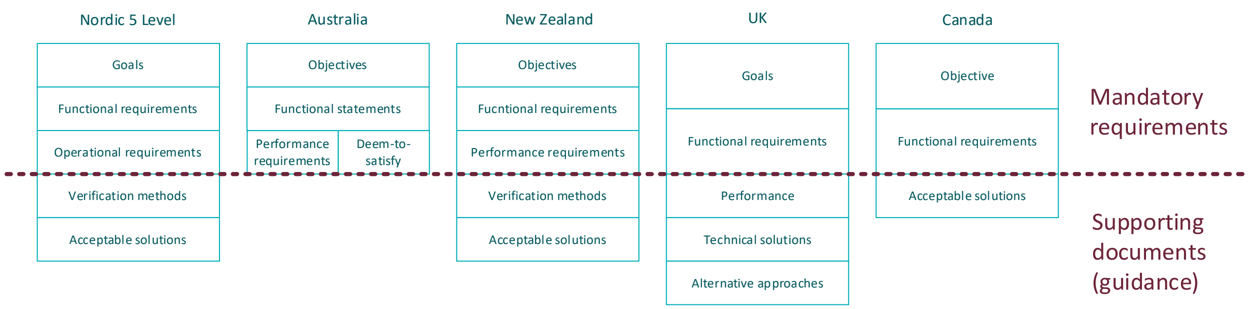


Figure 11 Comparison of different approaches to performance-based building regulations, reproduced from [25]

Even though the fundamental ideas are shared, the variation is obvious. Most jurisdictions have however placed acceptable solutions on a non-mandatory level (except Australia).

To allow for higher resolution in the communication around these concepts, the International Code Council adopted an eight-tier structure, as depicted below.

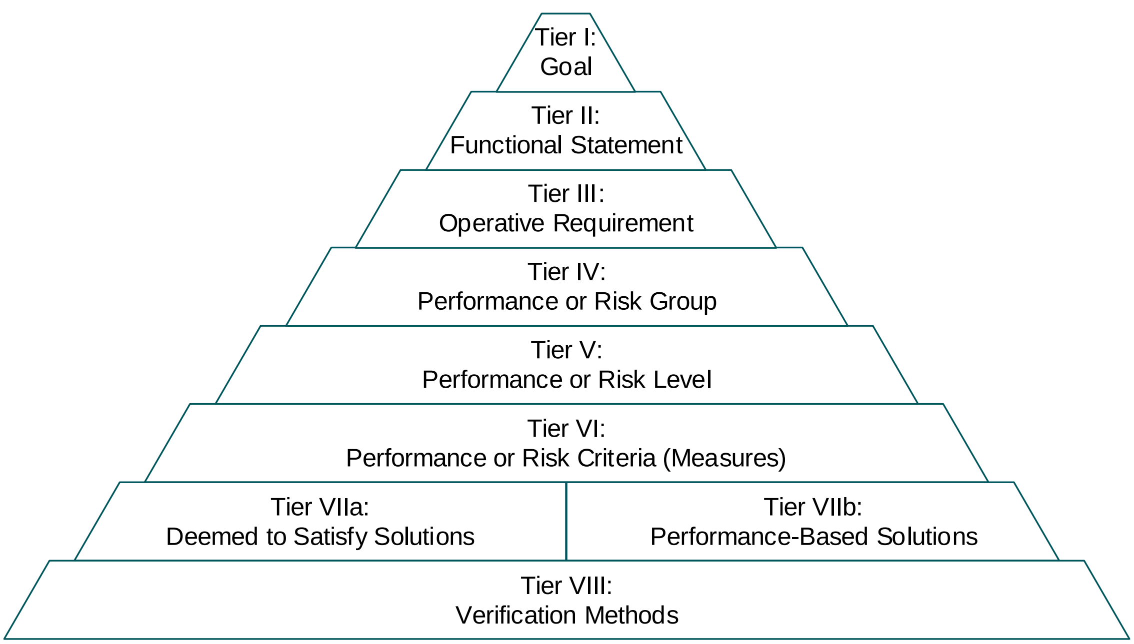


Figure 12 The ICC Eight-ties structure for performance-based codes [26]

3.4.1. Taxonomy

As demonstrated in this chapter, and further expanded by Coglianese [28], performance-based regulation is not a standardised term meaning the same across fields and disciplines. On the contrary, it may take many forms, and apply to different entities in different ways. Coglianese has proposed a framework of six dimension to classify and better understand the different variants. These are briefly presented in the following, with the purpose of creating a context for the performance-based regulations on building fire safety, but also to present alternative ways of approaching performance-based legislation.

1. Specificity – Loose vs. Tight

Loosely formulated requirements leave much flexibility in terms of which means or technology to apply and can in some instances resemble goals.

2. Proximity Between Legal Command and Regulatory Goal – Close vs. Distant

A distant connection means that there is a weak, unclear, or non-direct link between the requirement and the overarching goal.

3. How Performance is Determined – Measured vs. Predicted

The way performance is determined may impact how the requirement is stated. Coglianese describes 3 modes:

a. by direct observation of actual outputs or outcomes (continuously or periodically)

b. by testing under conditions meant to replicate the actual conditions (potentially simplified)

c. by modelling (calculations or simulations) where a relationship between inputs and output is deemed to represent the performance of the system under consideration.

For fire safety purposes, it may also be relevant to consider means of evaluating the performance of a system after an event (fire investigation).

4. Basis for the Standard – Ideal vs. Feasible

The regulations may state an ideal outcome, like vision zero for fatalities in road traffic. Similarly, goals and requirements can be set in more qualitative terms, stating that fire shall not spread between high-rise buildings, for the full duration of a fire. This way of presenting requirements and goals may resemble political goals and visions, and may be difficult to verify compliance with.

Although potentially more controversial, feasible goals and requirements can be set, acknowledging that a residual risk will remain, regardless of the mitigating efforts done. Furthermore, feasible goals and requirements allow for an open debate on cost-benefit and the most reasonable prioritisation of society's resources. An example of such a goal is found in [29], where the Norwegian government aims at a reduction of 30 % of fire related casualties over a period of 8 years. Also, the implicit level of safety resulting from pre-accepted performance levels will reveal a non-ideal, feasible level of performance.

5. Unit of regulation – Individual vs. aggregate

Coglianese exemplifies the unit of regulation by emission control for automobiles - individual requirements will apply to each individual automobile, whereas the aggregate requirement would apply to an average of a fleet of vehicles, or by air quality samples from an area.

For building fire safety, further detailing is useful. Although the automobile analogy is clear for the built environment within a jurisdiction (potentially subdivided by risk or occupancy classes), requirements for individual buildings must be seen as the aggregate where many components and systems contribute.

6. Burden of proof – Regulator vs. regulated

For speed limits on roads, the regulator holds the burden of proof, having to prove a violation of the speed limits. The opposite is the case where a designer is required to demonstrate compliance with functional requirements.

3.4.2. Management-Based Regulations

Coglianese also describes other forms of regulations, alternative to the performance-based approach. Management-based regulation can also be referred to as "enforced self-regulation", meaning the regulated party chooses what actions to take to achieve the public goal [28]. It is the planning or analysis that is regulated – not the outcome of the planning or analysis. Thus, no specified level of performance is required. Examples of this approach are found in quality assurance procedures pursuant to the Norwegian Planning and Building Act, but also the Norwegian implementation of the Seveso Directive on control of major-accident hazards involving dangerous substances.

3.4.3. Closing Remarks on Taxonomy

For fire safety engineering, one could also categorise the requirements by where the flexibility is placed. Imagine a building regulation requiring EI 45 fire barriers protecting all stairs. In context of the fire safety strategy, this is seen as highly rigid, and would by many be seen as not performance-based. For other parties in the project however, it is hardly relevant if the performance level is found in the fire strategy report or in the building regulations. Designers, contractors, and manufacturers are still free to choose how this fire resistance is achieved. Another example of how flexibility is restricted found in TEK section 11-11.2:

> *The time available for escape shall be greater than the time required to escape from the construction works. An adequate safety margin shall be included.*

Here, practically no restrictions are imposed on the design, but the verification method is determined on a legally binding level - although not enforced. If pre-accepted performance levels are applied, or if adequate means of egress is verified by comparative or other methods, an adequate safety margin is assumed.

Policies

- Evacuation or stay put/ defend in place
- Prevention, protection, or emergency preparedness
- Managing residual risk by insurance or by improved building performance

Solution

- Passive vs. active fire protection
- Separation distance vs. fire barrier

Performance levels of building elements or systems

- Fire resistance EI 30, reaction to fire B-s1,d0
- Fire safety systems complying to a given standard (e.g. EN 12845)

Verification

- Equivalency
- Specific metrics (e.g. individual risk)
- Analytical methods

3.5. The Reform of 1997

3.5.1. What?

The reform of 1997 (byggesaksreformen) marks a significant change in the regulation of the building industry in Norway, where two major changes were made:

- Privatisation of the building control
- Introduction of performance-based (function-based) building regulations

Until 1997, the municipality would review designs before approval. The fire brigade acted as advisor for both the builder and the local building authority in questions regarding fire safety. The municipality also had authority to approve dispensation where reasons were found to waver parts of the technical regulations. Privatisation of this process meant that this review and approval from local authority was to be replaced by private enterprises taking responsibility for the control and certifying compliance. The municipality retained the authority to give building permits but should primarily leave technical issues to industry.

The technical regulations of 1997 (TEK'97) had primarily functional requirements, and for fire safety, most of the mandatory performance levels and solutions were moved to a non-mandatory guide, as pre-accepted solutions/ acceptable examples.

3.5.2. Why?

The reform intended to [30, p. 27]:

- Reduce non-compliances in the building sector.
- Increase accountability and clarify responsibilities.
- Increase building legislation enforcement efficiency.

For fire safety, this change was part of a wider initiative described in STM 15 of 1992 [29], which gave specific goals, and further set forth a strategy to reduce fire losses based on

- Increased focus on preventive and information
- Improved coordination and collaboration (organizational)
- Development of better competence
- More efficient use of available resources

The White Paper STM 28 of 1998 express [24] gave some more information on the intentions of revising the technical regulations in 1997, including:

- Introduce functional requirements, to decouple the regulations from the technological development (thus making it more robust to new technology)
- Restructure the regulation, to better communicate requirements regarding health, safety and the environment.
- Facilitate European harmonisation.

See more on the expected benefits of performance-based building regulations in section 3.13.

3.5.3. How?

The reform was done under the same Planning and Building Act as previous building regulations. Three new regulations were however effectuated, as illustrated in Figure 13.

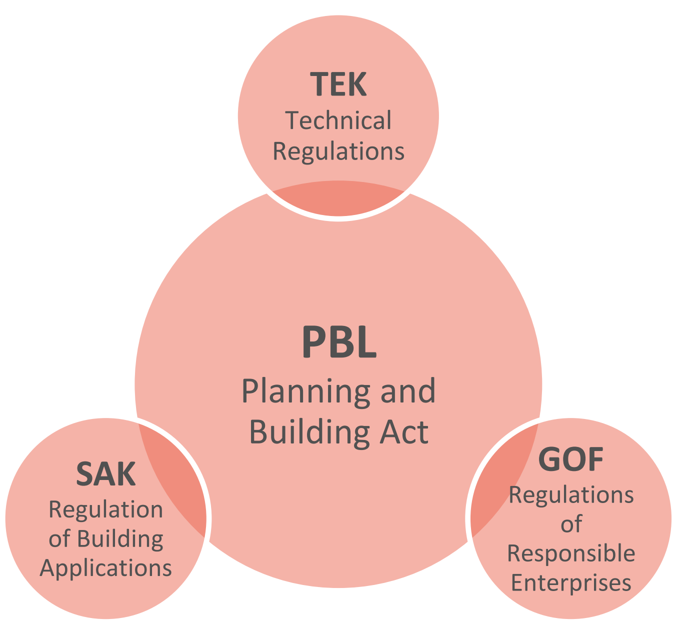


Figure 13 Legal structure per 1997

TEK – Technical regulation, now function-based, accompanied by a guide giving acceptable performance levels and solutions.

To ensure satisfactory effect of the new technical regulations, to other regulations were launched [31]:

SAK – Regulation of building applications, through stepwise building applications, giving the municipality insight to the design and building process, giving authority to require third-party review, and other means of intervention.

GOF – Regulations of responsible enterprises, setting requirements to ensure adequate qualifications for designers, controllers, and contractors, and regulating these actors' accountability and sanctions.

3.5.4. Level of Safety

The functional requirements of TEK'97 were implemented under the same Planning and Building Act as the previous prescriptive building regulation of 1987. Hence, both regulations were mandated to require the same level of safety. This premise also made the transition to functional requirements less controversial to critics.

Practically, this was solved by moving most of the mandatory provisions of the previous prescriptive building regulation into the guide to TEK'97 as pre-accepted performance levels and solutions, as proposed by NKB [32].

3.6. Fire Safety Engineering

Although fire safety consultants existed prior to 1997, the introduction of functional requirements marked a formalisation of fire safety engineering as a discipline in Norway. Fire safety engineering is defined by ISO [31]:

> *Fire Safety Engineering (FSE) is the application of engineering principles, rules and expert judgment based on a scientific appreciation of the fire phenomena, of the effects of fire, and of the reaction and behaviour of people, in order to:*
>
> *(a) save life, protect property and preserve the environment and heritage;*
> *(b) quantify the hazards and risks of fire and its effects;*
> *(c) evaluate analytically the optimum protective and preventative measures necessary to limit, within prescribed levels, the consequences of fire*

In Norway, the role of fire safety engineer in building projects is specifically linked to the fire safety concept (fire strategy, fire safety engineering brief) – a document containing performance levels and solutions chosen for the building, which is found to comply with the functional requirements. As such, the role came as a supplement to existing engineering disciplines and did not take over responsibility for detailed design of systems, even if they were fire related. Herein lies the distinction between level A and B Figure 1 on page 1. The deliverables from fire safety engineering were taking the place of the prescriptive building regulations. Fire safety design in this context, was thus to produce the project-specific rules and requirements – either by applying specifications from the guide to the building regulations (pre-accepted) or by analysis demonstrating that design alternatives would comply with the functional requirements.

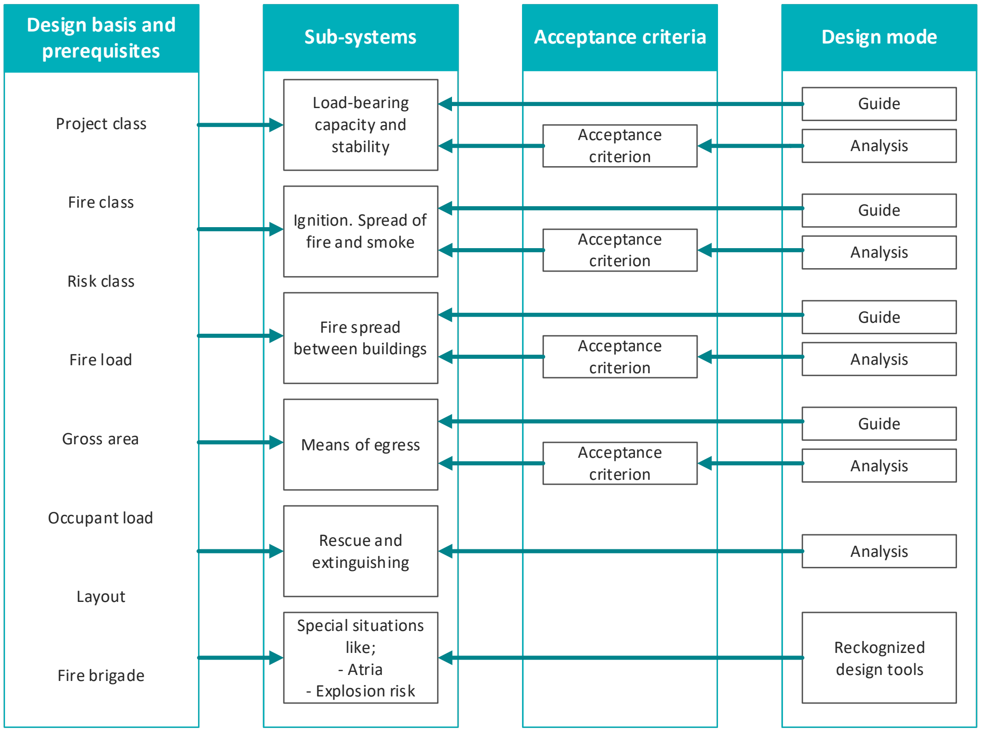


Figure 14 Main components of fire safety design, reproduced from first version of the guide to TEK'97 [33]

Figure 14 shows how the national building authority explained the fire safety engineering process in 1997 [33]. After establishing design basis and prerequisites, the guide acknowledged that different sub-systems could be treated differently (according to the guide or by analysis demonstrating compliance with an acceptance criterion). The lack of reference to acceptance criteria and analytical approach for rescue and extinguishing is not explicitly mentioned or further explained.

For the analyses, inspiration was drawn from international sources, like the National Fire Protection Association (USA), British Standards (UK), and other. Further discussion of details of this process will follow in subsequent chapters of this thesis, but Figure 15 provides an overview of the steps involved in performance-based fire safety design.

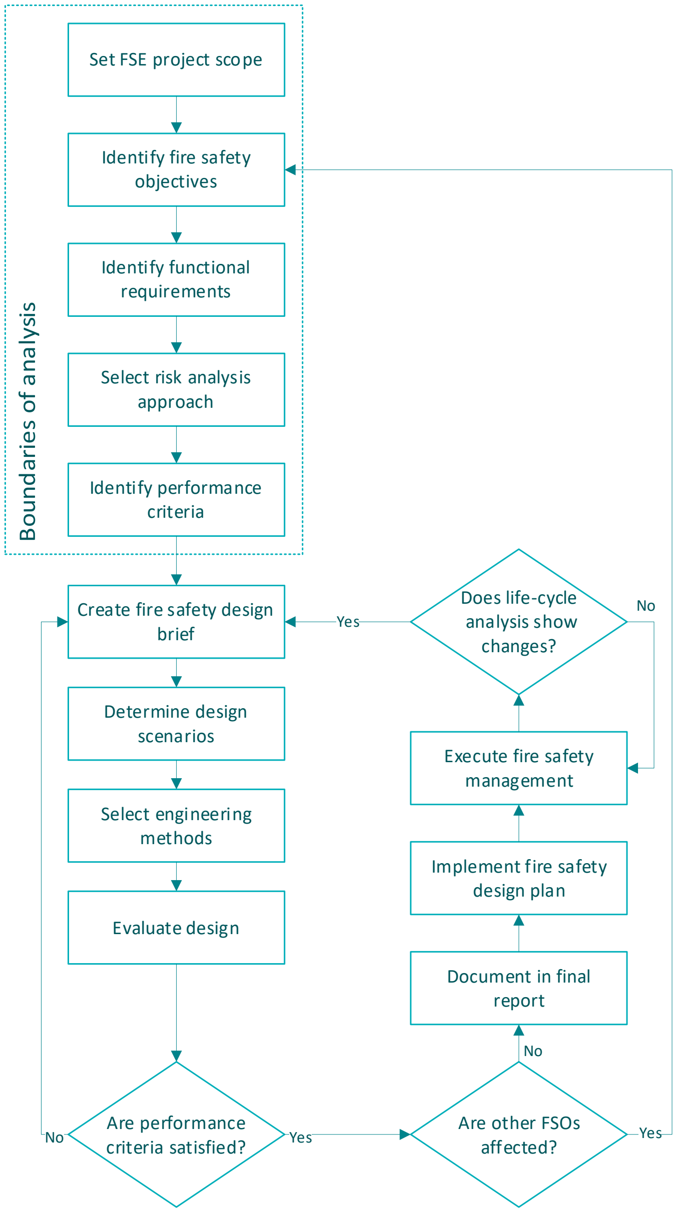


Figure 15 Fire safety engineering (FSE) process [34]. FSO = Fire safety objective,

Immediately after the introduction of performance-based building regulations, it was assumed that most buildings would be designed in accordance with pre-accepted performance levels and solutions, and that the analytical route would be reserved for the novel, non-standard buildings [33]. Over time it became apparent that a combination was needed, where most of the fire concept was according to pre-accepted performance levels, but one or a few deviations were made – also referred to as alternative solution. Therefore, the analytical option was not used only for large, special buildings, and the scope of the analyses was often limited to justifying one or a few deviations from known acceptable designs.

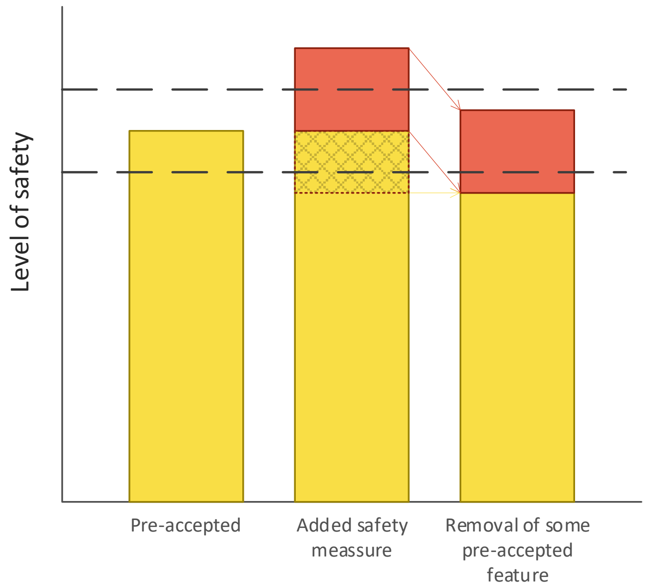


Figure 16 Illustration of trade-offs, reproduction from [35]

Figure 16 illustrates how the safety level resulting from a design complying with the guide is deemed acceptable. A common approach was to add some safety measure not required in the guide, and thus allowing for a reduction in performance level elsewhere – a trade-off. By this approach, the use of sprinklers and fire detection and alarm systems increased drastically.

3.7. TEK10

In June 2009 draft technical regulations were sent for public review, with a deadline for comments 1 October 2009 [36]. A 145 pages document summarised the proposed changes. Formally, it should be noted that the 2010 version of the regulations were pursuant of a new Planning and Building Act, passed in 2008, whilst the previous regulations of 1987 and 1997 both had warrant in the Planning and Building Act of 1985.

The changes compared to TEK'97 must be seen as an evolution – not a revolution. The main administrative changes with relevance to fire safety were:

- Restructuring so that all requirements regarding documentation of compliance are found in chapter 2.
- All fire safety requirements found in a separate chapter 11.
- Slightly changed structure of the fire safety chapter.

Generally, the level of safety was intended to be maintained as in previous building regulations, except for increased focus on safety for persons with reduced mobility. Of a more technical character, the following changes are worth mentioning in terms of fire safety.

- Automatic fire detection and alarm system mandated for more building types, where smoke alarms previously were allowed.
- New, explicit requirements for rescue of domestic animals

- Procedures for evacuation or rescue of disabled occupants in offices, commercial, and public buildings.
- Suppression systems mandated in hotels and health care facilities.
- Suppression systems mandated in residential buildings, where lifts are required.

Otherwise, the changes for safety in case of fire were editorial, and the discussion document explicitly stated that most sections were to be seen as continuation of the requirements found in TEK'97 [36]. Some supplementary comments on the changes to the guide and to the consideration of disabled persons is given below.

New Guide

New approach to the guide, VTEK, where the primary format is a website, rather than the printed documents accompanying TEK'97. Generally, the guide was given a stricter formatting, the relevant section of the regulation was presented above the guidance text. A clear distinction was also made between guidance text (non-mandatory) and pre-accepted performance levels and solutions (mandatory in leu of an analysis demonstrating compliance with the functional requirement). Furthermore, the use of modal verbs was thoroughly reviewed.

The transition to a web-based publication allowed for swifter updates, which also necessitated transparency on revision history. Compared to the four published versions of the guide to TEK'97 (average lifespan of 3 years and 3 months), the guide to TEK10 was revised far more frequent – several times per year.

Universal Design and Consideration for Disabled Persons

The consideration of disabled and elderly occupants was a considerable factor of the 2010 revisions of the building regulations. In addition to the above-mentioned regulation changes, new specifications were added to the guide, examples being the maximum allowable opening force for doors was reduced to 20 N, wayfinding systems were required to include tactile markings, and notification systems for hearing impaired occupants was required for certain building types.

The most significant change was however to mandate suppression systems for residential building where the regulation required lift – effectively residential buildings of more than 2-3 storeys. The guide also required fire sectioning between protected and unprotected parts of the building, which in most cases would mean a concrete or masonry wall with 2-hour fire resistance and substantial consequences for the load-bearing system.

The discussion document includes justification for the mandatory suppression systems, including cost-benefit assessments. The demographic changes and the increasing elderly population were acknowledged as at-risk-groups, for which it would be costly to provide health care facilities. Fire statistics also showed that these groups were over-represented in fire fatalities. Thus, the installation of fire suppression systems in buildings where egress through several stairs was required, should reduce the need for evacuation (hence the strict requirement for passive fire safety towards unprotected areas), effectively allowing elderly and disabled persons to keep living at home for longer, with adequate fire safety. See further discussion of fire safety for persons not capable of self-rescue in subsection 8.4.6.

It is worth noting that the performance levels and solutions found acceptable under TEK'97 were retained in TEK10, even after the introduction of fire suppression systems and fire detection and alarm systems. The discussion document makes reference to a Nordic research project (which would result in the report Verifying Fire Safety Design in Sprinklered Buildings [35] and eventually INSTA 950 [1]), where "pre-accepted trade-offs" agreed among the Nordic countries were expected. The national building authority therefore anticipated that a reduction in other performance levels would be possible when fire suppression systems, e.g., fire resistance [36, p. 84].

3.8. TEK17

For the 2017 revision of the technical regulations, two main objectives were presented by the government [37]:

- Simplification and clarification
- Reduced building costs

Some minor administrative changes worth mentioning include:

- The term verification was rejected, in favour of the term documentation.
- Chapter 2 on documentation of compliance was restructured to better align with the typical stages of a building project, and consequently being brought in alignment with levels A, B and C of the pyramid shown in Figure 1 on page 1.

The increase in fire safety (and cost) was acknowledged by politicians and national building authorities, so while preparing for the 2017 version of the building regulations, the ministry called for simplifications [38].

For safety in case of fire, the changes are not considered substantial. Due to its controversy, a short summary of the possibility of reducing pre-accepted performance levels in buildings where fire suppression systems are installed follows.

Relaxations on Other Performance Levels Where Fire Suppression Systems are Installed

A series of studies was conducted, looking for relaxations to pre-accepted performance levels, including where sprinklers and fire detection and alarm systems were present [39]. The report concluded with a list of proposed relaxations was given, accompanied with a list of pre-accepted performance levels which should be further considered for relaxations. When the draft regulations were circulated for comments in 2016, a table was included, where the designer was allowed to choose a maximum number of eight relaxations, four from each group.

The proposed approach had a mixed reception, where Rådgivende Ingeniørers Forening (RIF – the Norwegian Consulting Engineers' Association) were among the responders to express criticism, characterising the approach as "*non-scientific*" and that it demonstrated "*little or no understanding of the risks involved in replacing a passive fire protection with an active fire safety system.*" [40]

The proposed relaxations were not included in the final regulations entering into force 1 July 2017.

TEK17: A Step Forward on the Journey Ahead

The 2017 revision of the building regulations were preceded by a number of studies funded by the national building authority, made available through their website www.dibk.no. Furthermore, conferences were held, where industry was invited to give feedback to the authorities, primarily on possible simplifications and suggestions for cost-reduction, but also other forms of feedback was welcome.

TEK17 was also described as the first step forward on a greater journey ahead, as illustrated in Figure 17, a reproduction and translation of a presentation held by the national building authority, orienting on the status for TEK17.

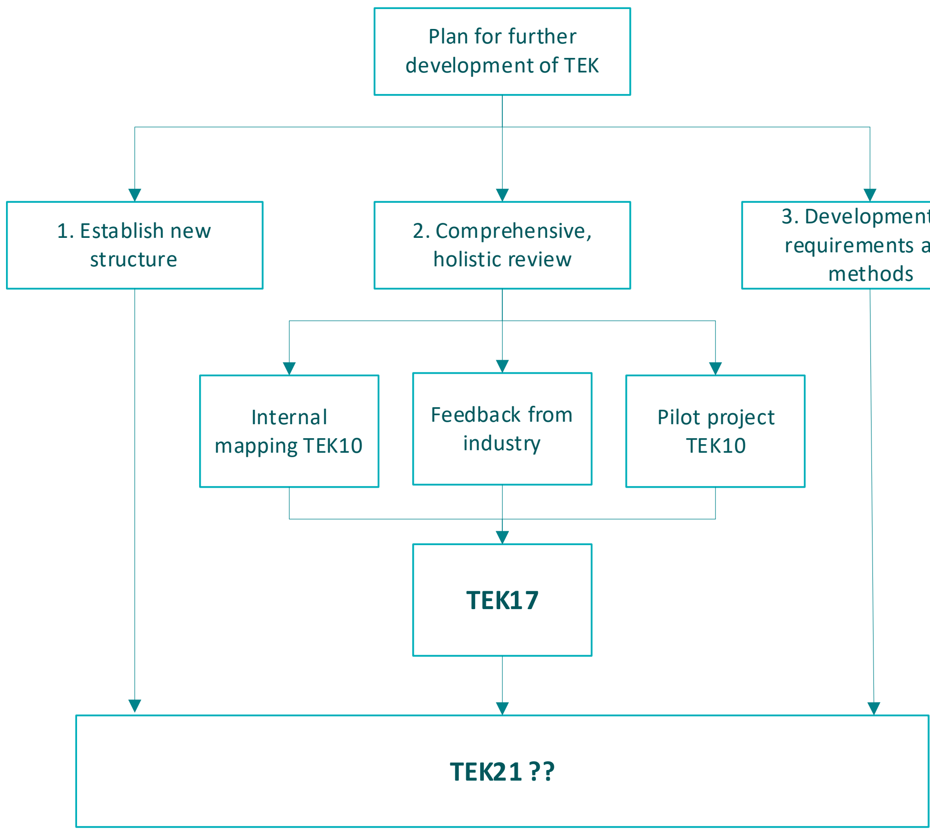


Figure 17 Illustration of the plan for further development of technical regulations as per 2016 [41]

Figure 17 shows how three parallel initiatives were feeding into the new regulations, but also that more substantial work was ongoing or planned, feeding into a new version of the regulation, tentatively five years from the date of the presentation.

At the time of writing this thesis, no official date is given for the predecessor of TEK17.

3.9. Demonstration of Compliance – Verification

3.9.1. Verification

Throughout this thesis, the definition of verification found in ISO/TR 16576 [5] is used, where verification is defined as the

> *process of determining that a fire safety design complies with the fire safety requirements by examining the design in the light of safety criteria*

Verification may also be seen as the end-result of said process.

The need for verification must be seen from two perspectives. The regulators must be able to assess whether the required level of safety is obtained, potentially imposing sanctions if the requirements are not met. As an extension of this perspective, is also builders, insurers and affected parties in a fire, who may be in position to require a certain level of fire safety. Conversely, the responsible designer (the regulated) must be able to demonstrate that the proposed design is adequate, and in accordance with the relevant requirements.

In the Norwegian building regulations, the verification process is not strictly regulated. TEK17 section 2 sets forth the following general requirements:

1. Verification demonstrating compliance for the finished building shall be provided.
2. It shall be in writing.

Where the pre-accepted performance levels are applied, no more verification is needed. Where verification is based on analysis, the following applies;

3. The analysis shall demonstrate compliance with the functional requirement.
4. The verification method shall be suited and valid for the application.
5. Assumptions made shall be described and justified.
6. Necessary safety margins shall be stated.

Some general guidance is given in the guide to the technical regulation, and reference is made to two standards, which when followed, are deemed to give a satisfactory verification: NS 3901 Requirements for risk assessment of fire in construction works [42] and SN-INSTA/TS 950 Fire Safety Engineering - Comparative method to verify fire safety design in buildings [1].

3.9.2. Documentation of Compliance

From 1997 to 2017, the Norwegian building regulations have used the term verification. Verification was described as “the part of the documentation demonstrating compliance with the regulations”[2] [43]. ISO 9001, on the other hand, gives the following definition;

> *confirmation, through the provision of objective evidence, that specified requirements have been fulfilled*

In a risk perspective, one can question the benefit of the pursuit of verification, as it implies that a facility is statically safe or unsafe [44], as will be discussed in subsequent chapters of this thesis.

As of 2017, the term documentation is used.

> *Å dokumentere innebærer å føre bevis, synliggjøre, begrunne og underbygge, ved hjelp av dokumenter. Forvaltningsloven definerer et dokument som en logisk*

> *Documenting implies providing evidence, demonstrating, justifying, and substantiating, by means of documents. The Public Administration Act defines a document as a logically*

[2] «*Verifikasjon er den delen av dokumentasjonen som viser at regelverket er fulgt*.», guidance to TEK10 § 2-1.4 [26]

avgrenset informasjons-mengde som er lagret på et medium for senere lesing, lytting, framføring, overføring eller lignende.	*defined amount of information that is stored on a medium for subsequent reading, listening, presentation, transfer or similar.*

3.10. Building Legislation and Fire Legislation

An illustration is made in Figure 18 to visualise how fire safety is regulated in the lifespan of a building. The Planning and Building Act regulate design and construction, whilst fire safety for buildings in use is regulated by the Fire and Explosion Prevention Act.

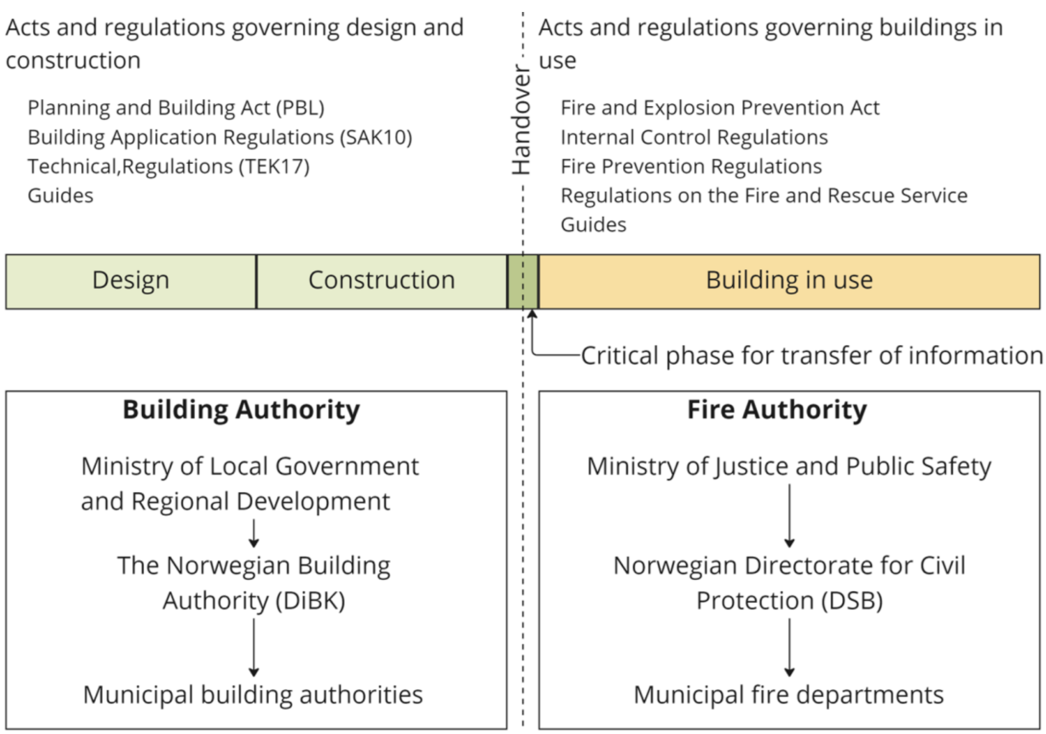


Figure 18 Interface between building legislation and fire legislation (based on [9])

Fire safety is only one out of many objectives for the building regulators. Similarly, setting technical requirements to the building elements is only one out of many means for the fire regulators.

Hazardous goods, gas installations, and implementation of the Seveso directives is under the jurisdiction of DSB.

Consumer product safety is also under DSB jurisdiction, including fire safety performance of furniture, stove protection, self-extinguishing cigarettes, product safety etc.

Fire Safety During the Construction Phase

PBL section 29-5, TEK17 section 2-1 and the accompanying guidance text stress that technical requirements relate to the completed construction works. PBL section 28-2 paragraph 1 states:

Building or demolition work, excavation, blasting or filling may not be initiated unless the responsible parties have taken necessary measures to safeguard against injury to persons or damage to property, and to maintain the flow of public traffic.

Although a wider meaning could be interpreted from the text, current practice is that fire safety engineers seldom have a role in the construction phase, with the exemption of alterations, expansions, or other projects with an interface with existing buildings in use.

Safety of workers on the construction site is primarily governed by Regulations concerning safety, health and working environment at construction sites (Byggherreforskriften).

Obligation to Upgrade Existing Buildings

The Fire prevention regulations lays down requirements to upgrade existing buildings, so that no building has a level of fire safety less than what follows of the building regulations of 1985. The upgrade can be done by technical upgrades of the building or its systems, by other risk reducing measures (managerial procedures, prevention, emergency preparedness, etc.), or a combination thereof.

3.11. Support Structure

As seen in section 3.5, the reform of 1997 involved more than the introduction of functional requirements. It was acknowledged that some support structure was needed to ensure the desired quality. Figure 19 and Figure 20 shows how the desired outcome of regulation is reliant on competency, accountability/ oversight, and constraints.

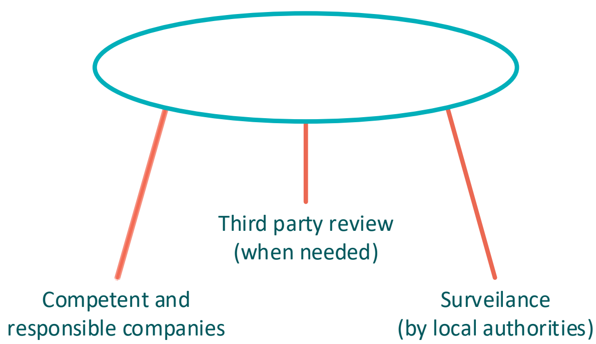


Figure 19 Three major dependencies for a well-functioning system [45]

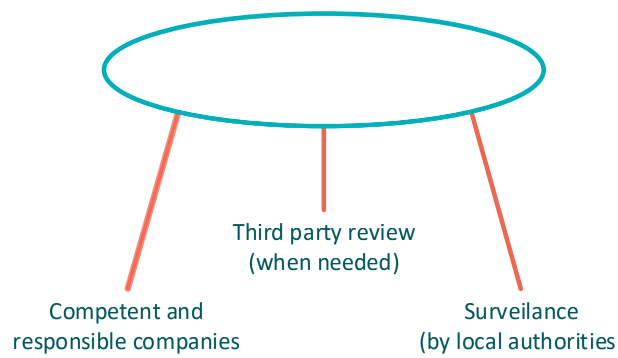


Figure 20 Three fundamental premises for adequate quality [46]

As seen in Figure 13 on page 25, the three regulations, TEK, SAK, and GOF reflect the same three dependencies illustrated in Figure 19.

With reference to Figure 22, one cannot discuss functional requirements and verification of compliance with these, neglecting the two other fundamental premises. As will be discussed in chapter 7, strictness in one of these premises can allow for relaxations in others and vice versa.

To provide the reader with a basic understanding of the context for verifying fire safety performance in Norway, a brief introduction to the current support structures is given below.

3.11.1. Project classes

There is a classification of building projects is the regulation on building applications, SAK10 section 9-4, as summarised below [47].

Table 2 Division into project classes, according to SAK10 [47]

	Consequences of deficiencies for health, safety, and the environment		
	Minor	**Moderate**	**Major**
Not very complicated. Low degree of difficulty	Project class 1	Project class 2	Project class 3
Moderately complicated. Moderate degree of difficulty	Project class 2	Project class 2	Project class 3
Very complicated. High degree of difficulty	Project class 3	Project class 3	Project class 3

The classification can be seen as a risk assessment, considering the complexity and difficulty of the tasks or the project probability of deficiencies or errors. By categorising the consequences, the above table resembles a risk matrix. The project class is assigned individually per responsibility role (applicant, designer, constructor, or controller) and per discipline – meaning a building can have a straight-forward load-bearing structure, with minor consequences in case of deficiencies, whilst the fire safety concept is designed fully performance-based. Thus, the structural design is low or medium risk (project class 1 or 2), and the fire safety engineering is high risk, and is classified as project class 3. Typically, control will be placed in a project class no lower than the controlled party.

Traditionally, project class have been linked to fire classes (as they reflect the consequences of fire), hazard classes (also an indication on consequences in case of deficiencies or errors), and finally whether pre-accepted performance levels are applied throughout, or if analytical design is used.

Table 3 Correlation between fire class, hazard class and project class. Project classes 1 and 2 shown with an asterisk indicate that the design must be according to pre-accepted performance levels and solutions [6].*

		Fire class			
		BKL1	**BKL2**	**BKL3**	**BKL4**
Hazard class	**RKL1**	1*	2*	3	3
	RKL2	1*	2*	3	3
	RKL3	2*	3	3	3
	RKL4	1*	2*	3	3
	RKL5	2*	3	3	3
	RKL6	2*	3	3	3

The above correlation between fire, risk, and project class has seen slight variations over time, but the concept of increasing project class with increased risk has been key throughout.

The project classes are used to regulate the qualifications of those assuming responsibility in the project, as applicant (responsible permitting and liaising with authorities), designer, controller, or contractor. As seen in Figure 21, increasing project class calls for higher qualifications.

	Years of relevant experience → 4	5	6	7	8	9	10	11	12	…
Responsible designer										
120 ETCS	Project class 1						Project class 2			
180 ETCS	Project class 1		Project class 2							
300 ETCS	Project class 1		Project class 2		Project class 3					
Responsible controller										
120 ETCS	Project class 1									
180 ETCS	Project class 1		Project class 2							
300 ETCS	Project class 1		Project class 2		Project class 3					

Figure 21 Minimum requirements for relevant work experience and relevant education for project class 1-3 [6].

ECTS in Figure 21 refers to the European Credit Transfer and Accumulation System, and 180 ETCS represents a bachelor's degree or similar, whilst 300 ETCS equates a master's degree or equivalent. Both the education and the work experience shall be relevant to the role and discipline for which the actor is taking responsibility.

The current model for "central approval for the right to accept responsibility" is under review. For information on this process, and further reading on qualifications and accountability in Norwegian building projects, reference is made to von der Fehr et al [30] and the Building Application Regulations [47] including the guide to the regulations [6].

3.11.2. Oversight

Municipal building authorities are required to draw up a supervision strategy and execute this by supervising enterprises accepting responsibility in building projects. Additionally, nationally determined focus areas are included in the building application regulations, where certain project types, roles, or disciplines are placed under extraordinary scrutiny. Reports are sent to the national building authority.

The national building authority performs supervision of enterprises being centrally approved for the right to accept responsibility. As opposed to the municipal surveillance, which inspects the individual projects, and whether these are compliant, the national building authority emphasis procedures, quality assurance, and other aspects of a more systemic nature.

3.11.3. Third-party review

The building application regulations give municipal building authorities the mandate to require third-party review at their own discretion. Certain roles and disciplines do however require third-party review in all projects. The design of fire safety concepts in project classes 2 and 3 are required to undergo third-party review.

3.12. Legal Considerations

The intentions for performance-based building regulations in Norway were to leave pre-accepted performance levels as not legally binding [25, 33]. The past 10 years, increasing focus has been put on potential legal issues with the way pre-accepted performance levels are treated in Norway.

Tasked by the Norwegian National Building Authority, a legal firm, Hjort DA assessed the legal basis for functional requirements in the building regulations, and whether the principle of legality was respected.

The principle of legality in can be described as [48]:

> *[I]f Parliament wishes to infringe basic common-law norms it must do so through express language or by necessary implication.*

Hjort gave several recommendations, but generally concluded that the principle of legality was respected as long as the option of verifying compliance by analysis is maintained [49]. These legal issues were also mentioned in subsequent evaluations [50, 51].

Hjort furthermore drew attention to what they characterised as disguised prescriptive performance requirements. These are functional requirements where compliance is near impossible without applying the pre-accepted performance levels – rendering the pre-accepted performance levels practically mandatory.

As will be further discussed in subsection 8.3, the phrasing in the guide has changed slightly over time, where the first three version [33, 52, 53] stressed that the pre-accepted performance levels were non-mandatory, and that the guide did not intend to take the position of a regulation, but gave interpretations of the functional requirements and examples which were deemed acceptable and in compliance with the functional requirement. Consequently, the regulation was the source of the legally binding safety level. As of 2007 the guide is claimed to be the source of the minimum allowable performance-levels [54, p. 10].

When the 2010 edition of the technical regulations was on public review, the phrasing of pre 2007 was reintroduced [36], but the final official version again claimed that the pre-accepted performance levels were minimum requirements [55].

In their instructions to the National Building Authority, the Ministry clearly indicate their view on the status of pre-accepted performance levels [56]:

Endring av preaksepterte ytelser i veileder som innebærer endring av kravsnivå, skal foretas som forskriftsendring.	*Changes to pre-accepted performance levels in the guide that involve changing the level of requirements must be made through regulatory amendments.*

As will be further discussed in chapter 4 and 8, the regulation (legally binding document) allows for demonstrating compliance by analysis, and does not limit this possibility to equivalency assessments against the pre-accepted performance levels of the guide. Burden of proof is however on the responsible designer - meaning if pre-accepted performance levels are not applied, the responsible designer is obliged to demonstrate in writing that the functional requirement is fulfilled.

Considering the loose regulation and guidance of fire safety engineering [57], it may be challenging in a dispute to document violation of the functional requirements or even breach of the formal requirements given for the analysis.

3.13. Expected Benefits

The intended benefits from regulating building fire safety by functional requirements is seen in subsection 3.5.2, but is also formulated clearly by the government in STM 15 of 1992 [29]:

Det er […] ofte slik at regelverk i stor grad utformes i samsvar med dagens teknologi og således lett kan bli umoderne eller uaktuelt. I det pågående arbeid med revisjon av detaljregelverket tas det så langt det er mulig sikte på å unngå et detaljorientert og statisk regelverk. Et mål er derfor å utarbeide mest mulig funksjonelle forskrifter. Dette innebærer at forskriftene innholdsmessig orienteres mer mot hva en ønsker å oppnå snarere enn å stille detaljerte krav til spesifikke løsninger eller fremgangsmåter. Dette	*[…]it is often the case that regulations are largely based on current technology and can easily become outdated or irrelevant. In the ongoing work of revising the detailed regulations, efforts are made to avoid a detail-oriented and static regulatory framework as far as possible. One goal is therefore to develop regulations that are as functional as possible. This means that the regulations are oriented more towards what one wants to achieve rather than imposing detailed requirements on specific*

vil gi brukeren av regelverket et reelt valg med hensyn til bruk av teknologi samtidig som rammene til sikkerhet blir ivaretatt.	*solutions or procedures. This will provide users of the regulations with real choices in terms of technology use, while ensuring adequate safety.*

In a recent survey, representatives from European legislations were asked for reasons to allow fire safety engineering approach [58]:

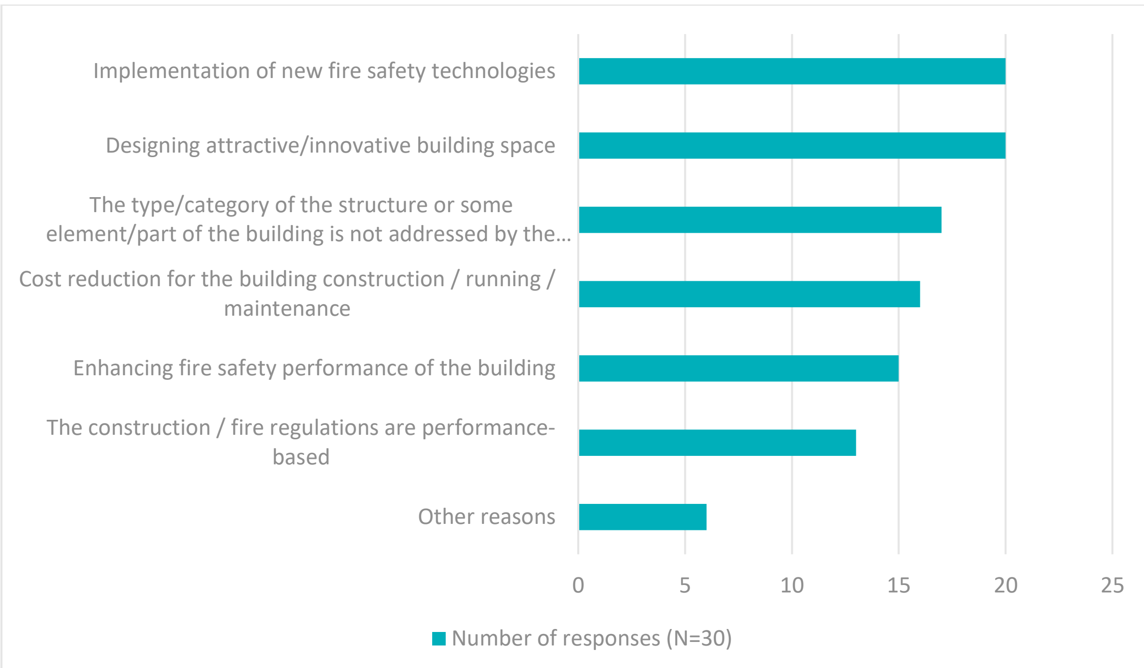


Figure 22 Reasons to allow fire safety engineering approach [28]

Most notable benefits found in the reviewed literature is listed below.

Benefit 1 More robust to change, as regulations are decoupled from technology [24, 29, 59].
Benefit 2 Allowing for innovation/ implementation of new fire safety technologies [58, 59, 60].
Benefit 3 Allowing for designs not covered by prescriptive guidance [58].
Benefit 4 Reduced construction costs [61, 60] and running/ maintenance costs [58].
Benefit 5 More “safety for the dollar” [61, 58].
Benefit 6 Enhanced productivity [61].
Benefit 7 Removal of trade barriers [61, 24, 59, 60].
Benefit 8 Increased international cooperation and harmonisation [61, 60].
Benefit 9 Better integration into multi-functional building performance requirements [61].
Benefit 10 Higher confidence in achieving desired results [61].
Benefit 11 More flexibility for the designer [61, 29, 59, 60].
Benefit 12 Reduced pressure for more costly fire protection [61].
Benefit 13 Ability to better evaluate existing building stock [61, 59].

Benefit 14 Reduced administration (less/ no need to grant exemptions from regulations) [59, 60].

3.14. Known Limitations and Challenges

The fire safety engineering community is not blind to the limitations and challenges of performance-based building regulations. Most of these challenges were also known at the time the decision was made to pass new legislation based on these principles.

The intended benefits of performance-based building regulations also have some inherent challenges, as it aims for flexibility. Flexibility and freedom will always constitute a counterpart to predictability and uniformity.

Reference is made to Coglianese [28] for a thorough, general discussion on the limits of performance-based regulations, and to Alvarez et al [57] a more fire safety specific review looking back on twenty years of experience with performance-based design.

Below is a list of the challenges most prominently mentioned in the reviewed literature.

Challenge 1 Variability and randomness – Different actors will conclude differently when faced with the same problem [62, 63]
Challenge 2 Difficult to define quantitative levels of safety (performance criteria) [60, 61]
Challenge 3 Lack of (validated) tools and methods [59, 61]
Challenge 4 Uncertainty regarding compliance [59, 60, 61]
Challenge 5 Shortage on competency [59, 60, 61, 58]
Challenge 6 Many subsystems are unfit for analysis. [59]
Challenge 7 High resource demand on analyses [60]
Challenge 8 Resistance to change [61]
Challenge 9 Fear of liability and lawsuits [61]
Challenge 10 Lack of data [58]
Challenge 11 Lack of sufficiently specific guidance documents [57]

3.15. Emerging Philosophies – Systemic Thinking

The interest in systemic thinking is increasing within fire safety engineering, and over the last decade a number of publications have been produced, advocating for a shift in paradigm [44, 64, 65]. This section aims to give an introduction to the concept.

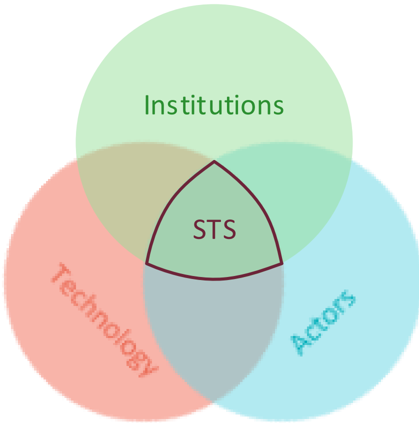


Figure 23 Simplified representation of Sociotechnical systems (STS) interaction, adopted from [65]

3.15.1. Background

Building on system engineering created by aerospace engineers after World War II, inspired by the work of Jens Rasmussen, Systems Thinking and Systems was established at the turn of the millennium by Nancy Leveson. She deemed the contemporary approaches to safety inefficient and inadequate, and gave the following reasons for a change in paradigm [66]:

- **Technology changes at a fast pace**, so knowledge based solely on experience from past accidents will not suffice.
- **Reduced ability to learn from experience**, as new technology is brought to market with less testing and experience. Experience based on obsolete technology may not be transferred to the new technology.
- **Changing nature of accidents** as a consequence of technological and societal changes.
- **New types of hazards** as a side-effect of technological advancements (chemical toxins, radiation, antibiotic resistance, etc).
- **Increased complexity and coupling**, by interaction between the components, dynamically over time, or nonlinear, where we are unable to comprehend the link between cause and effect.
- **Decreasing tolerance for single accidents**, as society is increasingly interconnected, hence the ripple-effect of single accidents may reach far from the origin (e.g., infrastructure and financial systems).
- **Difficulty in selecting priorities and making trade-offs**, seeing that although the potential losses are greater, the rate of production and revenue is also higher. In highly competitive markets there will be pressure to reduce time and cost – potentially on the expense of safety.
- **More complex relationships between humans and automation**, introducing new types of human error, like lack of communication or misunderstanding between human and machine.
- **Changing regulatory and public view of safety**, where safety responsibility shifts from the individual to the government as regulations replace the function of the individual’s caution.

3.15.2. Application for Design

The STS design principles of Cherns are presented and set in fire safety engineering context by Meacham [65]:

- The process of design must be compatible with its objectives.
- No more should be specified than is absolutely essential, but the essential must be specified.
- For groups to be flexible and able to respond to change, they need a variety of skills.
- Information must go, in the first instance, to the place where it is needed for action.
- Boundaries should facilitate the sharing of knowledge and experience. They should occur where there is a natural discontinuity – time, technology change, etc. – in the work process. Boundaries occur where work activities pass from one group to another, and a new set of activities or skills is required. All groups should learn from each other despite the existence of the boundary.
- Systems of social support must be designed to reinforce the desired social behaviour.
- The recognition that design is an iterative process. Design never stops. New demands and conditions in the work environment mean that continual rethinking of structures and objectives is required.

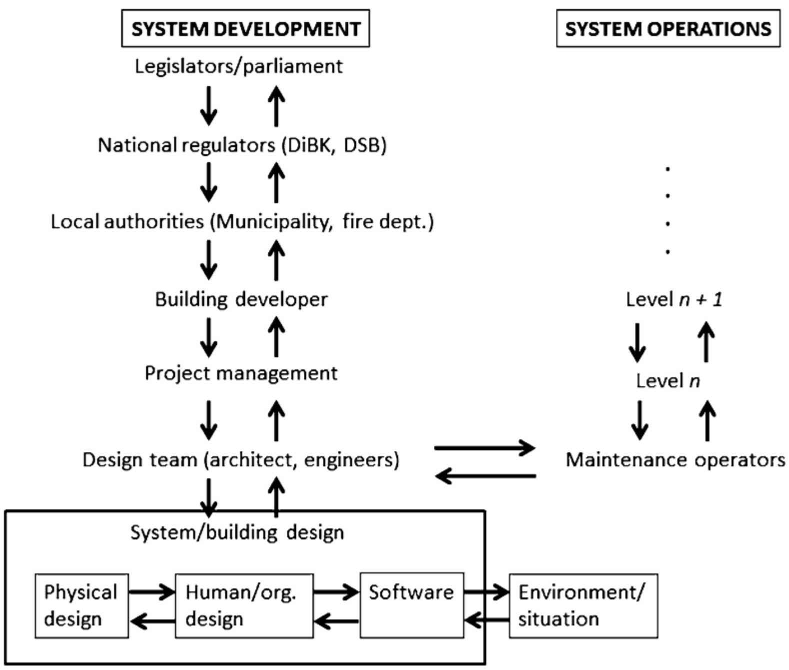


Figure 24 Socio-technical control structure for a building project, as illustrated by Bjelland et al [44]

As illustrated in Figure 24, the hierarchical control structure extends beyond the building elements, and considers the interaction with humans and organisations, software, and the environment. Furthermore, the system is seen in a societal context.

3.15.3. Implications for Fire Safety Engineering

Applying systemic thinking, fire safety cannot be understood by looking at individual parts of the system. The system may be in a state of safety, but only remains safe if risk increasing factors are identified by the system, and being controlled by the safety constrains.

Key to this thinking is an agnostic attitude regarding the source of fire safety. As will be further discussed in this thesis, fire safety engineer for building fire safety is a product of the legislation, and legislation is distinctly segregated in terms of 1) design stage vs. operation, and 2) technical properties of the building vs. fire safety management vs. fire service operations.

With a traditional approach, a sizable concert arena is deemed unsafe with a limited egress width (say 1 m) because the evacuation time would be too long if the arena was in use by the number of people found by multiplying its area with the expected occupant load factors. By treating this venue as a system, one would acknowledge the limited egress width, which would be one of many factors to consider when defining the safety constrains. For this venue to remain in a safe state, the owner and other stakeholders would have to adhere to a restrictive policy in terms of occupant load, which most likely would not be acceptable. Furthermore, systemic thinking treats the building as an adaptive system throughout its lifetime. If changes occur to the building, its environment, occupants, etc, the system shall have information loops to inform about these changes, allowing for appropriate safety constrains to be activated. Reverting to the concert arena example, one may have to reduce the allowable occupant number if the muster points outside the arena are affected by roadwork, weather, or other factors reducing the evacuation flow – even if the building itself has code-compliant design. Similarly, the safe occupant load may differ for different audiences, or different staffing situations.

Bjelland et al propose a framework with the following steps for fire safety engineering [44].

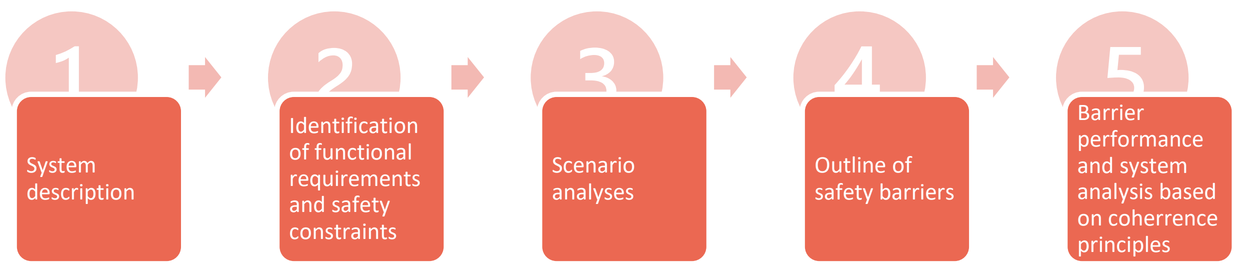


Figure 25 STS fire safety engineering framework [44]

A slightly different representation of the process is presented by Meacham [67]:

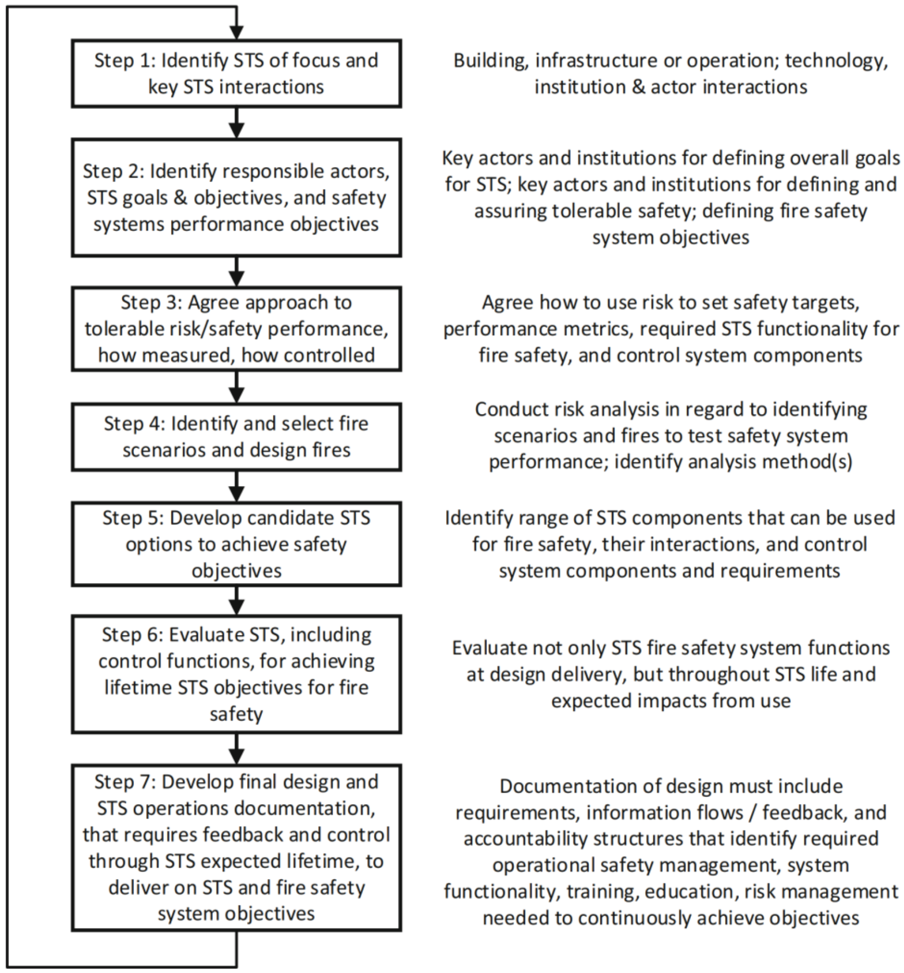


Figure 26 Socio-technical systems framework for performance-based fire safety design [67]

3.16. Summary

Fire safety has for ages been an integral concern in building regulations, and has historically been regulated by mandating certain solutions, dimensions, or risk mitigating measures. From the 1990s, a global trend of deregulation fed the introduction of performance-based regulations, where the regulator no longer dictated the specific solutions or dimensions, but rather expressed the required outcome, allowing for greater freedom in design. There are many ways to implement these ideas, and different jurisdictions emphasise different levels of the hierarchy ranging from overarching goals to detailed descriptions of how to perform analytical verification, via functional requirements, operational requirements, performance criteria, and examples of acceptable design (pre-accepted/ deemed to satisfy).

The introduction of performance-based fire safety design in Norway came with the 1997 version of the building regulations. Here functional requirements were adopted from a Nordic collaboration called NKB, and with few exceptions, the only requirements on a legally binding level were functional requirements.

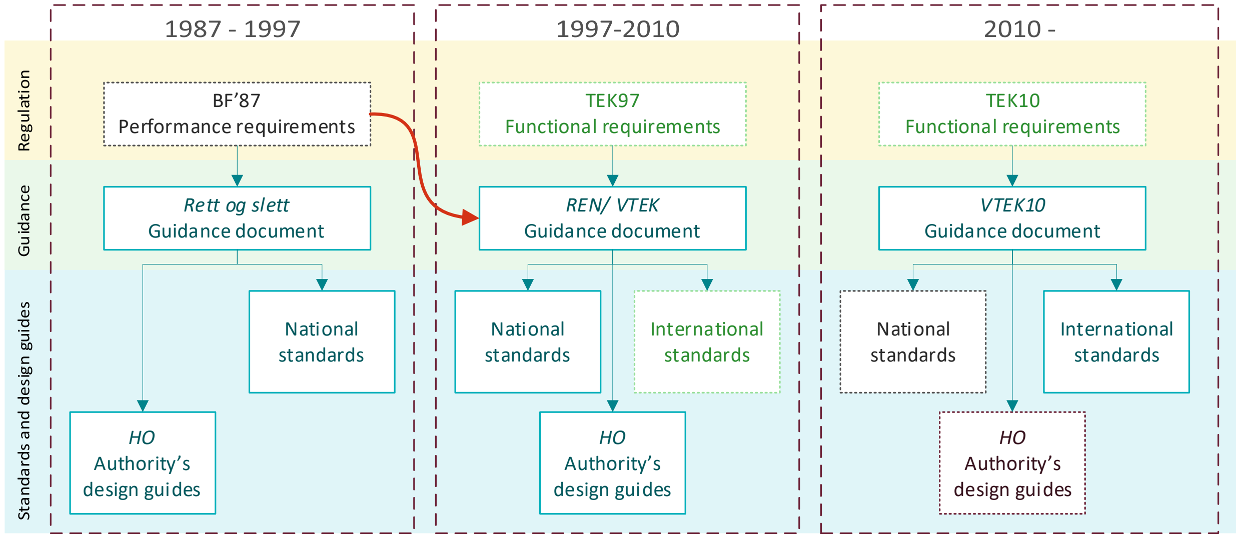


Figure 27 Development of National building authority's direct regulation of fire safety, reconstructed from [31]

Although the change to performance-based building regulations was a brave shift, Figure 27 shows how the performance requirements of the more prescriptive previous building legislations were retained as examples of acceptable design – pre-accepted performance levels – yet on a level not legally binding. The advantage of this approach is consistency, but it may also undermine the value and importance of the functional requirements, contributing to raising the status of the pre-accepted performance levels.

Fuelled by harmonisation, the guidelines produced by the national building authority and national standards were withdrawn and replaced by international standards. These are documents regulating the detail design of fire safety systems and classification of building element's fire performance, but regulating the practice of fire safety engineering and analysis.

Parallel with the introduction of performance-based building regulations, Norway introduced self-certification in 1997, meaning the municipal building authority would no longer approve the technical quality of a design, but left to responsible enterprises to declare compliance. To retain control, a support structure was created, consisting of

- Qualification requirements,
- Municipal supervision, and
- Third-party review for selected disciplines and roles.

Over the last decade, systemic thinking has gained momentum in the fire safety engineering community. The concept stands in stark contrast to the current practice, where the building regulation mandates verification of compliance with the requirements pursuant of the planning and building act, disregarding fire safety management, managerial procedures, and fire and rescue service performance. By treating buildings as socio-technical systems, a more holistic understanding can be applied to fire safety, encompassing more factors affecting fire risk in a full life-cycle perspective, rather than a static analysis for the technical properties of the building at the time of design.

4. Brief Review of the Norwegian Building Regulations

4.1. Introduction

The objective of chapter 4 is to give an overview and some examples of how the Norwegian building regulations are formulated and how this affects the possibility of performance-based design. Chapter 3 gave an overview on how the development has led to the current state, whilst chapter 4 will highlight certain aspects of the current regulation of relevance to the thesis – either by directly clarifying the current regulations for fire safety, or serving as inspiration for alternative approaches.

4.2. Documentation of Compliance – Chapter 2

Chapter 2 of TEK17 sets requirements for documentation of compliance. Section 2-1 general requirements requires that written verification of compliance with the technical regulation shall be provided for the completed building.

Section 2-2 addresses the basis for detailed design (e.g., fire safety strategy report/ concept). The second paragraph gives the designer freedom to choose between applying pre-accepted performance levels, or performance-based design, where compliance with functional requirements is demonstrated by analysis.

Section 2-2 paragraph 3 states:

If compliance with the Regulation's functional requirements is verified by analysis, it must be demonstrated that the method of analysis applied is suitable and valid for the purpose. The assumptions used shall be described and the reasons for using them given. The analysis shall state the necessary safety margins.

In the guide, reference is made to standards giving support for the process of documenting compliance. Since 2003, the Norwegian standard NS 3901 [42] on fire risk assessment has been referenced, and since January 2015, SN-INSTA/TS 950 [1] has been referenced for comparative analysis. Throughout, reference has been made to Byggforsk-serien, as series of guidance documents produced by SINTEF, providing supplementary advice on a more detailed level than found in the guide to the building regulations, including compliance with functional requirements.

None of the above-mentioned guidance documents are mandatory, but reference to NS 3901 and INSTA 950 is made with a statement that analyses in accordance with these standards will meet the requirements of TEK section 2.

4.3. Safety in Case of Fire

4.3.1. Structure

Both structure and content of the chapter shows clear relation to the work of NKB [32] – most of the functional requirements are direct implementations. Furthermore, the structure is well-aligned with CPR Annex I, 2. Safety in case of fire [69]

The construction works must be designed and built in such a way that in the event of an outbreak of fire:

(a) the load-bearing capacity of the construction can be assumed for a specific period of time;

(b) the generation and spread of fire and smoke within the construction works are limited;

(c) the spread of fire to neighbouring construction works is limited;

(d) occupants can leave the construction works or be rescued by other means;

(e) the safety of rescue teams is taken into consideration.

The fire safety chapter consists of 17 sections, grouped as seen below.

- I. General requirements relating to safety in case of fire
  - Section 11-1 Safety in case of fire
  - Section 11-2 Hazard classes
  - Section 11-3 Fire classes
- II. Load-bearing capacity and stability in case of fire and explosion
  - Section 11-4 Load-bearing capacity and stability
  - Section 11-5 Safety in case of explosion
- III. Measures to prevent ignition and the development and spread of fire and smoke
  - Section 11-6 Measures to prevent the spread of fire between construction works
  - Section 11-7 Fire sections
  - Section 11-8 Fire compartmentations
  - Section 11-9 The fire properties of products and materials
  - Section 11-10 Technical installations
- IV. Facilitating escape and rescue
  - Section 11-11 General requirements relating to escape and rescue
  - Section 11-12 Measures that influence escape and rescue times
  - Section 11-13 Exits from fire compartments
  - Section 11-14 Escape routes
  - Section 11-15 Facilitating rescues of domestic animals
- V. Facilitating the extinguishing of fires
  - Section 11-16 Facilitating the manual extinguishing of fires
  - Section 11-17 Facilitating the work of rescue and firefighting personnel

4.3.2. Fire and Hazard Classes

As many other jurisdictions, building and occupant types are grouped and classified, which serves two purposes:

1) Categorise occupancies for which the same requirements apply in the building regulations.
2) Organise the pre-accepted performance levels, so that they can reflect differences in risk.

Fire Classes

Fire classes are meant to differentiate construction works based on the consequences a fire may give, based in terms of

- Danger to life and health,
- Societal interest, and
- The environment.

Four fire classes exist, where 1 implies slight impact in case of fire, and 4 implies very serious impact in case of fire. Although TEK gives the above criteria for determining fire classes, VTEK introduces a table which sets a direct relation between hazard classes and number of storeys. Deviations from this table in VTEK is somewhat controversial, as it may be seen as way of by-passing the requirement for an analysis of all relevant consequences.

Fire classes are instrumental when applying pre-accepted performance levels, VTEK differentiates its pre-accepted performance levels on fire class. The functional requirements do however neglect the term, except for the case of load-bearing structures, where fire class 1 and 2 are treated differently compared to 3 and 4.

VTEK describes certain construction works which will have no fire class. For these buildings no pre-accepted performance levels are given, and the level of fire safety is left at the owner's discretion, assuming basic means of escape are provided.

Lastly, it is noted that no pre-accepted performance levels are provided for fire class 4. These are buildings with so severe consequences in case of fire, that pre-accepted performance levels only can be applied if the responsible designer assess their applicability and find them suitable and adequate. Generally, demonstrating compliance by analysis is mandatory for fire class 4.

Hazard Classes

Hazard classes are meant to categorise buildings, or parts thereof, by the "*threat a fire could entail in relation to danger to life and health*", pursuant to Table 4.

Table 4 Determination of hazard classes [4]

Hazard classes	Construction works designed for only the sporadic presence of people	People in the construction works are familiar with the opportunities for escape, including escape routes, and can get to safety unassisted	Construction works designed for overnight stays	Intended use of the construction work does not represent a serious fire hazard
1	Yes	Yes	No	Yes
2	Yes/no	Yes	No	No
3	No	Yes	No	Yes
4	No	Yes	Yes	Yes
5	No	No	No	Yes
6	No	No	Yes	Yes

For all practical purposes, the table is a direct implementation of the proposal from NKB [30]. VTEK does however present a list over occupancy types and corresponding hazard classes, which is applied more actively than the above table found in the regulation. The occupancy type list in VTEK has a more apparent heritage from previous Norwegian building regulations (pre-1997), and fails to show direct relation to the more generic table in TEK. The only difference between hazard class 2 and 3 is that hazard class 2 can have more hazardous activity. From previous guides and regulations, we recognize the solutions and performance levels for offices and industrial buildings in hazard class 2, while solutions and performance levels for hazard class 3 are clearly linked to schools. Kindergartens are placed in hazard class 3, although children may be sleeping, and some may be unable to evacuate unassisted.

Following the logic of Table 4, higher hazard class should result in stricter requirements, but by introducing hazardous activities in a kindergarten, the hazard class and pre-accepted performance levels would be reduced, using the yes/no questions in the table.

Compared to fire classes, hazard classes are more actively used in the regulations, although they are even more instrumental in categorising pre-accepted performance levels applicable for different building and occupant types in the guide, VTEK.

4.3.3. Fire Compartments

Requirements to fire compartments are given in two paragraphs. The first, setting forth where to introduce fire barriers, and the second requires that their fire resistance should be sufficient to allow for safe escape and rescue.

Division Into Fire Compartments

The functional requirement requires that "[a]reas posing differing risks to life and health or in which the risk of fire occurring differs shall be separate fire compartments unless the same level of safety can be obtained by other means."

The intended perspective is assumed to be that high-risk areas should be separated, so that the risk in the other parts of the building is reduced. If one half of a building has higher risk than the other, compliance can be obtained by introducing fire separation, or by increasing the risk of the low-risk area. This is obviously not the intention, but it is a paradox that is being made relevant by requirements for means of egress using fire compartments as basis (see subsection 4.3.5 on Exits from Fire Compartments).

VTEK gives a list of rooms and occupancies which are to be compartmentalised, including apartments, classrooms, hotel rooms, patient rooms in care facilities etc. Although there may be good reason for keeping fire separations between each of these rooms, no warrant is found in the functional requirement, as these areas of the building will have similar fire risk and similar fire frequencies.

A master's thesis from 2022 investigated how the modern school design is in conflict with pre-accepted solutions and performance levels, focusing on the pre-accepted limitation that fire compartments in schools shall not extend over several floors [70]. The use of open plans, opposed to traditional, separate classrooms connected with corridors is also mentioned. As a result, many conventional (by modern standards) school designs are required to be verified by analysis. In this situation, the functional requirement gives no support to the analyst, as nothing in the functional requirement indicates that the pre-accepted design is required. Thus, the most viable approach would be a comparative analysis, where the objective for the reference building is not stated.

Fire Resistance

The functional requirement clearly states that the time needed for escape and rescue is decisive for the fire resistance of fire compartments. Methods and data for estimating the time required for escape is readily available, but the Norwegian fire safety engineers have traditionally been reluctant to give estimates for fire brigade intervention. Consequently, "the time necessary for rescue" is seen as an obstacle to an analytical approach to fire resistance.

The pre-accepted performance levels are linked to fire classes, generally requiring EI 30 for fire class 1 and EI 60 for fire class 2 and 3.

For fire class 1 and 2, the functional requirement for load-bearing structures is virtually the same as for fire compartments – time necessary for escape and rescue. For a detached house, relaxations are given, so that many can be erected with R 15 load-bearing structures, even if many of these building may be placed where the fire brigade will need more than 15-30 minutes to arrive. Similar relaxations are however not given for fire compartments.

4.3.4. Fire Sections

The first paragraph of TEK17 section 11-7 states three different objectives for fire sections:

> *Construction works shall be divided up into fire sections in order to:*
> *a) preserve life and health where escape and rescue may take a long time;*
> *b) prevent unreasonably large financial or material losses; and*

c) help ensure that a fire, given the anticipated extinguishing efforts, is limited to the fire section in which it started.

Division Into Fire Sections

The wording used has a predisposition towards passive fire protection, and the functional requirement is mainly focused on establishing fire separations (sectioning walls) obtain the required functions. The pre-accepted performance levels do however differentiate on gross area, fire load density, and the presence of smoke ventilation, sprinkler system, or fire detection and alarm system.

Traditionally, emphasis has been put on property protection for fire sections, and life safety was explicitly added in 2017.

It is noted in VTEK that special considerations regarding loss control are required for fire class 4. Here it is explained that the pre-accepted performance levels are not deemed to give adequate protection of critical infrastructure, material societal interests, or other sites where a fire may have very serious impact. Thus, the owner/ builder should be involved in the for further divisions into fire sections or other measures to reduce the fire risk.

Financial and Material Losses

The Planning and Building Act states in section 29-5 that the objective of stating technical requirements is to protect "*lives and material assets*". The protection of lives is universally understood to be at the centre of fire safety building regulations. Financial and material losses are however not an obvious matter for national building authorities to regulate, and in many jurisdictions, this is left to the owner and the owner's insurer.

Figure 28 Financial losses between 1993 and end of 2022, categorised by loss per fire [71]

The relevance of gross area per storey as a metric for property protection has been questioned by many (e.g., [72]), also pointing out a significant lack of consistency resulting from the allowance of vertical openings between three storeys in sprinkler protected buildings.

The possibility of activating insurance as a mechanism to ensure adequate quality during design, has been addresses by von der Fehr et al [30]. Thus, statistics and insurance premiums can be used as tools to manage residual risk to property, rather than regulating the property protection through building regulations.

4.3.5. Means of Escape

Section 11-11 contains overarching functional requirements, to which compliance is assumed when the design complies with the subsequent sections 11-12 through 11-14.

Although no dimensions or component performances are mandated in the regulation, many requirements must be categorised as specification, particularly fire safety systems in section 11-12.

Furthermore, the wording of TEK presumes a certain passive fire safety strategy. Even though § 11-8 accompanies the requirement for fire compartments with a text allowing "*the same level of safety can be obtained by other means*", means of escape is required per fire compartments - not per floor, occupied space, or other units. Consequently, alternatives to a pre-accepted approach to fire compartmentation are discriminated, and fire compartments are not treated as measures to safeguard the occupants and the fire service during evacuation and rescue. The resulting challenge is presented below.

Exits from Fire Compartments

The first paragraph of section 11-13 reads:

> *Fire compartments shall have at least one exit to a safe location or exits to two independent escape routes or one exit to an escape route that has two alternative directions of escape that lead to independent escape routes or safe locations.*

The main objective of the paragraph is to ensure sufficient means of escape from every fire compartment. The wording, however, gives implications for the fire compartmentation of the building – especially if the building deviates from a typical corridor-based layout, as seen in Figure 29.

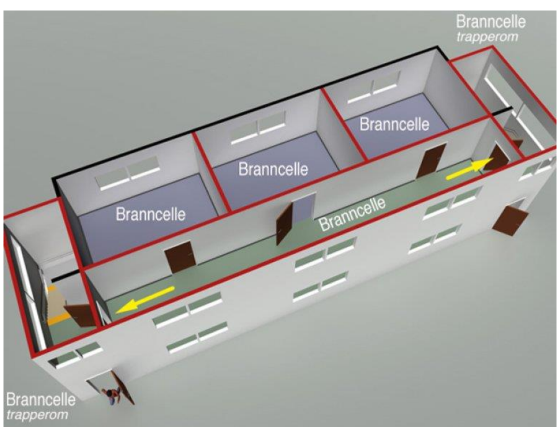


Figure 29 Illustration of Tr2 stairs: Protected corridor placed between the staircase and the fire compartment from which evacuation is expected [73].

For an open-space office area, section 11-8 does not require compartmentation, and for buildings not more than 8 storeys, VTEK allows for direct access from the office area into the stairs, without airlock/ lobby/ corridor. Security, property protection, or other concerns may however trigger a need for fire separation of the office area, creating a formal challenge with how the first section of 11-13 is phrased.

Without the fire separation, the office space is compliant, but if a fire barrier is introduced, the two fire compartments will no longer have exits according to TEK 11-13, seeing that one exit leads to a stair, whilst the other exit leads to the neighbouring office space (neither "*safe location*", "*two independent escape routes*", nor "*an escape route that has two alternative directions of escape that lead to independent escape routes or safe locations*").

For long, interpretations and practice varied among different practitioners on this wording. Without being mentioned in the discussion document and the draft for public comments, a new paragraph was added to the 2010-version of TEK:

> *The exit from fire compartments designed for only the sporadic presence of people can pass through another fire compartment.*

Although this amendment allowed some exits to pass through other fire compartments, it also cemented the understanding that the aforementioned office space is violating the regulation – thus the increased fire protection, beyond the pre-accepted fire compartmentation is prohibited.

The shortcomings of this wording were discussed and proposals for change were made in 2016 [74], as preparation for the 2017 revision of the building regulations, but no changes were implemented.

Accessible Means of Egress

Much of the preparatory work for the 2010 version of TEK revolved around accessible means of egress and universal design [75, 76, 77]. Thus, as of 2010, section 11-11 has included the following paragraph:

> *Construction works shall be designed and constructed to allow speedy and safe escape and rescue. Account shall be taken of people with disabilities.*

In isolation, this functional requirement does not disclose to what extent account shall be taken. Shall disabled persons be able to self-evacuate from any building? The discussion document for TEK10 describes how the consideration of people with disabilities is the reason for mandating fire suppression systems in hazard class 6 and residential buildings where lifts are required [36, p. 80].

So, what does this functional requirement mean for other buildings?

> *Construction works in hazard classes 5 and 6, other construction works for the general public and work buildings, shall have evacuation plans drawn up for them before they are occupied.*

Thus, it seems the requirement for taking account of people with disabilities gives warrant to mandate fire suppression systems in certain buildings, whilst for others an evacuation plan is adequate. Although some other measures were added to the guide as pre-accepted performance levels or solutions (e.g., more onerous maximum opening force for doors and visual notification of fire), the functional requirement in TEK 11-11 fails to give direction. The subsequent requirements and pre-accepted performance levels are clearly stated and possible to comply to but cannot be used to better understand the functional requirement, as the extent to which one accounts for people with disabilities varies greatly between building types.

4.3.6. Facilitating the Work of Rescue and Firefighting Personnel

Section 11-17 contains three paragraphs of qualitatively formulated functional requirements on facilitating for safe fire and rescue operations. The requirements are to design for "*useful access*", so that fires can be "*easily located and fought*", and that technical installations of importance to fire and rescue operations are "*clearly marked*".

Here, the meaning of the functional requirements must be understood in view of the pre-accepted performance levels and solutions. Fire safety designers have traditionally been reluctant to do substantial deviations from the pre-accepted performance levels without dialogue with the local fire brigade. Fire brigades are however increasingly unwilling to take part in detailed discussions regarding the design of buildings, in fear of litigation, claiming the responsible designer must take full responsibility for the design.

4.4. Other Chapters

This section gives examples of how the building regulation addresses other aspects of buildings – other than fire safety. The intention is to present alternative ways of regulating a building's performance under the Norwegian Planning and Building Act, rather than giving an exhaustive review.

4.4.1. Protection Against Acts of Nature – Chapter 7

Chapter 7 regulates how construction works are to be protected against acts of nature, but also gives requirements to prevent building projects increasing the risk of damage to the adjoining terrain, land or constructions works. The requirements are given in four sections.

- Section 7-1 General requirements relating to protection against acts of nature
- Section 7-2 Protection against flooding and storm surges
- Section 7-3 Protection against landslides and avalanches
- Section 7-4 Protection against landslides and avalanches. Exemption for tsunamis due to rock falls

For protection against flooding and storm surges, construction works are categorised based on the expected consequences in case of flooding, as seen in Table 5. If flooding is expected to pose a life safety risk, another table is to be used.

Table 5 Safety classes for construction works in flooding-prone areas TEK sect. 7-2 [4]

Flooding safety class	Impact	Greatest nominal annual probability	Example of construction works per flooding safety class [73]
F1	Slight	1/20	Garages, storage buildings with low occupant load
F2	Moderate	1/200	Most buildings; Residential buildings, carparks, schools, offices, industrial buildings.
F3	Severe	1/1 000	Health care, hospitals, and other buildings for at-risk-groups. Fire stations, telecom stations, and other buildings of regional or national importance. Waste handling sites, where flooding may give severe environmental consequences.

The safety classes are comparable to fire classes, where construction works are categorised based on the potential consequences of an event. More interesting for comparison with fire safety is the explicit quantification of acceptable frequencies. By applying risk conversion factors, these nominal annual probabilities can be converted into benchmarks for fire safety, as seen in INSTA 951 [78, p. 15].

During the autumn of 2022, a draft for a revised chapter 7 of TEK was on public enquiry, where changes to the requirements regarding avalanche and flooding were proposed [79]. This hearing is of particular interest to fire safety design, as it encompasses a discussion on the relaxation of technical requirements to the construction works in the presence of managerial procedures (monitoring of landslide and flooding risks and notification). The Ministry gave the following description in their instructions to the national building authority, DiBK [80]:

Et forslag til endringer i byggteknisk forskrift om sikkerhet mot naturfarer er på høring ved årsskiftet. DiBK må lage veiledning til disse bestemmelsene innen de trer i kraft. Departementet legger videre opp til en helhetlig gjennomgang av lov- og forskriftskrav til sikkerhet mot naturfarer, herunder å utrede og foreslå hjemmel for organisatoriske tiltak.

A proposal for changes to the building regulations regarding protection against acts of nature will be open for public enquiry at the turn of the year. DiBK is required to provide guidelines for these provisions before they come into effect. Furthermore, the ministry plans to conduct a comprehensive review of legal and regulatory requirements concerning protection against acts of nature, including exploring and proposing warrant for managerial measures.

The discussion document also points towards other elements of great relevance to this thesis:

- The safety is regulated by more legislations than the Planning and Building Act. For landslides and floods, the Act Relating to the Emergency Planning Duty of Municipalities, Civil Protection Measures and Norwegian Civil Defence (sivilbeskyttelsesloven) and the Police Act both lay down requirements of importance to protection against acts of nature [79, p. 10] – equivalent to the Fire and Explosion Prevention Act for building fire safety.
- The construction works themselves are not capable of providing adequate safety, but an emergency preparedness program consisting of monitoring, notification, and evacuation is required [79, p. 10]

It is furthermore interesting to see how increased risk acceptance is communicated explicitly, acknowledging that protection against acts of nature will pose a barrier to rational use of society's resources if requirements are too stringent:

Det er heller ikke være mulig å lovregulere en absolutt garanti mot alle farer. Plan- og bygningslovens intensjon er å legge til rette for en fornuftig og forsvarlig samfunnsutvikling, jf. pbl. § 1-1	*It is also not possible to legislate an absolute guarantee against all hazards. The intention of the Planning and Building Act is to facilitate sensible and responsible societal development, as stated in Section 1-1 of the Act.*

4.4.2. Structural Safety – Chapter 10

Structural safety is regulated through functional requirements, which neither dictate a level of safety nor mandate certain strategies, solutions, materials, or verification methods.

> *The fundamental requirements relating to the construction works' mechanical resistance and stability, including ground conditions and safety measures during construction and upon completion, can be complied with by designing construction works in accordance with Norwegian Standard NS-EN 1990 Eurocode: Basis of structural design, and underlying standards in the series NS-EN 1991 to NS-EN 1999, with associated national additions.*

It is noteworthy that structural safety treats the Eurocode like how the pre-accepted performance levels are handled for fire safety. The modal verb "can" is used, meaning the use of Eurocodes is not mandatory, and in theory, structural safety can be demonstrated independent of the standards, using whatever methods and criteria found acceptable by the designer, as long as the requirements in section 2 are met.

The references to the Eurocode are not dated, and consequently, the most current version is to be used. Although there is reference to national annexes, where nationally determined parameters can be presented, national building authorities have reduced direct control on the level of safety with this approach.

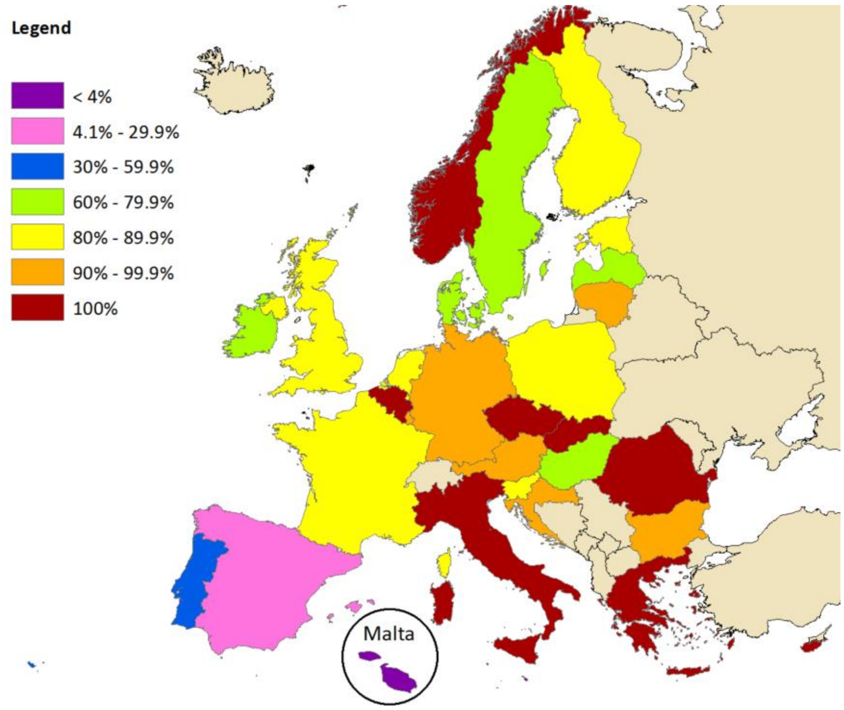


Figure 30 Publication of national annexes to the Eurocode parts (59 parts = 100 %) [81]

Eurocodes are currently under revision, a time-consuming process, which leaves national regulators time to intervene if any proposed changes are deemed unacceptable.

4.4.3. Chapter 12 Layouts of and Building Elements in Construction Works

Chapter 12 contains requirements relating to layouts, safety in use, and building elements – typically the responsibility of the architect. The requirements are given in 18 sections, structured as seen below.

- I. Introductory provisions relating to layouts of and building elements
  - Section 12-1 Requirements for layouts and universal design of construction works
  - Section 12-2 Requirements concerning accessible dwelling units
  - Section 12-3 Requirements for lifts in construction works
- II. Entrances, safety in use, communication routes, rooms and similar
  - Section 12-4 Entrances
  - Section 12-5 Safety in use
  - Section 12-6 Communication routes
  - Section 12-7 Requirements for the design of rooms and other areas for people
  - Section 12-8 Entrance halls and cloakrooms
  - Section 12-9 Bathrooms and toilets
  - Section 12-10 Storage rooms and storage spaces
  - Section 12-11 Balconies, terraces and similar
  - Section 12-12 Waste system and separation of waste
- III. Building elements

- Section 12-13 Doors, gates and similar
- Section 12-14 Stairs
- Section 12-15 Balustrade design
- Section 12-16 Ramps
- Section 12-17 Windows and other glazed areas
- Section 12-18 Signage, control and operating panels, handles, fittings and similar

Functional requirements are given for many building elements in this chapter of the regulation, as seen in this example from TEK17 section 12-13 first and second paragraph [4]:

> *(1) Doors, gates and similar elements shall be easy to see and use and shall be designed in a way that prevents harm to people, domestic animals or equipment.*
>
> *(2) Their width and height shall be designed for the expected traffic and transport, including escape in case of fire and shall, as a minimum, comply with the following:*

The second paragraph is however followed by a list of five specifications of mandatory dimensions, like letter e):

> *Doors shall have a minimum clear height of 2.0 m.*

The chapter generally has a considerable higher degree of specification, compared to the fire safety chapter, and must in many instances be considered a prescriptive regulation.

4.4.4. Radiation Environment – Chapter 13 III

A requirement is given for radon concentration not more than 200 Bq/m³ in the first paragraph of section 13-5.

The second paragraph requires a radon barrier and ventilation for continuous occupancy, but this is wavered provided compliance with the threshold of the first paragraph is documented.

In this instance, measurable properties of the final building are regulated by an Environmental Performance Criterion (see section 5.4). Measures and solutions are proposed, but in a way that allows for alternatives. No methods for predicting radon levels for design purposes are mandated. As pointed out in VTEK, mitigating measures may be introduced if high values are measured in the completed building. The acceptable levels of radon can be determined scientifically, to concentrations where the increased risk of lung cancer caused by radon is deemed acceptable.

4.4.5. Sound And Vibrations – Chapter 13 IV

A functional requirement for satisfactory acoustic conditions is given inside construction works an in outside areas for recreation and play. Compliance with the functional requirement "can" be demonstrated by complying with sound class C of the 2012 version of the national standard NS 8175.

Compared to structural safety, acoustic conditions are regulated by a national standard, and with reference to a dated version of this standard. NS 8175:2012 is withdrawn and replaced by a new version as of July 2019.

In an article on dibk.no 11 November 2019, DiBK gave a statement confirming that the 2012 version was to be used as until a change was done to the technical regulations [49]. The statement further underlined that acoustic conditions better than required are allowed, and that the 2019 version could be used in cases where the 2019 version is known to be more stringent.

Although this approach shows how the precise reference to a standard hinders the application of new and updated knowledge, it also demonstrates how the national building authority remains in control. A change in Eurocodes will be adopted if authorities do not intervene, whilst a change in NS 8175 will not be adopted until an action is taken to revise the regulation.

The wording of the news article implies that NS 8175:2019 is more stringent, and that the regulators have not found grounds for imposing more stringent or costly requirements.

4.4.6. Electrical Engineering

As opposed to the other traditional engineering disciplines within buildings, electrical installations are not primarily regulated by the Planning and Building Act, but by the Electrical Supervision Act [83] – with some exceptions, like lifts and escalators, emergency lighting and wayfinding systems. The Norwegian Directorate for Civil Protection (DSB) is delegated authority on matters regarding design, maintenance, and operation of electrical installations – interestingly the same body being responsible for the Fire and Explosion Prevention Act.

A set of regulations are found pursuant to the electrical supervision act, which are largely performance-based. Compared to the planning and building act, these regulations regulate more holistically all stages of the life cycle of the electrical installations, as seen in section 2-1 of the Act [83]:

Elektriske anlegg skal prosjekteres, utføres, drives, vedlikeholdes og kontrolleres slik at de ikke frembyr fare for liv, helse og materielle verdier.

Electrical installations shall be designed, installed, operated, maintained, and controlled in such a way that they do not present a danger to life, health, and property.

The regulation on low voltage installations (≤ 1 000 VAC or ≤ 1 500 VDC) includes introductory description of how its performance-based nature should be understood and discusses the relation to pre-accepted performance levels and solutions found in standards/ norms [84].

At forskriften er funksjonell innebærer at forskriften ikke inneholder detaljerte tekniske krav for utførelse av lavspenningsanlegg, men gir grunnleggende sikkerhetskrav som viser hvilke farer forskriften tar sikte på å verne mot. Forskriften viser til normer som beskriver hvordan sikkerhetskravene kan

That the regulation is functional means that it does not contain detailed technical requirements for the execution of low voltage installations, but provides basic safety requirements that show which hazards the regulation aims to protect against. The regulation refers to standards that describe how the safety

oppfylles. Forskriften med veiledning og de normene det er vist til, viser samlet det sikkerhetsnivået som skal legges til grunn. Det er imidlertid bare forskriften som er juridisk bindende slik at man kan velge andre løsninger. Ved valg av andre løsninger må det kunne dokumenteres bl.a. ved analyse av risiko at minst tilsvarende sikkerhet oppnås som om de normene forskriften viser til skulle vært lagt til grunn. Dersom det viser seg at det oppstår konflikt mellom de sikkerhetskravene forskriften stiller og løsninger som normene eller eventuelle alternative løsninger legger til grunn, er det forskriftens sikkerhetskrav som skal være oppfylt.	*requirements can be met. The regulation, together with the guidelines and the referenced standards, shows the overall safety level that should be applied. However, only the regulation is legally binding, so alternative solutions can be chosen. If alternative solutions are chosen, it must be demonstrated, e.g., through risk analysis, that at least an equivalent level of safety is achieved as if the standards referenced in the regulation were applied. If there is a conflict between the safety requirements in the regulation and the solutions that the standards or any alternative solutions rely on, the safety requirements in the regulation must be met.*

The similarities are profound between the above description and what is being stated in the guide to fire related requirements in the Norwegian building regulations and the accompanying guide. One key difference is however that the pre-accepted performance levels are found in standards, which have a significantly different way of being published, amended, and revised. Although rules and regulations apply to changes in regulations, the same strict requirements are not given explicitly for guidelines. Standards and norms are privatised undertakings, but are generally strictly governed to ensure predictability, trust, and stability.

The relevant standards are managed by Norwegian Electrotechnical Committee (NEK), which mirrors the relevant committees of International Electrotechnical Commission (IEC). NEK has a website for frequently asked questions (FAQ), comprising more than 1 600 questions and answers [85].

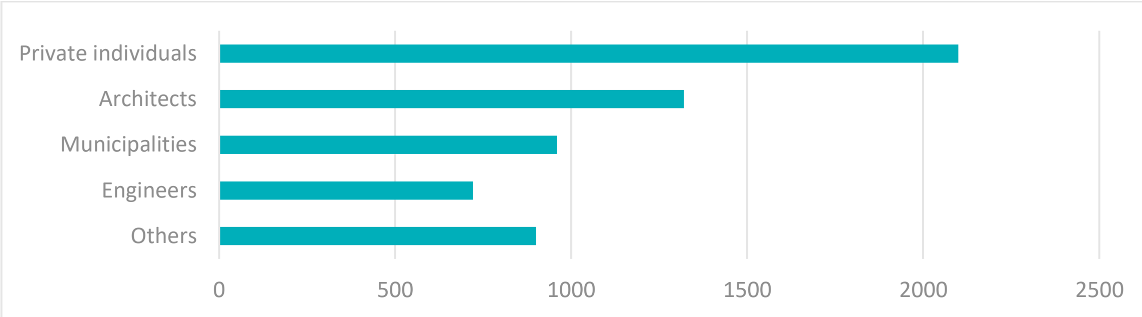


Figure 31 Questions raised to the Norwegian Building Authority during 2022 [86]

Figure 31 shows the number of questions raised to the Norwegian Building Authority in 2022 (all disciplines). Despite this staggering number of questions (considering a total population of 5.4 million), the website for frequently asked questions (FAQ) only has 72 questions and answers, with the most recent answer posted July 2015. A total of 10 questions and answers are given for fire safety.

4.5. Harmonisation

The design and construction of construction works is a multidisciplinary activity, making some interaction and overlap between the different chapters of the regulations inevitable. Herein also lies a risk of conflicting requirements, especially when different regulatory approaches are taken.

An example is found in TEK section 12-14 paragraph 1h, where stairs are required to have a width of no less than 0.90 m, and a clear height of minimum 2.1 m. The width and height of egress components in the fire safety engineering chapter of TEK are governed by functional requirements. On one hand, it is acceptable to have different minimum requirements in different contexts – the more onerous would apply – but this example shows that also the intent in TEK sect. 12-14 overlap with chapter 11 (authors underlining):

> *Stairs must be easy and safe to use. The width and height of stairs shall be designed for the expected traffic and transport, including escape in case of fire. […] Entrance doors and doors in communication routes shall have a minimum clearance width of 0.86 m. The minimum clearance width in construction works designed for large numbers of people shall be 1.16 m.*

On the other hand, the functional requirement for minimum width of egress components in chapter 11 are undermined and made irrelevant with the existence of prescriptive dimensions in chapter 12.

Similar harmonisation can be seen across regulations, e.g. requirements for emergency lighting are being regulated by the Workplace regulations (FOR-2011-12-06-1356), intending to prevent harm to workers due to outage of artificial lighting. Additionally, the Workplace regulations have independent requirements for fire safety but is also relevant for safety in case of fire, thus creating an overlap with both TEK and the Fire prevention regulations. For emergency lighting, the Workplace regulations mandate "*sufficient emergency lighting to cover the need should the ordinary lighting fail*" in "*escape and evacuation routes, as well as emergency exits*". Thus, an analytical approach to the need for emergency lighting in case of fire, is not a single-discipline-affair, but a task which typically will involve the fire safety engineer, the electrical engineer, and the architect, who in most cases handle the applications to the Norwegian Labour Inspection Authority (Arbeidstilsynet). It is however unclear who should take lead in the process when regulatory objectives overlap.

4.6. Existing Buildings

As seen in section 3.10, the fire safety design of building projects is regulated by the Planning and Building Act, whilst buildings in use are regulated by the Fire and Explosion Prevention Act. When substantial alteration is done to an existing building, the relevant sections of current building regulations come into force on the affected parts of the building project. If a renovation project aims to upgrade an existing façade, the current regulations for energy efficiency of external walls and windows would come into force, but nonrelated requirements, like parking, and internal layout would not.

For fire safety, change in occupancy type and increased height are examples of building projects where the building project may have an impact beyond discrete building components. Similarly, some building projects may result in unreasonable requirements. The Planning and Building Act gives provisions for wavering requirements, assuming the project adequately addresses safety.

4.7. Review Summary

Technical Regulations on Safety in Case of Fire

The functional requirements are stemming from the work of NKB in the 1990s and no substantial changes are made since. At the time of the formulation of the functional requirements, little experience was available on the application of functional requirements, and hence, one would expect practice to reveal room for improvement. 25 years after their introduction, there is a lasting focus on the guide to the regulations, where the functional requirements seem to be of no relevance. The examples in section 4.3 show how the functional requirements to varying degree regulate the fire safety performance of buildings, and that the guide becomes key to understanding the expected performances. Examples are also given on unfortunate phrasing and bias towards established building tradition, posing a barrier to alternative design approaches.

Other Chapters

Although TEK section 2 applies to all chapters of the regulation, the different disciplines have varying approaches to compliance to the same act:

- Protection against acts of nature considers the frequency of loads (equivalent to the fire frequency), and differentiates on both frequency and expected consequences.
    - On-going work assesses the possibility of relaxing technical requirements based on managerial procedures and emergency preparedness.
- Structural engineering is practically fully regulated by European standards, the Eurocodes.
- Functional requirements for acoustics are comparable to fire safety, but here the pre-accepted performance levels are given in a national standard – not in the guide to the building regulation as for fire safety.
- Building elements have a significant amount of specification placed in the regulation – some of which with the intention to provide sufficient egress capacity in case of fire.
- Radiation environment is clearly regulated by environmental performance criterion.

- Electrical engineering is primarily regulated by another legislation but is still an integral participant of the design team.

The Guide to the Regulation

Fire safety is the most extensive chapter of the guide and constitutes 28 % of the technical content of the guide.

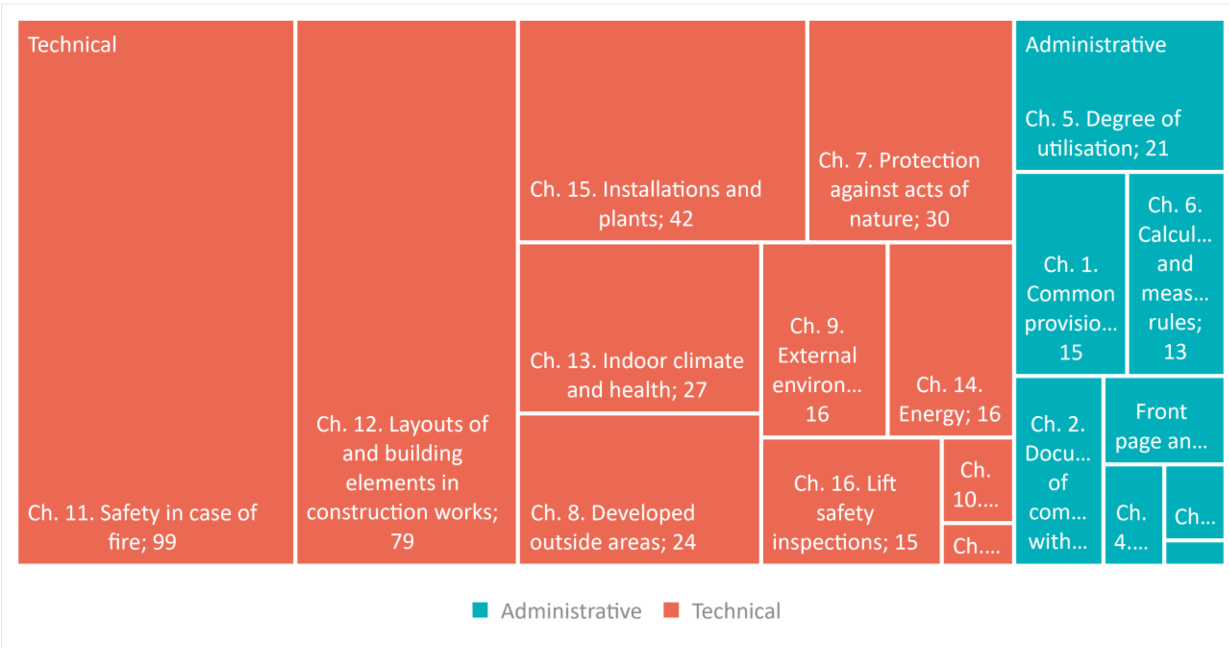


Figure 32 Disposition of the guide to the Technical Regulations, TEK17

Compared to the other disciplines, safety in case of fire is more reliant on the pre-accepted performance levels of the guide, as other disciplines either have more prescriptive content in the regulation, or reference is made to standards giving examples of acceptable designs.

One other possible explanation for the intense focus on pre-accepted performance levels could be a lack of confidence in the functional requirements and the analyses made to document compliance with these. Thus, a set of metrics describing the level of fire safety, equivalent to the performance requirement for radon, would give better regulatory control, whilst retaining the intended flexibility in design.

5. Potential Metrics for Fire Safety Performance – How to Quantify

5.1. Introduction

Chapter 5 explores different way of quantifying fire safety performance, analogue to the concept of length being measured in metres, stone's throws, or lightyears. For certain dimensions and applications, a ruler may be a suited method of assessing an object's length or a distance, while in other cases other means are required. Similarly, chapter 6 will address the different methods for applying the metrics discussed in chapter 5.

If all relevant aspects of building fire safety can be predicted and measured by metrics, these metrics can form the basis for a regulation, where government set the bar for fire safety, whilst still allowing flexibility in design.

It is important to keep in mind that the metrics used in regulations also may dictate what verification methods are applicable: As seen for radiation levels from radon in subsection 4.4.4, a mandatory level of maximum 200 Bq/ m^3 is not readily compatible with a risk-based verification method, and the height of a door cannot be less than 2.0 m to be compliant of the regulation's requirement as referred in subsection 4.4.3 – regardless of any reasoning finding lower doors acceptable.

As described in chapter 3, the performance-based concept can apply to many levels, but for this chapter emphasis will be on metrics which still allow for flexibility for fire safety design.

5.1.1. Types of Performance

The SFPE Handbook of Fire Protection Engineering describes 5 types of performance [20]. These are used as a framework for the subsequent sections of chapter 5:

- Specification (5.2)
- Component Performance (5.3)
- Environmental Performance (5.4)
- Threat Potential Performance (5.5)
- Risk Potential Performance (5.6)

Additionally, a few other concepts not falling entirely into the above-mentioned categories are presented in section 5.7 Other Miscellaneous.

5.1.2. Ways of Expressing Tolerable Risk

An Official Norwegian Report (NOU) from 2012 on fire safety for risk groups, discusses different possible criteria for acceptable or tolerable risk [87]:

- Thresholds (number, length, weight, etc).
- Barriers (number, performance, etc).
- Statistical or probabilistic acceptance criteria (e.g., fire frequency).
- Cost-benefit-based societal criteria.
- Required processes (e.g., ALARP[3] processes).

[3] As Low As Reasonably Practicable. See further description in section 7.4.2, page 120.

Required processes implies setting mandatory activities and processes without explicitly requiring performance levels, and consequently falling outside the scope of chapter 5. This approach is however discussed in chapter 6.

These ways of expressing tolerable risk are however of importance to chapter 5, as there is an interconnection between metrics, verification methods, and how requirements are set. Strict specification of barriers is traditionally assumed to give more regulatory control, albeit there is a loss in flexibility, and the resulting level of safety is not explicitly stated, informing policy decisions or novel designs.

Imagine that a tank for wastewater treatment is to be constructed. The client is worried about the liquid freezing during winter but has otherwise need of input from the contractor on the most efficient way of constructing the tank. In this example, the client could communicate his requirements in many ways, which would impact degrees of freedom for the bidder:

1. The tank should be placed in a building, in which the temperature should be not less than 5 °C.
2. The tank shall have a thermal conductivity of not more than 0.02 $\mathrm{W/mK}$.
3. Liquid heater type XYZ or equivalent shall be installed. Power not less than 750 kW.
4. The probability of the contents of the tank freezing shall be less than 10^{-2} per year.

In this example, temperature may be seen as the obvious choice of metric. In the first example, temperature is used as metric, but the requirement assumes that the tank is placed in a building. This may not be the most rational solution. Examples 2 and 3 also include presumptions, limiting the possible solutions to the problem at hand. Although they apply different metrics, certain assumptions are integral to the metrics – meaning a strategy has been chosen to either insulate the tank or to install a heater. Finally, alternative 4 defines a clear intent for the bidder, but does not impose restrictions as to how the criteria is met, and the requirement is not quantified. This could involve adding antifreeze solution to the tank, having alarms and procedures for frosty weather, stirring, or pressurising, but all the strategies 1-3 are also still possible candidates. The fourth alternative may however be challenging to verify.

When choosing a form of requirement, many factors affect the preferred alternative. Are the potential bidders to be trusted? Are there ways for the client to comment on the solution before implementation? How certain is that the requirement is met? How likely is frosty weather in the first place? Is frost damage and subsequent losses covered by insurance?

Similar factors must be considered when selecting metrics for fire safety design of buildings:

- Trust,
- Accountability,
- Ability to model future events,
- Frequency of events,
- Ability to adjust practice, if necessary,
- Consequences of undesired outcome,
- Availability of data, etc.

5.1.3. Necessary Knowledge Base

As the example above demonstrates, the choices made in formulating the requirements will have profound consequences for the ones who shall demonstrate compliance to the requirements. The requirements may come from the client, as in the example in subsection 5.1.2, or the requirement may come from legislation. All relevant requirements must be known to the designer.

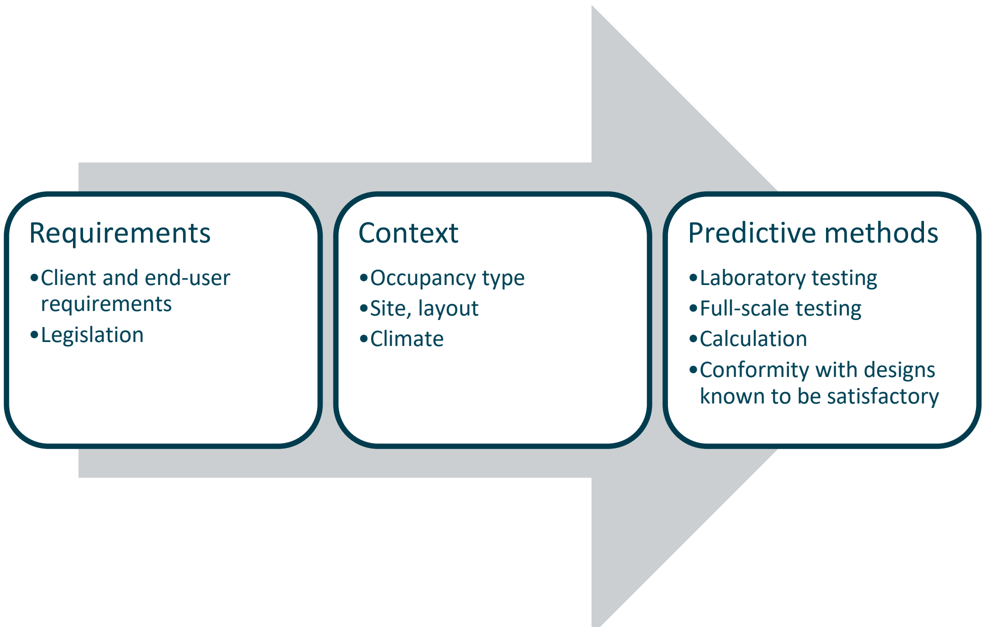


Figure 33 Required knowledge base for performance-based design, inspired by [88]

For the designer to succeed, it is also necessary to have knowledge about the context. Following up on the example from in subsection 5.1.2, the location and its climate would be essential information to the designer if alternative 4 was chosen as the requirement. On the other hand, if a strict specification was used – meaning a certain technology, dimensions, and materials was mandated, the climatic information would be of less importance. Other factors of the site and use would however be of interest.

For the construction industry, performance will have to be predicted. If performance is unknown until the building, system, or component is completed, the uncertainty would be unbearable – even more so for fire safety performance. Thus, different predictive models and their application to performance-based fire safety design will be discussed in chapter 6.

For fire safety performance post-fire assessment of performance may be relevant and useful, but this is outside the scope of this thesis. Full-scale testing to fully demonstrate the fire safety performance of a building is practically impossible, considering the immense variation of possible circumstances affecting the outcome of a fire. Hence calculations, simulation, and laboratory experiments be the focus of chapters 5 and 6. Conformity with designs known to be satisfactory (pre-accepted/ deemed to satisfy) is also a key concept of interest to this thesis.

5.1.4. Equivalency

As a natural extension of conformity with designs known to be satisfactory, comes evaluations of equivalence – A concept where adequacy of an alternative design is demonstrated by comparing the performance or solution to a pre-accepted one. This will not give an explicit measure on performance but is discussed in chapter 6 as a verification concept (see section 6.5), as this approach is widespread in fire safety engineering. From a regulator's perspective, it is also a way of allowing for flexibility, whilst ensuring a consistent level of performance compared to past, prescriptive building regulations.

5.2. Specification

Specification in this context means a strict requirement to dimensions, construction materials, methods, or other properties. Many pre-accepted performance levels (and solutions) are categorised as specification. This could be requirements for non-combustible materials, a certain clear width of exit components, minimum number of exits, etc.

Specification reduces variability amongst the practitioners and gives the regulator great control over the range of allowable designs.

On the other hand, specification leaves little room for flexibility, although equivalency wavers may reintroduce some flexibility. An example of specification in combination with a functional requirement is found in TEK17 section 11-6 paragraph 4:

> *High-rise construction works shall be a minimum distance of 8.0 m from other construction works, unless the construction works are constructed to ensure that fire will be prevented from spreading throughout the full duration of a fire.*

The specification is given on a legally binding level (regulation), meaning no further verification is required if the specification is met. If the distance is less than specified, the functional requirement comes into force, and a greater degree of flexibility is given.

Caution must be exercised when formulating specifications, as they are vulnerable to loopholes, misinterpretation, and misuse, especially if they are used in leu of trust, competency, review, or other support structures (see introduction in section 3.11 and further discussion in section 7.5).

Considering the example above, an analysis of a given building may indicate a significant risk of fire spread despite a distance greater than 8.0 m. Based on the above specification, no mitigating measures are required, regardless of the consequences of fire spread.

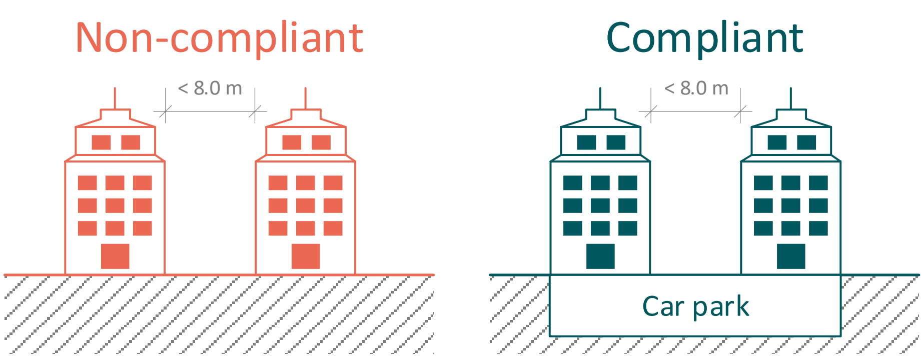


Figure 34 Example of two high-rise buildings separated by less than 8.0 m. On the left, the buildings are detached, whilst on the right the buildings are connected by an underground car park.

As seen in Figure 34 specification may lead to paradoxes, like when the introduction of an underground car park reduces the requirement for fire separation between buildings. This example may seem caricatured, but represent a real dilemma for densely populated areas, where ownership changes over the centuries, and where there are strong incentives for optimal utilisation of the available real estate – both the lot and any existing buildings.

Furthermore, compliance with specification may direct attention away from fire risk, and towards definitions and semantics, and there is risk of the emergence of a “compliance culture” in the fire safety engineering community. This is further discussed in subsection 8.2.7.

Some specification may be based on decades of building tradition, and in Norway these specifications are practiced as “designs known to be satisfactory”. As will be discussed further in section 8.2, there is a significant difference between “deemed to satisfy” and “designs known to be satisfactory”. Specification is typically based on tradition, but the resulting safety level is not explicitly stated, and for non-residential buildings, the empirical knowledge on the performance is limited.

5.2.1. Specification as a Metric for Fire Safety Performance

Specification is not fully compatible with performance-based fire safety design. Specification may play a role in performance-based building legislation, but mainly applicable as pre-accepted performance levels – which can 1) provide a “fast track” for standardised and well-known building and occupancy types, 2) from a benchmark/ reference building for comparative analysis, and 3) improve the understanding of goals and functional requirements by providing acceptable examples. Finally, specifications will be highly relevant as output of fire safety design, being passed on for detailed design by other disciplines.

5.3. Component Performance

Component performance specifies the required capacity of a single component or a system – several ways of achieving the requirement are allowed if the component’s performance is in accordance with the requirement. Component performance may be set for a sprinkler system, or for each individual sprinkler nozzle. Other typical examples of component performance would be fire rated walls EI 30, beams R 45 or internal surfaces B-s1,d0. Many pre-accepted performance levels fall into this category.

The performance of discrete components can be assessed and quantified but does not necessarily give an indication of the fire performance of the building in which they are placed. Component performance is well-suited for tendering products and systems in the open market, but single values will most often be too restrictive for design purposes [88].

Component performance is further discussed below, in some more detail for the most prominent examples: Fire resistance (5.3.2) and reaction to fire (5.3.3). A general description of system performance is also provided (5.3.4). The most used component performance in fire safety is classification according to standardised tests, which is discussed first.

5.3.1. Standardised Classification of Building Component Performance

Classification of building component performance by standardised tests is widely adopted for fire resistance (load-bearing capacity and separating building elements) and for reaction to fire (materials and products contribution to the fire development, their ignitability and combustion products). Similarly, water mist suppression systems, manual fire extinguishers, and other fire safety systems may have their performance classified by standardised tests.

When establishing a standardised test two key questions must be answered [89]:

1. Does a test adequately capture the relevant physical phenomena?
2. What are the appropriate criteria (cut-off between fail and pass)?

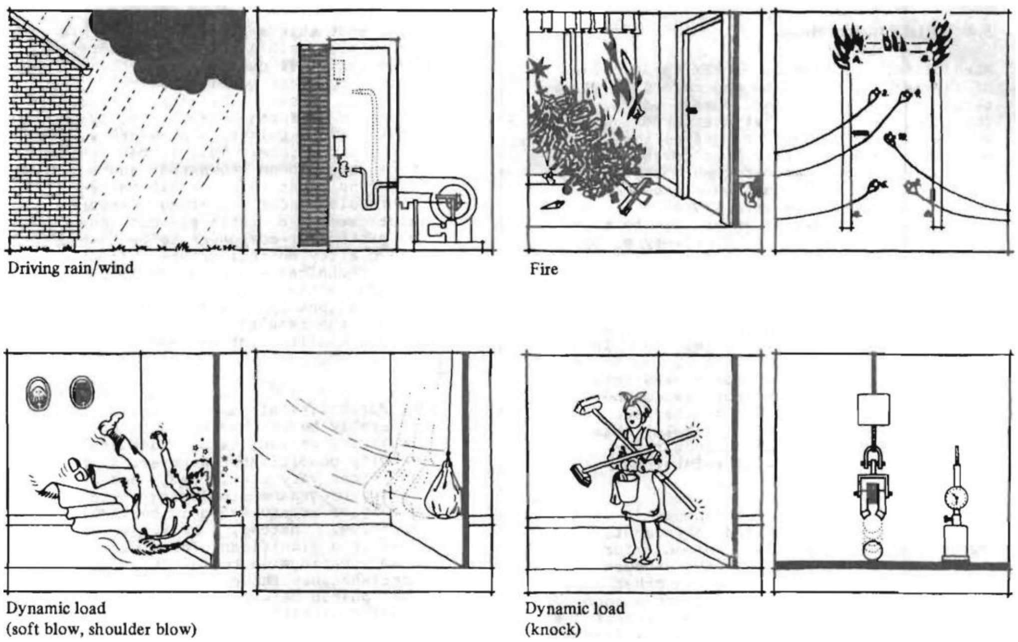


Figure 35 Illustration of different test methods meant to represent real life situations [88]

As illustrated in Figure 35, test methods are created to simulate loads and conditions in the end-use situation. Repeatability and consistency are imperative, and the test aims to disclose precisely a few selected properties of the building component or system. The end-use situation may vary greatly from building to building, so the loads, measurements, criteria, conditioning procedures, etc., are designed to be conservative but representative.

An overwhelming number of variables influence the fire exposure and the response of a system or component. It is therefore necessary to simplify, creating a proxy for reality. This also brings down cost and increases the possibility to have a full picture of the execution of the test.

A brief discussion of standardised classification of building components is given in subsection 5.3.5, after the most used three forms are presented.

5.3.2. Fire Resistance

Temperature Curve

For more than a century the performance of building elements under fire exposure have been assessed with basis in what has been called the standard time temperature-curve seen in Eq. 1 and Figure 36 – a logarithmic relation between the gas temperature, Θ_g [°C] in the furnace and time, t [min] [90].

$$\Theta_g = 20 + 345\, log_{10}(8t + 1) \qquad \text{Eq. 1}$$

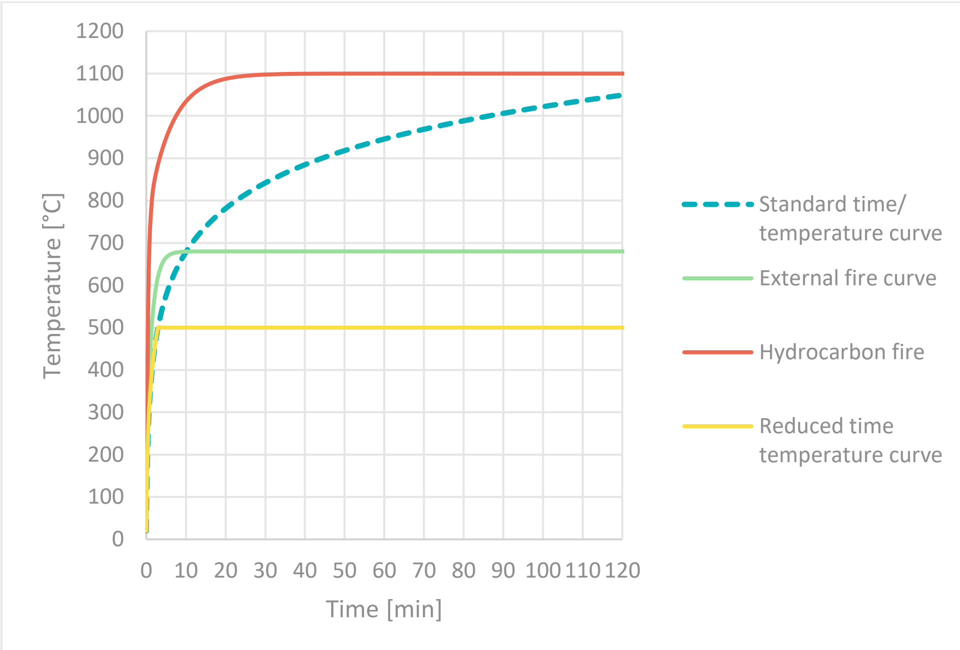


Figure 36 Standard time temperature curve, compared to three variants for special situations: External, hydrocarbon, and reduced time temperature curves.

Standard time temperature curve as described in ISO 834 [91] has been practically unchanged since its introduction in 1916. Variations have been introduced through Eurocode, EN 1991-1-2 external fire curve and hydrocarbon fire curve [92]. Another example is EN 1366-6 [93].

Criteria and Classes

Criteria are set for several types of performance, where the most common are:

- R – Load-bearing capacity
- E – Integrity, measured by gap gauges, observations of sustained flaming, and ignition of a cotton pad.
- I – Insulation, where the temperature on the unexposed side is measured. Maximum allowed temperature rise is 180 °C above initial mean temperature, and the mean temperature rise for all measurements shall not exceed 140 °C.
- W – Radiative transmittance, measured 1 m from the unexposed face. Not more than 15 kW/m² is allowed.
- M – Dynamic horizontal load mad to simulate collapsing building elements or the force from a fire hose to separating walls.

The different types of fire resistance can be classified individually, meaning that a load-bearing fire separating wall may be REW 90 EI 60, if the insulation criterion was breached after 60 minutes, while criteria for load-bearing capacity, integrity and radiative transmission were fulfilled for 90 minutes. Standards for the different product categories (doors, curtain walls, raised floors, etc.) dictate which classes can be determined, meaning that a window satisfying the criteria for EI for 42 minutes will not be classified to EI 42, but to EI 30. Intervals vary slightly but are typically in the range of 15-30 minutes.

Additional classes and sub-types exist for dampers, ventilation ducts, smoke leakage, and self-closing devices for doors.

Equivalent Time of Fire Exposure

A concept called equivalent time of fire exposure is presented in EN 1991-1-2 annex F [92]. The concept involves:

1. Calculating the fire load – a measure of the total amount of energy released if the available fuel is consumed.
2. Calculating the surrounding surface area, taking into account their thermal properties.
3. Determining the opening factor – a ratio between the total area of openings to the total area of the fire compartment, including a factor for the opening height.

By these calculation steps, the analyst may estimate the duration of a fire, given that it shall maintain gas temperatures according to the standard time temperature curve (Eq. 1, Figure 36). Thus, this concept can be used to bridge the gap between the standardised test conditions and a case-specific compartment.

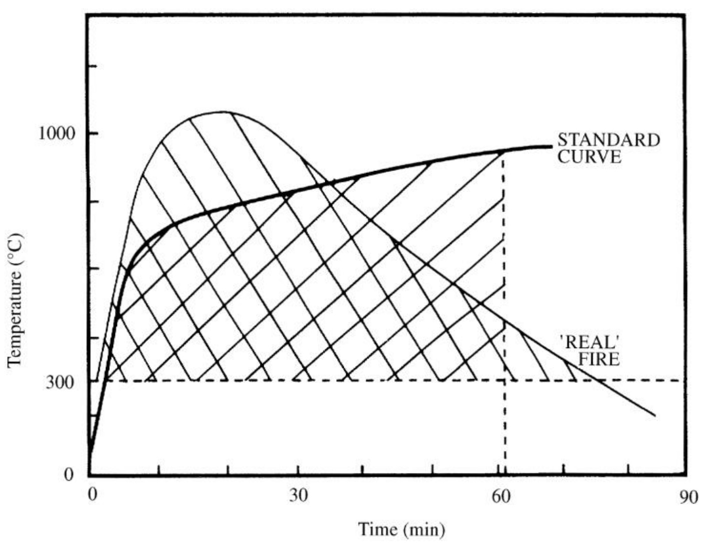


Figure 37 Illustration of the theory of real fires being equivalent of exposure to the standard curve [94]

The concept is however disputed and is not allowed in Sweden [95], whereas the other two Scandinavian countries allow the use of annex F, albeit with national annexes modifying the calculation of fire load, which also has direct consequences for the calculated equivalent time of fire exposure.

In annex F of EN1991-1-2, a list of limitations is given for the application of the method. It is only valid for certain opening / ventilation factors, and being material dependant, it cannot be used for timber or composite steel and concrete constructions. Furthermore, the approach may only be used where the structural design is based on tabulated data or other simplified approaches related to the standard time temperature curve.

5.3.3. Reaction to Fire

Euroclasses

During the 1990s and early 2000s, European harmonisation led to a common approach to the assessment of products' reaction to fire – the Euroclass system. Law et at give a thorough description of the development of the Euroclasses and discusses the process of reaching consensus amongst the member states [89], which was further discussed by Messerschmidt and Węgrzyński [96].

The result of these compromises is a European harmonised test and classification system for building materials. The classification system was intended to give an indication of time to flashover, whilst also ranking materials in terms of production of smoke and debris/ burning particles.

Table 6 Euroclasses

Euroclass	Description
A1	Non-combustible. "Best"
A2	
B	"Intermediate"
C	
D	
E	"Worst"
F	"Unclassified"

A separate set of criteria applies for the non-combustible classes A1 and A2, where A2 is the more liberal of the two, designed to allow for gypsum plasterboards, with thick facer and backer paper. A1 however, will require only minuscule amounts of combustible materials.

Additional classes are used for smoke production s1, s2, and s3, ranked from lowest to highest smoke production. If no flaming droplets or particles are observed in the classification test, the component can be classified d0. Otherwise, the component should be classified as d1 or d2, depending on the extent (d2 means no restriction). The classes are combined, e.g. into D-s2,d0 or A2-s1,d0.

Variants of classifications are also created for roof coverings, electrical cables, pipe insulation, floor coverings, as described in separate parts of EN 13501.

Single Burning Item and Room Corner Test

The testing for intermediate classes is done with a test called Single Burning Item (SBI) [97], where the test specimen is placed in a corner – one side being 495 mm wide, the other 1 000 mm wide, the height being 1 500 mm for both. The thermal attack comes from a triangular tray burning propane, diffused through sand, giving a heat output of 30.7 ±2.0 kW. The test duration is 20 minutes, where observations are made regarding heat production, smoke production, horizontal flame spread, and flaming droplets/ particles.

Annex A of EN 13501-1 [98] gives some background to the classification in the standard, including a reference to the larger scale room corner test ISO 9705-1 [99]. Annex A suggests that classifications based on the SBI test can be extrapolated into time to flashover (total heat release rate > 1 000 kW i.e., 1 MW) when tested in the room corner test. These times and the burner heat release rate are illustrated in Figure 38.

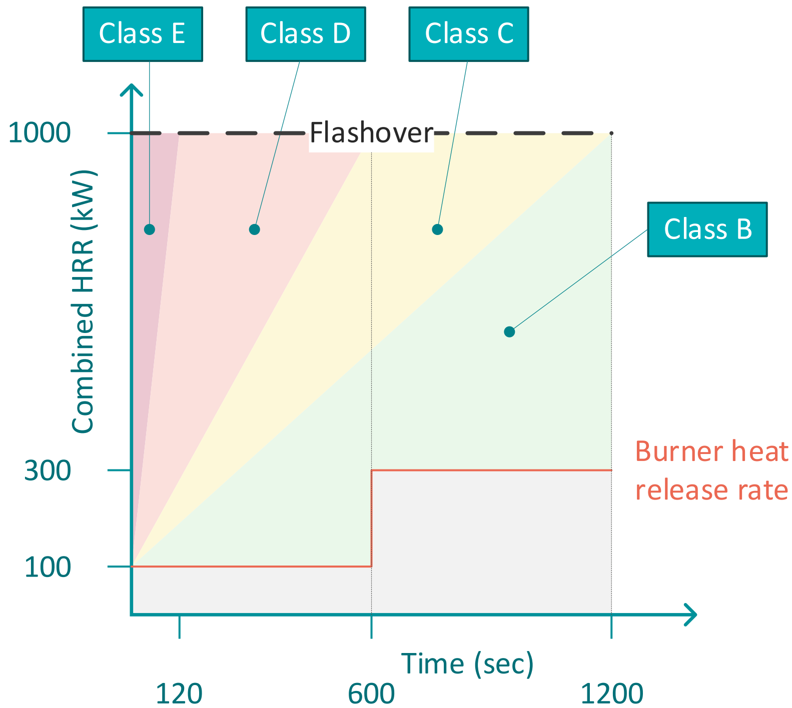


Figure 38 Illustration of correlation between Euroclasses E through B and room corner test results. Red line indicates the heat release of the gas burner, and the black dashed line indicates the flashover criteria [69]

The initial heat release rate of the burner is 100 kW. If the specimen contributes with 900 kW, bringing the total to 1 MW within 2 minutes, the material should be class E. Similarly, if the total heat release rate exceeds 1 MW within 10 minutes, the material is class D. 10 minutes into the test, the burner heat release rate is increased to 300 kW, but the flashover criterion of 1 MW is obtained. Thus, if the specimen contributes with 700 kW, reaching a total of 1 MW within 20 minutes, the specimen is class C. For classes A and B no flashover is allowed to occur.

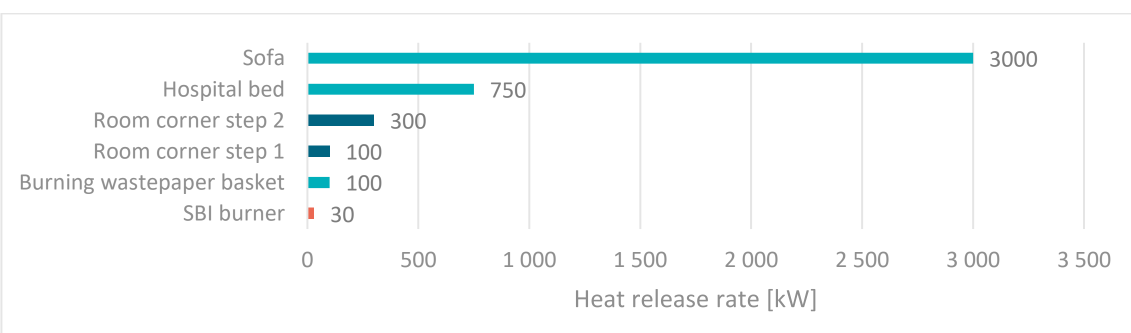


Figure 39 Typical heat release rates [100] compared to the output of the SBI burner [97] and the room corner test heat output [99]

As seen in Figure 39, the heat release rate of the SBI burner is significantly lower than a burning wastepaper basket, whilst the first 10 minutes of the room corner test is equivalent to a wastepaper basket burning.

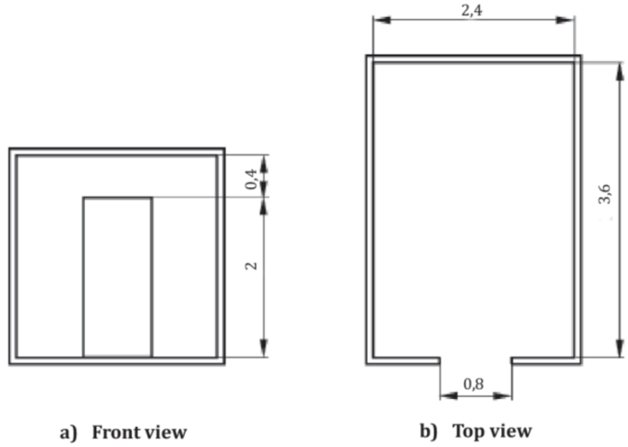


Figure 40 Dimensions [m] of the room to be used for room corner test [99]

For the room corner test, the standard configuration for test specimens is to cover the ceiling and all internal wall surfaces excluding the wall with the opening [99]. Consequently, the room fire test is more expensive, but will be a closer representation of the initial stage of a real fire. Certain scaling laws applies to fire science, but turbulence, radiative heat, and flashover are examples of phenomena which will not translate easily from small scale to large scale.

Finally, the dimensions of the specimen are not scaled. Let us imagine a sandwich panel containing of an 80 mm polyurethane (PUR) core between two sheets of 0.5 mm steel plates. When subjected to a small thermal attack, the 0.5 mm steel plate may provide sufficient protection of the combustible core for the panel to obtain a B rating. The performance of the element when subjected to a more onerous thermal attack is simply not known.

5.3.4. Fire Safety Systems

As with building products, standards are produced to classify and set minimum performance requirements for fire safety systems and its components. These could be smoke extraction fans with a certain capacity (m^3/s or air changes per time), temperature ratings, or compliance to a certain design standard.

Similar examples as discussed for reaction to fire exists for the various standards for commercial and residential sprinkler systems, where technical details in a design standard become intertwined with national building legislation.

The development of tests for water mist systems is also an example of standardisation of systems with the potential of competing with more established technology, where existing actors in the market already have invested in research, development, and classification of their systems. Thus, the process of gaining consensus for a new technology becomes a challenge involving many factors other than technical issues. Sprinkler systems may use water density as a metric for their performance, and some would argue that water mist systems should demonstrate equivalence with conventional sprinklers to be accepted. As one of the key benefits of water mist systems is to suppress fires with a less water, it would be absurd basing equivalence assessments against conventional sprinkler on water density.

Several European standards exist for fire safety systems and their components: Fire detection and alarm, smoke control and pressurisation, emergency lighting, etc. It is beyond the scope of this thesis to examine these in detail, but generally, they set minimum requirements to systems and components, leaving requirements on where to mandate the systems up to others. Assessing equivalence between different standards (e.g., American NFPA 13 against European EN 12845 standards on sprinkler systems) is a highly complex endeavour, and assessing equivalence between different systems would be even more challenging.

5.3.5. Discussion on Standardised Classification of Building Element Performance

The tests and classifications are meant to be indicative for real life application, but the resulting classes are primarily fit for comparison between different products and materials – not as a measure for the performance in a real fire event.

As described in ISO/TR 17252 [101], there may be significant differences between the tested situation and a real-life fire scenario:

- Thermal attack
- Conditioning
- Ageing effects
- Mounting and fixing
- Heat flux measurements at the specimen surface

ISO 17252 further describes a number of other properties (in addition to those being part of the classification) being of interest: Melting, shrinking, slumping, dripping, spalling, charring, delaminating and intumescing. These properties are generally not declared by the manufacturer, so the information is not readily available to the designer. Furthermore, the fire safety strategy shall ideally allow for bids from several suppliers, not discriminating or giving preference to one technology.

Synthetic products will in many cases need fire retardant additives to obtain certain classifications for reaction to fire. Considering cost and environmental factors, one aims to limit the amount of fire retardants, so the product can be designed to the criteria given by the test standards.

Generally, the system for classification of building elements allows pre-accepted performance levels and fire safety strategies to set the required performance yet facilitating competitive tendering.

A load-bearing element classified to R 60 has proved to maintain its load-bearing capacity for 60 minutes under standardised conditions. During a real fire event, the loads applied to the element may be different than in the test (dead, live, and dynamic loads), and the fire exposure will be different.

Material vs. Product and Consistency Over Time

Principles are laid down for the field of application for the results from standardised tests. Generally, the test specimen should represent the final product as it is being used in end-use conditions. Hence, the classification report shall state for which situations the classification is valid. Depending on the product, restrictions could involve dimensions, fastening mechanisms, corner joints, substrate, colour, and other properties.

The example of the sandwich panel above is also fitting for the discussion of the scope of a component performance. Polyurethane may not on its own satisfy criteria for B-s2,d0, but when the right additives and fire retardants are added, the final product can be classified as B-s2,d0 when protected by sheet metal. Prior to the introduction of Eurocodes, the Norwegian standard had a focus on materials, rather than products, and defined a material as a "*[h]omogeneous substance or evenly distributed mixture, such as metal, stone, wood, concrete, mineral wool*"[4] [102]. The standard further explicitly requires claddings to either be a single material, or each individual material should be homogeneous and comply with the reaction to fire criteria.

With the implementation of Euroclasses in Norwegian pre-accepted performance levels in 2003, Norwegian building authorities had to provide a "translation" of the old national classes, providing equivalents in the new Euroclasses:

Table 7 Equivalence between classes found in NS 3919 [102] and Euroclasses [98], as described in the 2003 version of the guide to the Norwegian building regulations [53]

Old national class	New Euroclass
Non-combustible or limited combustible	A2-s1,d0
In1	B-s1,d0
In2	D-s2,d0
K1-A	K10 A2-s1,d0
K1	K10 B-s1,d0
K2	K10 D-s2,d0

Interestingly, the cladding classes K1-A, K1, and K2 had not been in use until the introduction of the Euroclasses in 2003. However, the definitions of material above differ from how the Euroclasses are determined. Norwegian pre-accepted performance levels were based on requirements to the outer material and its substrate. Both of which assumed to be homogeneous. When the Euroclasses were introduced, they allowed for assessing the product as a whole, thus allowing for materials previously not accepted in Norway.

[4] «Homogen substans eller jevnt fordelt blanding, f.eks. metal, stein, tre, betong, mineralull»

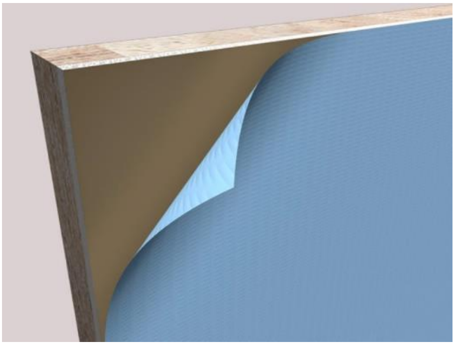


Figure 41 Illustrations used in VTEK to explain the term surface (overflate): The outer, thin layer of a building element – what you can touch

Previously, the requirement in an exit corridor would be In1 on a non-combustible or limited combustible substrate [33, 52], but as of the third version of the guide to TEK'97, a figure similar to Figure 41 has been presented, and the pre-accepted performance level has been surface B-s1,d0 [In1] and cladding K10/A2-s1,d0 [K1-A] [53], where squared brackets indicate equivalent national classes.

Either under-communicated or unintentionally, requirements for fire resistance (K10) in all internal walls and ceilings were introduced. RISE Fire Research proposed some changes to the guide to make the topic clearer to the users of the guide [103], revealing that the cladding requirement never was meant to apply unless there were underlaying layers requiring protection (like combustible insulation materials). Some responders to the public enquiry interpreted this as a drastic relaxation, allowing both fire-treated timber walls and sandwich panels where previous practice had been non-combustible.

Favourable Temperature Rise

Intumescent materials may be used in fire rated doors, cavity barriers, penetration seals, and to improve the fire resistance or reaction to fire of materials. When subjected only to the standard time temperature curve for classification, little information is gained about the performance of the products in other fire situations. If no explicit requirements are given, there are no incentives for manufacturers to develop products that will reduce the spread of colder smoke, or to provide protection of materials at a lower temperature rise rate than the standard curve. Criteria and test procedures are also adapted to what is obtainable with the current technology, e.g., allowing intumescent materials time to activate before observations of flaming above a cavity barrier commences. These adaptations reduce the incentives for manufacturers to improve beyond the criteria of the classification standards.

Too Conservative?

Fire resistance is a well-established system for measuring performance of building elements, assuring separating and/ or load-bearing capacity of an element for a given duration under standardised fire exposure. The exposure in a real fire may (or will most likely) not equate the standardised fire exposure, which is a necessary simplification done during standardisation.

Similarly, there are several settings where the standard fire curves are overly onerous for real fires. For that reason, the external fire curve and other milder fire curves are defined, to represent a standardised exposure where flashover is not expected (e.g., external structural members or fire or smoke barriers in the upper layer of an atrium).

Conservative Enough?

Although the standard fire curves are assumed to be conservative for most applications, the adequacy of standard temperature-time curves for buildings with exposed mass timber has been debated parallel with the increasing use of engineered wood and use in taller buildings. For combustible specimens, it is observed that the furnace requires noticeable less propane to obtain temperatures as given in ISO 834 [104], both due to the combustibility of the specimen and the different boundary conditions for heat transfer.

Some tests indicate that the hydrocarbon curve (see Figure 36 on page 71 and [92]) is a better representation of the temperature in enclosures with predominantly exposed mass timber.

For further reading, reference is made to [105].

Synergy Between Systems and Components

To make standardised tests affordable, comparable, and transparent, simplifications are required, and one intends to focus on a limited set of properties of the test specimen. Fire safety is however a complex interplay between many components and systems.

Some suppliers also market their products with a certain fire resistance, under the condition that sprinklers are present, as seen in this example from a Norwegian distributer of fire curtains:

Tilfredstiller E-klasse inntil 120 min	*Meets the criteria of E up to 120 min*
Tilfredstiller EI-klasse inntil 120 minutter ved sprinkling	*Meets the criteria of EI up to 120 minutes with sprinklers*

Similarly, Eurocodes allow for a reduction in the calculated fire load ($\delta_{n1} = 0.61$) where automatic water extinguishing system is present [92]. An operational fire suppression system will obviously reduce the exposure to the fire curtain, and thus it is reasonable to argue that passive performance of the building elements can be reduced. In both situations, one could also argue that the cumulative performance is higher than passive performance alone. A successfully operational suppression system is expected to reduce the equivalent exposure time by more than a factor of 0.61, and a fire rating beyond 30 minutes is most likely not needed for partitions.

It is however necessary to keep a holistic perspective on the fire strategy, considering how the different systems and building elements are meant to interact. In the context of fire sections (TEK § 11-7), sprinklers are used to allow for increasing the area between fire sectioning walls from 1 800 m² with fire detection and alarm system only, to 10 000 m² with sprinklers [73]. Thus, for a building with a gross area of 20 000 m², sprinklers and one fire sectioning wall is called for by VTEK. In this situation, the fire sectioning wall must be seen as a barrier independent of the passive fire partition, reducing the fire losses in case of sprinkler failure. Hence the synergy or interaction between the suppression system and the passive barriers should be assessed in the fire safety strategy – not by the structural engineer or the manufacturer of fire curtains. Therefore, the national annex to Eurocode states;

For automatiske slokkesystemer settes δ_{n1} normalt lik 1,0. Ved brannteknisk analyse kan det benyttes verdier ned til 0,6 forutsatt at fastsettelsen av valgt verdi for δ_{n1} inngår som en del av brannsikkerhetsstrategien for byggverket.

δ_{n1} is normally set to 1.0 for automatic fire suppression systems. Values not less than 0.6 can be used in performance-based design, under the condition that the value δ_{n1} is anchored in the fire safety strategy for the construction works.

5.3.6. Component Performance as Metrics for Fire Safety Performance

Component performance can play a central role in performance-based fire safety legislation. As seen in this presentation, component performance based on standardised testing is the result of compromises, affected by the interests of many parties. As Law concludes [89]:

> *Herein lies a key tension with standardised testing: the gains of simplicity and interoperability are likely to come at the expense of user understanding and expertise.*

And

> *By reducing complexity through classification and simplification, standardisation seeks to impose order on the world. Individual users gain simplicity and interoperability at the expense of giving up understanding and control.*

Although regulation through component performance may seem strict, implying greater regulatory control, the resulting fire safety performance of the final building is not known.

Finally, if component performance is the predominant requirement in legislation, a “compliance culture” may emerge, where incentives for reducing risk is lost, and the most cost-efficient way of ensuring compliance is rewarded [89].

For fire safety design, component performance will, like specification, be fit for pre-accepted performance levels and as output of an engineering analysis. Component performance will in most cases not be a suitable metric for the fire safety performance of a building, seeing that it only is designed to capture certain properties of some of the components or systems involved in a simplified proxy for a fire scenario.

5.4. Environmental Performance

Environmental performance means formulating the cut-off for acceptable conditions within the building, given the occurrence of a fire. As opposed to threat potential performance (section 5.5), environmental performance neglects the targets being protected, and states acceptable states for the environment.

The designer is free to choose any means of achieving the required performance. Examples of environmental performance include maximum smoke layer temperature, smoke layer height, and radiative flux.

The further presentation of different environmental performance criteria is structured according to basic requirements for construction works [69]:

a) the load-bearing capacity of the construction can be assumed for a specific period of time (5.4.1);
b) the generation and spread of fire and smoke within the construction works are limited (5.4.2);
c) the spread of fire to neighbouring construction works is limited (5.4.3);
d) occupants can leave the construction works or be rescued by other means (5.4.4);
e) the safety of rescue teams is taken into consideration (5.4.5).

Concluding remarks are made in subsection 5.4.6.

5.4.1. Load-Bearing Capacity

Although load-bearing capacity often is treated with component performance, ensuring load-bearing capacity in case of fire can be regulated by environmental performance criteria.

This approach can be extrapolated from pre-accepted performance levels being reduced for load-bearing constructions in carparks with open façades, assuming carparks with more than 1/3 of its external walls being open, allows for venting of hot smoke, reducing the likelihood of flashover. Following some larger fires in carparks in the last decades (Switzerland 2006, Great Britain 2006, France 2014, Ireland 2019), and especially the Kings Dock car park 2017 and Stavanger airport Sola carpark 2020, RISE Fire Research was tasked to re-evaluate the performance levels for open carparks [106, 107]. The evaluation finds grounds for proposing changes to the pre-accepted performance levels and solutions, and states [107]:

It is, therefore, our recommendation that the possibility of reducing the fire resistance in open car parks in fire classes 1 and 2 be reconsidered. This option should be considered removed, or other criteria could be employed to reduce the fire resistance, such as e.g. sprinkler systems (as in Sweden).

The likelihood of flashover, and thus the risk of thermal attack to the load-bearing structure represented by the standard time temperature curve affected by smoke ventilation. The question is if 1/3 of the external walls being open is an adequate way of requiring the intended effect. An environmental performance criteria of gas temperatures less than 500 °C, or other established criteria for the onset of flashover could be considered.

Another possible approach could be using critical temperatures for steel or timber structures as environmental performance criteria. Assuming the structural engineer finds critical steel temperature of exposed steel members to be 450 °C, this could also be a reasonable environmental performance criterion for the room in which the steel members are placed. In this situation, it would be crucial to include all relevant heat transfer modes, meaning that the radiative heat from the fire can rise the critical steel temperature even in situations where the gas temperature is below 450 °C.

Similarly, the criteria proposed by RISE Fire Research, limiting the temperature of timber constructions below app. 300 °C – the onset of charring and significant contribution to the fire development by pyrolysis.

5.4.2. Generation and Spread of Fire and Smoke

Generation of Smoke and Heat

Requirements regarding generation of fire and smoke, are for buildings typically set as component performance requirements (see subsection 5.3.3). The intention is however to ensure certain properties of the environment for the initial stages of the fire development. In this perspective, it may not be crucial to achieve the same performance of all products, assuming the performance criteria for the environment are fulfilled. This line of thought has gained some momentum by the increasing use of wood in taller buildings, i.e., by Spearpoint et al assessing the effects of rooms partially lined with timber [108].

As the environmental performance criteria relevant for generation of heat and combustion products are motivated of providing acceptable conditions for escape and rescue, this topic will be discussed further in subsection 5.4.4.

Spread of Smoke

For pressurisation systems, environmental performance criteria are common, where an enclosure can be required to be pressurised to more than 30 Pa and not more than 90 Pa in relation to adjacent parts of the building.

Restricting spread of smoke could also be regulated by requiring maximum smoke densities, smoke obscuration, etc., as will be discussed further in subsection 5.4.4 in relation to means of escape and rescue.

Spread of Fire

Regulation of spread of fire is most usually done by component performance requirements, as discussed in subsection 5.3.2. An alternative would however to regulate the environment in the room of origin, not allowing for a fire to grow to the point where fire spread is likely. This would invite to assess alternative means of achieving the same objective, like suppression systems or smoke control.

Although not explicitly stated, this approach is found in the pre-accepted performance levels and solutions. A prescriptive approach would require windows with fire resistance, if the distance between windows is low as seen in Figure 42. By the introduction of sprinklers, the environmental performance of the room of fire origin is assumed or deemed to reduce the likelihood of fire spread to the point where fire resistance is no longer required for the windows. Here the environmental performance is assumed by reference to a standard for design of sprinkler systems.

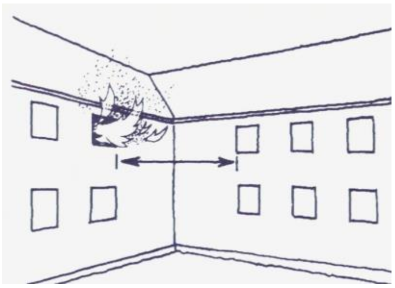


Figure 42 External fire spread in corners [52, p. 75]

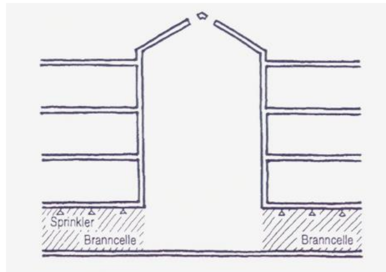


Figure 43 No fire separation against atrium when sprinklered [52, p. 101]

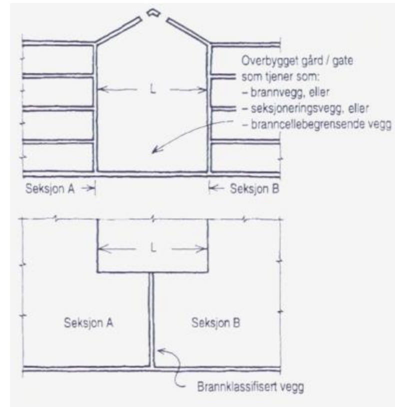


Figure 44 Atrium with smoke ventilation serving as fire sectioning wall [52, p. 77]

Similarly, as illustrated in Figure 43 and 44 a reduced fire resistance is allowed towards atria when it is mechanically or naturally smoke ventilated. Until 2017 reference was made to a guide published by the national building authority, where the environmental performance requirement of maximum upper smoke layer temperature of 500 °C was stated for the atrium [109, p. 20].

This way of explicitly requiring performance makes the legislation more transparent and easier to understand for the user. Furthermore, it is more apparent that other means and technologies given by the pre-accepted performance levels and solutions are viable – and it is clear what performance is required.

5.4.3. Spread of Fire to Neighbouring Construction Works

As opposed to spread within the construction works, there has been no tradition to account for the effect of fire safety systems when considering fire spread between buildings. Although this is not explicitly stated in legislation, it is assumed that a passive fire barrier is less reliant on the service and maintenance done by different actors – meaning the fire safety in your building should not be adversely affected by your neighbour's ability to maintain an operational fire safety system.

With reference to BS 9999 and work done by Margaret Law and Fredrik Nystedt, INSTA 950 propose a maximum radiation criteria for 15 kW/m² for 30 minutes for receiving facades with a reaction to fire class less than A2-s1,d0 [1]. The radiation is to be calculated as 30 s average.

As discussed in the evaluation of the fire in Lærdalsøyri in 2014, radiation is not the only mechanism of fire spread between buildings, and flying embers has been recorded to spread fire over distances of 20 km [110]. Thus, the example from INSTA 950 shows how different phenomena of one objective can be regulated with different forms of performance requirements or differentiating environmental performance criteria based on relevant component performances.

5.4.4. Means of Occupants Escape or Rescue

Naturally, the safety of persons in case of fire is instrumental in fire safety design. Therefore, environmental performance criteria relating to safe escape are more frequently used and more available in literature. Representative examples are found in INSTA 950 [1], as shown in Figure 45.

Parameter	Criteria	
Visibility	Visibility no less than 3 m in the primary fire compartment at area of ≤ 100 m^2). Visibility no less than 10 m at height of 2 m in escape routes and compartments of areas > 100 m^2. As an alternative to determine visibility, a smoke-free height of 1,6 m + 0,1 x H.	
Thermal[a]	Continuous radiation intensity of maximum 2.5 kW/m^2 and,a short-term radiation intensity of maximum 10 kW/m^2 if the maximum radiant dose is less than 60 kJ/m^2.	
Temperature	Gas temperature not higher than 80 °C.	
Toxicity[b]	CO CO_2 O_2	< 2 000 ppm < 5 % > 15 %
[a] In addition to the energy from background radiation. [b] Toxicity does not need to be calculated when the visibility surpasses 5 m.		

Figure 45 Example of environmental performance[5] – tenable conditions when evaluating available safe egress time [1]

These environmental performance criteria can be applied in different ways:

- *Steady-State Conditions*
  For certain systems and situations, one can design for steady-state conditions, a typical example being smoke ventilation. Here steady state would mean providing a smoke extraction capacity which is at least equivalent to the smoke production of the design fire. The smoke-free height criteria can then be applied to design tools, ensuring sufficient capacity in the smoke extraction fans or natural vents.
- *Available Safe Egress Time (ASET)*
  For time-dependant conditions, the environmental performance criteria are used as a threshold for when the space is no longer safe for occupants. As will be discussed in more detail in subsection 6.8.2, the time required to evacuate the occupants is compared to the time available until the untenable conditions occur.

Different approaches are taken when it comes to defining the cut-off the available safe egress time: Visibility through smoke is a useful criterion to allow occupants to orientate in the building, to avoid trips and falls, and to allow evacuation to take place in an orderly fashion. As seen in footnote b, visibility is also used as a proxy for toxicity, meaning smoke densities where visibility of at least 5 m is obtained can be assumed to have toxic contents within acceptable limits. The physical parameters may also have different uses, where the most usual thresholds are related to lethal conditions, conditions where the average person is expected to lose consciousness (incapacitation), or conditions where research suggest that evacuating persons will not enter – see further discussion under threat potential performance in section 5.5.

Figure 45 further shows how environmental performance criteria can be both prescriptive (seemingly arbitrary) quantities, like a smoke-free height, where the requirement becomes more stringent with increasing ceiling height, or physical parameters which can be scientifically justified with links to the

[5] The thermal criteria must be seen as a threat potential performance criterion, as discussed in section 5.5.

human physiology. The latter is obviously preferable, as this can be understood and adapted over time or to individual cases in a more transparent manner.

5.4.5. Safety of Rescue Teams

Facilitating fire and rescue operations is the subsystem with the poorest availability of performance-based assessment methods [58, p. 31], meaning most designs are confined by the pre-accepted performance levels and solutions.

The safety of rescue teams is highly influenced of previously mentioned performance criteria, like structural stability and fire spread. However, trained, and equipped firefighters will have other tenability criteria than the ones discussed for means of escape. According to PD 7974-5, gas temperatures below 100 °C can be categorised as routine operations for the fire service [111], which can be considered as a environmental performance criterion.

Standards and legislation on protective clothing and gear for firefighters can provide useful environmental performance criteria for the safety of rescue teams, but it is recommended to confer with the local fire brigade to seek more specific details about their gear, procedures, and policies.

The tenability of firefighters is highly influenced by other factors than the gas temperature. In many cases it would therefore be more appropriate to assess the safety of rescue teams by threat potential performance, as seen in subsection 5.5.2 on heat exposure to fire fighters.

5.4.6. Environmental Performance as Metrics for Fire Safety Performance

Compared to specification and component performance, environmental performance is considerably more fitting for regulating performance-based fire safety design. Most performance criteria discussed in this chapter must be seen in a more specific context, meaning they are more fit for guidance documents, or to be defined for each specific analysis – not for mandatory building legislation.

One must be aware the embedded assumptions in environmental performance criteria, as environmental performance does not consider the targets being protected. Thus, an environmental performance requirement aimed ensuring acceptable conditions for evacuation for the average population may be inappropriate for a health care facility or other occupancy types where the users are expected to be more vulnerable to smoke. Similarly, environmental performance criteria for load-bearing capacity assuming steel structures may be inadequate for timber structures.

The reader is also reminded to view performance criteria in of the verification method, and particularly how uncertainties are treated (section 6.2). Environmental performance does not take fire prevention into consideration, and simply assumes a fire can occur, so there are no incentives for the designer/ analyst to investigate mechanisms to reduce the fire frequency – although this assumption is in alignment with the phrase safety *in case of fire*, found in both the Norwegian building regulations [4] and the CPR basic requirements to construction works [69]. See further discussion on this approach in subsection 8.6.1.

Environmental performance criteria could also form output from fire safety design, where e.g., a mechanical engineer is tasked with designing a system complying with a performance requirement of a certain positive pressure.

5.5. Threat Potential Performance

Threat potential performance involves defining maximum allowable exposure to the target being protected, whilst environmental performance as discussed in section 5.4 focus on the environment in which the targets are found.

Threat potential performance also assumes that a fire has occurred, without regard to fire prevention efforts. In other terms, threat potential performance can be seen as the upper limit for tolerable outcome of a fire, where the outcome is measured as exposure to the item being protected.

Threat potential performance does not define how to achieve the required criterion.

5.5.1. Fractional Effective Dose (FED)

The concept of fractional effective dose (FED) is widely adopted, and found in sources like the SFPE Handbook of fire protection engineering [20], ISO 13571 [112], and INSTA 951 [78]. Rather than measuring the concentrations in the environment, FED involves calculating the cumulative exposure to persons.

$$FED = \int_{t1}^{t2} \sum_{i=1}^{n} \frac{C_i}{(Ct)_i} \Delta t \qquad \text{Eq. 2}$$

, where C_i is the average concentration of the asphyxiant gas i over the time increment Δt [min]. $(Ct)_i$ is the dose exposure (product of dose and duration in minutes) of asphyxiant gas i deemed to cause incapacitation or other adverse effects decided as the endpoint of safe egress time.

The SFPE Handbook goes into further detail on how the concept can be applied for incapacitation or lethal doses, asphyxiating or irritating gases. It is also noted that not only the exposure time, but also the inhaled concentrations are relevant – meaning a person walking on ascending stairs will most likely be incapacitated more rapidly than a person queuing when both are exposed to the same toxic and irritant gases.

Often a FED value of 0.3 is used as threat potential performance criteria [78]. ISO 13571 states that the probability of incapacitation can be described as a lognormal function of FED, where $\mu = 0.0$ and $\sigma = 1.0$, as seen in Figure 46.

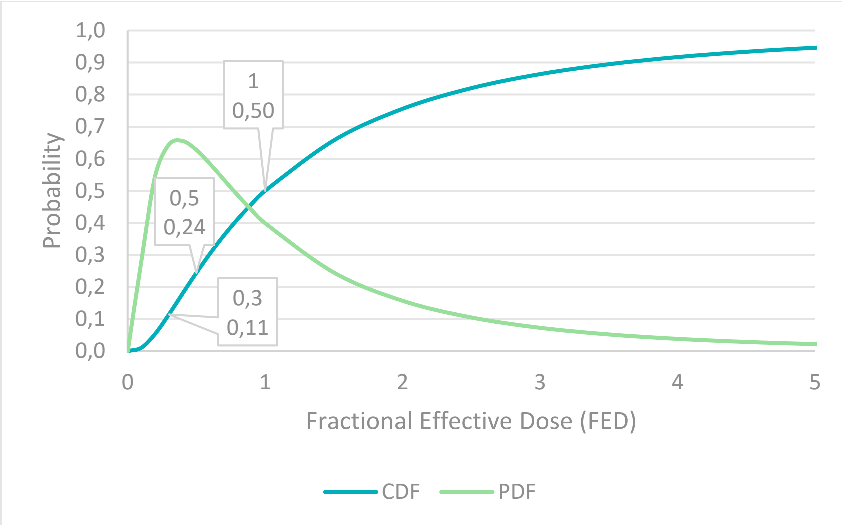


Figure 46 Lognormal distribution showing the probability distribution (PDF) and cumulative probability (CDF) of incapacitation for different FED exposures.

A threat potential performance criterion of FED=0.3 would imply that 11 % of the population would be incapacitated when exposed to these conditions. This probability distribution is meant to represent the general public, and thus, would need adjustments to be appropriate for scenarios where a more vulnerable population is expected.

5.5.2. Heat Exposure to People

Persons Evacuating

As seen in Figure 45, INSTA 950 proposes a threat potential performance criterion for heat exposure to persons under evacuation. Most criteria in the example are environmental criteria, but the thermal criterion considers the person receiving the exposure, making the criterion a threat potential criterion. The thermal exposure is deemed acceptable for maximum intensities of 10 kW/m² for no more than 10 seconds, or a lower intensity where the product of intensity and duration is no more than 60 kJ/m².

Fire Fighters

As mentioned in subsection 5.4.5, an environmental performance requirement of maximum gas temperature may be an adequate metric for firefighter safety. Threat potential performance can to a greater degree take into account the fire fighter's activity and other ways a fire fighter would be affected by the environment in which search, rescue, and firefighting operations are conducted.

PD 7974-5 proposes thermal classes for firefighting environments as illustrated in Figure 47. Temperatures below 100 °C and heat fluxes below 1 kW/m² are considered routine conditions, where prolonged exposure is seen as acceptable. The range 100-160 °C and 1-4 kW/m² is categorised as hazardous, proposing 10-25 minutes as maximum duration, calculated as a time-weighted average.

160-210 °C and 4-10 kW/m² is categorised as extreme conditions, where exposure for up to 1 minute may be tolerable if required to save life. Beyond 210 °C and 10 kW/m² is deemed critical – conditions where firefighters are not expected to operate.

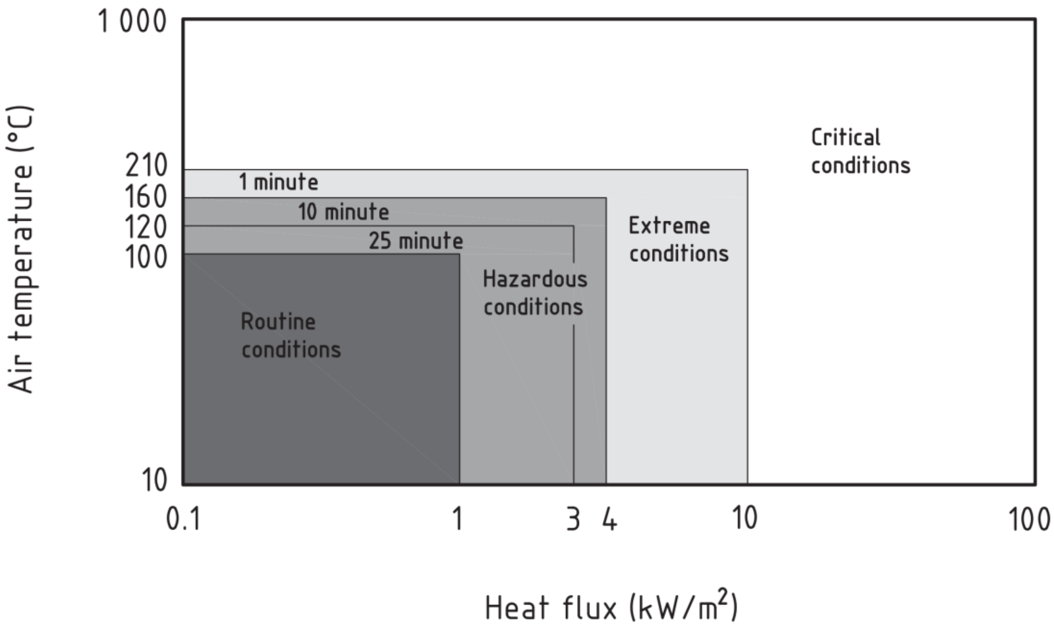


Figure 47 Recommended thermal classes for firefighting environments [111]

If a firefighter is exposed to 250 °C for 2 minutes and 110 °C for 10 minutes, the time-weighted average thermal exposure can be calculated as shown in Eq. 3.

$$\frac{(2\ min\ \times 250\ ℃) + (10\ min\ \times 70\ ℃)}{2\ min + 10\ min} = 100\ ℃ \qquad \text{Eq. 3}$$

The weighted average thermal exposure is found to be 100 °C with a duration of 12 minutes. The weighted average is within the limits shown in Figure 47, but this exposure is still not acceptable, as it exceeds the maximum value of 210 °C.

5.5.3. Protection of Property, Business Continuity, and the Environment

Although life safety most often is at the centre of attention in fire safety design, some situations call for an analysis of the threat posed to the building itself, items, equipment, processes, or the natural environment. In this context, the threat potential performance is meant to define the threshold for these targets to obtain their value – beyond this threshold an unacceptable loss is expected.

Gas temperature and heat flux may be a relevant criterion and can in many cases be obtainable based on the target's material properties. Reasonable estimates are obtainable for safe temperatures of stone sculptures, silk flags, paintings, and other artefacts. Similarly, technical equipment vital to the continuity of business and process will most likely have temperature ranges within which the manufacturer guaranty for their operation.

For electrical components and artefacts, soot deposition may also be defined as a threat potential performance.

5.5.4. Threat Potential Performance as Metrics for Fire Safety Performance

Threat potential performance allows for using physical quantities for defining unacceptable conditions and creating a clearly defined link between the fire induced conditions and the target being protected, with its particular vulnerabilities.

Although this approach may appear superior to the previously discussed performance metrics, the criteria do not say anything of fire safety, unless they are applied a holistic analysis, also involving factors like prevention, managerial procedures, and emergency preparedness.

Thus, threat potential performance are highly relevant criteria for performance-based design, and they can in many instances be a useful metric for alignment with stakeholders or subject matter experts on other fields (medicine, electronics, conservation, etc).

5.6. Risk Potential Performance

Risk is a metric gaining increasing support in the fire safety engineering industry. There is an ongoing initiative to quantify the performances of Australian building codes [113], where the intention is that "*[t]hese new risk and probability metrics provide a consistent and holistic method of measuring the fire safety performance of buildings*" [114].

In an approach with risk potential performance, all potential scenarios should be identified, for which the expected consequences (losses) are quantified. The likelihood of all scenarios (or scenario clusters) is determined. The risk potential performance is the sum of the risk for all scenarios, and can be expressed mathematically as:

$$Risk = \sum Risk_i = \sum [P_i C_i] \qquad \textit{Eq. 4}$$

, where

$Risk_i$ is risk associated with scenario *i*,
P_i is the frequency of scenario *i* occurring, and
C_i are the consequences (losses) associated with scenario *i.*

As an example, consider a 1 000 m² facility where fires are estimated to occur with a frequency of 0.1 fires per year. Sprinklers are installed and are assumed to be efficient in 90 % of fires, limiting the damaged are to 5 m², whilst for sprinkler failure, a total loss of the facility is expected. The risk potential performance, thus can be expressed as:

$$Risk = 0.1[(0.9 \times 5) + (0.1 \times 1\,000)]\, {m^2}/{yr} \approx 10.5\, {m^2}/{yr} \qquad \textit{Eq. 5}$$

This approach can be used for most fire related analyses. The analyst would be required to quantify the consequences of fire relevant to the objective. Herein lays a connection to other types of performance, meaning that the analyst must define the onset of loss for each scenario, typically stated as environmental or threat potential performance. The significant difference for risk potential is that it addresses the inherent uncertainty of fire safety: Fire frequency and the myriad of potential fire scenarios. Consequently, risk potential performance can also take into consideration the effect of fire prevention, fire service intervention, and any factors affecting the likelihood of the different fire scenarios and their outcome.

5.6.1. Individual Risk

Individual risk is a measure of the statistical expected number of lives lost per year within the site of interest. INSTA 951 proposes a criterion of 10^{-6} per year for loss of life, meaning fire casualties are statistically expected once every 1 000 000 years [78]. As with other types of risk potential performance, an exhaustive analysis of the possible scenarios is conducted, in which the probability for each scenario (or scenario cluster) is calculated and multiplied with the number of expected casualties in each scenario. The sum of all branches of this event tree will give the individual risk.

This performance criteria includes many factors not covered in previously mentioned performance criteria, although it should be noted that the individual risk criteria potentially will mask unacceptable scenario where a greater number of lives is lost. Society tends to have higher tolerance to frequent low consequence than less frequent catastrophic events, even if they statistically result in the same individual risk. This may be addressed by societal risk criteria.

5.6.2. Societal Risk

Societal risk criteria regulate not only the statistically expected loss of lives per year, but also regulates the number of fatalities per event. This allows for taking risk aversion into account for events involving many casualties.

INSTA 951 suggest the following societal risk criteria:

1-10 fatalities

$$F(N) = 10^{-6}\frac{1}{N} \quad \text{Eq. 6}$$

10-100 fatalities

$$F(N) = 10^{-5}\frac{1}{N^2} \quad \text{Eq. 7}$$

, where F is frequency and N is the number of fatalities.

Societal risk is typically visualised in FN diagrams, where the number of fatalities is shown on the horizontal axis, and the corresponding frequency is shown on the vertical axis.

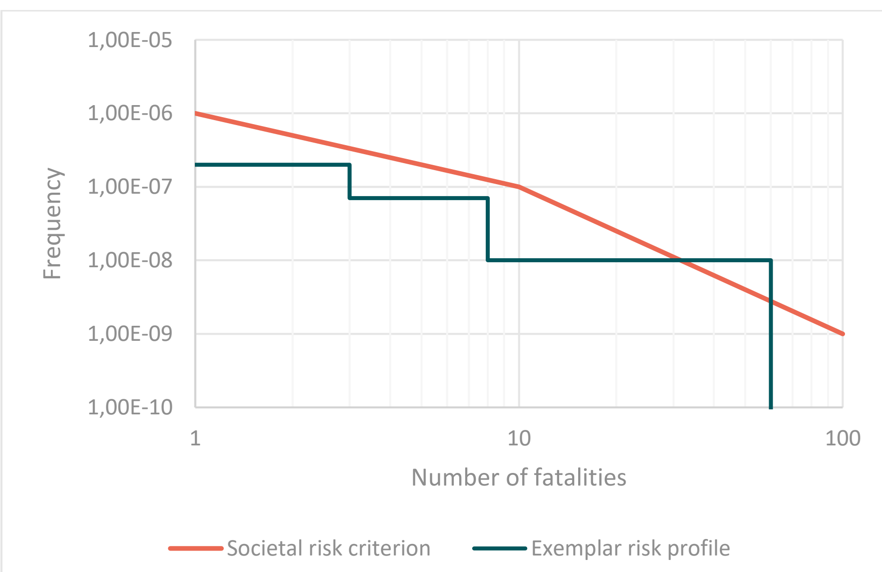


Figure 48 FN diagram showing societal risk criterion and exemplar risk profile

The red curve in illustrate the societal risk criterion from INSTA 951, while the blue line is an exemplar risk profile, indicating a frequency $2 \cdot 10^{-7}$ per year for events with 1-3 fatalities, which means the curve is below the criterion, indicating satisfactory safety. Towards the upper end of the x axis, it is shown that the risk profile crosses the criteria, and the calculated risk is higher than the criteria deemed acceptable. In this example, the designer would have to implement measures to reduce the risk, specifically for events with a potential of more than 30 fatalities.

5.6.3. Risk Matrices

Risk matrices are widely used, as they communicate clearly beyond the audience educated in risk analysis. They are however often used qualitatively, but for the purpose of chapter 5, the quantitative approach is of interest.

Table 8 Example of risk matrix [20]

Frequency (yr^{-1}) → Consequence ↓	Beyond extremely unlikely $f \leq 10^{-6}$	Extremely unlikely $10^{-4} \geq f > 10^{-6}$	Unlikely $10^{-2} \geq f > 10^{-4}$	Anticipated $f > 10^{-2}$
High		7	4	1
Moderate	10	8	5	2
Low		9	6	3
Negligible	11	12		

Legend:				
	High risk	Moderate risk	Low risk	Negligible risk

As seen in the exemplar matrix in Table 8, frequency is quantified, and the different categories of consequences can be quantified, depending on the objective of the analysis. These categories can be defined in collaboration with stakeholders (owner, users, fire service, authorities, insurer, etc), a process which can serve as a catalyst for engagement and ownership to the fire risk question.

The frequency may however be difficult to grasp for non-professionals. Statistics is widely used in society, and some have been involved in occupational health and safety (OHS) risk assessments. Fire, being a low frequency, high consequence event will differ significantly from the matrices for OHS.

Risk matrices could form a useful alternative or supplement to other performance criteria for fire safety. Such an approach could serve as an extrapolation of existing fire classes, used to classify the consequences of fire (see subsection 4.3.2 Fire and Hazard Classes).

Furthermore, with matrices it is common to define not only acceptable and unacceptable limits. Low risk is typically accepted without requirements for further risk reduction. High risk is usually not accepted, and risk mitigation or other designs are required. For moderate risk, however, other concepts can be introduced to assess the tolerability, like cost-benefit analysis and ALARP. This will be discussed in subsequent chapters of this thesis.

5.6.4. Risk Potential Performance as Metric for Fire Safety Performance

Risk potential performance is the only type of performance found to be a potential metric for fire safety performance. By introducing likelihood (both frequency of fire occurring, and probability of different fire scenarios), key aspects of fire safety can be addressed, whilst neglected by performance types discussed in previous sections of chapter 5.

The concept of mapping possible scenarios and assessing their respective probabilities and consequences is highly adaptable, and can be used on many scales, applied to many objectives.

Risk potential performance as a design parameter has a pedigree from industrial safety, where the consequences for third party are analysed and presented by risk profiles. As will be further discussed in subsection 8.5.1, there may be inherent differences between industries, making adoption of methodologies challenging. If the industrial site in question has a tank of flammable gas, the design scenario for third party safety is rather limited and graspable: Its location, capacity, fuel properties, and several other parameters are given. For building fire safety, the possible variations in fire location, growth rate, species production are immense. Furthermore, commercial, public, and residential buildings are typically less restricted, and both staff and visitors are usually less trained in safety related procedures.

Thus, the weakness of risk potential performance is the availability of reliable data, and the ability of the designer to exhaustively address all possible scenarios and their consequences.

5.7. Other Miscellaneous

Some concepts are discussed in the following, as they had no obvious place in the structure proposed by the SFPE Handbook [20]. These performance criteria are further discussed in relation to relevant verification approaches in chapter 6.

5.7.1. Maximum Allowable Damage

Maximum Allowable Damage will be further discussed as a verification approach in subsection 6.8.5, but as a metric, the extent of fire damage or loss is a concept which can be used to communicate the safety level and involve the owner, insurer, fire service, or other stakeholders with terms to which most can relate.

The approach can be summarised as a deterministic analysis of the consequences of a sufficiently onerous fire. Thus, relevant metrics would be extent of fire damaged area, number of floors involved in fire, or extent of fire spread, or other ways of measuring fire damage or loss.

5.7.2. Probability of Failure

Using probability of failure as a performance metric may be perceived as a risk potential performance criterion, but seeing that the consequences are grossly simplified, it is discussed briefly in the following.

Here the term probability of failure is the sum of probabilities for all scenarios whose outcome is considered a failure.

Probability of Exceeding Deterministic Criteria

Let us assume that threat potential performance criteria are identified for ancient artefacts at display in a museum. The trial design has three fire protection measures with their associated reliability, and an event tree like the generic example in Figure 51 can be produced.

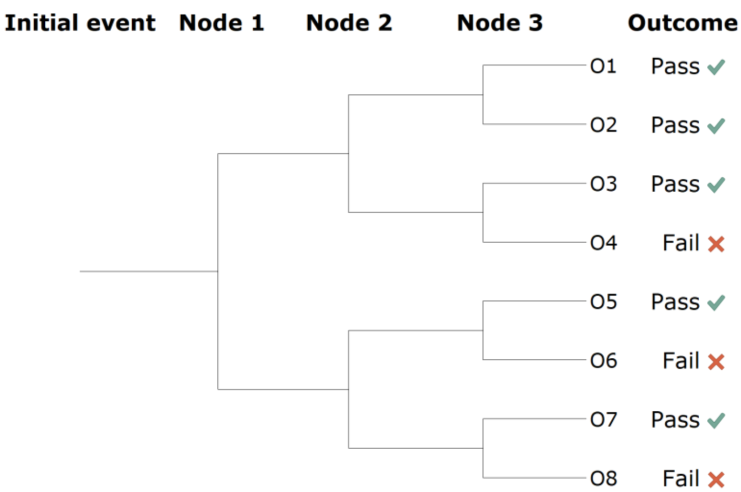


Figure 49 Generic event tree with three nodes, where the outcomes either pass or fail a certain criterion.

In this example the treat potential performance criteria are satisfied for most scenarios, but if the system in node 3 fails, the criteria are only met if also nodes 1 and 2 operate (outcome O2). The probability of failure will be the sum of probabilities for outcomes O4, O6, and O8. Depending on the specific analysis, the above event tree could include the fire frequency, or it could simply assume that a fire occurs (frequency = 1).

Safety Index (β) Method

The above concept bears similarities to the safety index method, or beta method (β), as described in INSTA 951 [78], but introduced to fire safety engineering in the 1980s and 90s from structural engineering [115, 116]. Although one must be vigilant when adopting methodologies from elsewhere, there are several benefits of using the same metrics and philosophies from other disciplines and industries. As seen in INSTA 951, the existence of β values for structural engineering or landslides could be used justification for a level of safety found acceptable to society in leu of fire specific criteria.

Safety Factors, Margins, and Acceptable Uncertainty

Most fire safety assessments will have a considerable uncertainty - regarding models, data, knowledge etc. The certainty by which one can demonstrate compliance is a potential metric.

Safety factor applied to	Suggested safety factor
● Calculation of occupants' travel time in evacuation	2
● Calculation of fire load required to cause structural failure	1–1.5
● Calculation of time to reach untenable conditions	2–3
● Calculation of primary structural member failure	2
● Calculation of structural frame failure	1–2
● Calculation of evacuation times	2–3

Figure 50 General suggestions for safety factors found in literature [117]

Figure 50 indicates some general suggestions found in literature. Similarly, some verification methods include guidance on safety factors to compensate for margins of error. Both the Eurocode and the guide to TEK17 include margins to be added or multiplied, depending on fire compartment size, fire class, or other parameters.

Hypothetically, two designers assess the same fire safety problem. Designer A may choose the most probable input parameters and set a required safety margin to account for the probability of more onerous events occurring, but also other sources of uncertainty. Designer B may choose conservative input data, well beyond the most probable, and thus setting a required safety margin lower than designer A, mostly accounting for model uncertainty. Ideally, these two designers would find the same level of safety acceptable.

5.7.3. Time to Critical Events

Events or conditions within the construction works can in many cases be estimated by available tools and methods. This can be the onset of flashover, untenable conditions for egress, or collapse of structures. Pre-accepted performance levels are typically set in relation to these critical events, by fire rated building elements, structures, or systems.

Examples also found internationally for setting a nominal maximum evacuation time, both implicitly and explicitly [118].

Type of zone	Critical time to reach untenable conditions in means of escape (min)
Unprotected fire zone (zone of occurrence of fire)	
● Normal sized room ($\leq 100\ m^2$)	2–2.5
● Larger compartments or room (height > 4 m)	4–6
Partially protected zone (zone with heat and smoke resisting barriers for a limited time)	
● Natural smoke expulsion	5
● Pressurization or extraction system	10
Fully protected zone (zone where protection remains acceptable for the whole duration for which protection is required in the building)	
● Natural smoke expulsion, no lobby	30
● Natural smoke expulsion, lobby	45
● Pressurization or extraction system	60

Figure 51 Example of generalisations of critical times for reaching untenable conditions [117]

Although the examples given in Figure 51, may be indicative for many buildings, using these times as performance criteria is no guaranty for adequate safety [118].

For performance-based design, a more flexible approach may be achieved by expressing the time in qualitative terms, relating them to other events, like available safe egress time (ASET), complete burnout, available time for safe search and rescue, arrival time for the fire service, etc. This will however not result in a quantitative metric for fire safety performance, unless a minimum margin of safety is specified, as discussed in subsection 5.7.2.

5.7.4. Cost-Benefit

Although fire safety is closely linked to risk and cost, there is not a strong tradition of formalising cost-benefit analyses, neither in building fire safety design nor in regulation [87, p. 23].

Cost-benefit analysis can either be done comparatively, where one design option is compared to another to find the optimal choice, or it can be compared to absolute criteria, where the design being above a certain cost-benefit ratio is acceptable.

Monetary Value of Spared Lives

Building upon the principles discussed for risk potential performance in section 5.5, one would have to introduce a way of estimating the costs and benefits of a given design. For life safety, this would require an estimate of the monetary value of a human life – or rather the monetary benefit of a spared life. Both ethical and technical aspects are discussed in a Norwegian Official Report (NOU) from 1997, where the committee concludes that cost-benefit analyses can be appropriate for assessing the change of accidental risk [119, p. 111]. The discussion also includes considerations regarding the age of the individual, reduced health, productivity, quality of life etc. For fire safety purposes, the methodology may be more important than finding exact numbers. Furthermore, the metrics can also include factors which reflects society's difference in risk tolerability, it should be regularly updated, and include any factors necessary to reflect the political will to spare lives lost in fire.

Cost

In a building project, the right actors are available for obtaining a fair estimation of the cost of different design options. The cost could include the initial investment, implications for the construction and assembly phase, but also factors like power consumption, maintenance cost, technical longevity, and other factors affecting the operation of the building. The cost should also reflect possible adverse effects of the fire safety systems and concepts being assessed, like the water damage from a suppression system, or unwanted alarms and evacuations.

Engineering economics is a field where fire safety can absorb established concepts and models, applying them in the context of fire safety design and analysis. Project management, contractors, the client, and the rest of society have currency as a common performance metric. Reference is made to the SFPE Handbook for further reading on engineering economics [20, pp. 3137-3157].

Material Benefit

Different design options may also have different impacts on the income for a building. This must be included if a balanced presentation of different options is to be obtained. Typical examples of factors affecting the income is rentable area, commercial attractiveness, and allowable occupant load (e.g., ticket sales).

Material Loss

The estimation of material loss of fire is probably the most applied concept of cost-benefit analysis within building fire safety. Not all jurisdictions have regulation of property safety, and leave this to the owner and insurer. In Norway, however, both the Planning and Building Act and the technical regulations have property safety within their scope.

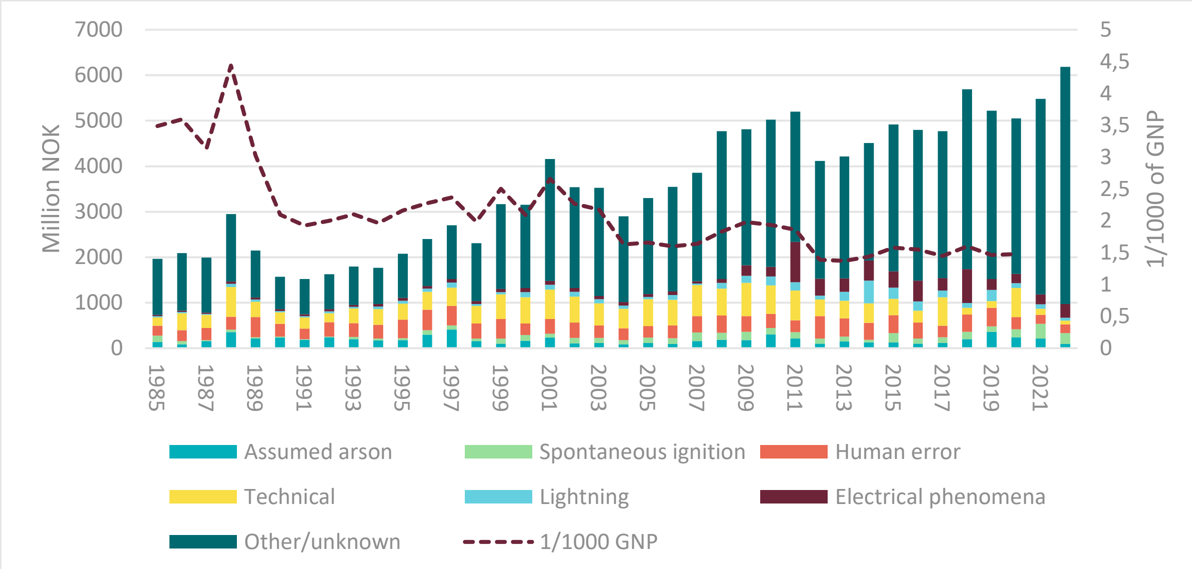


Figure 52 Annual monetary fire losses in Norway [71], compared to gross national product (GNP) [120]

As seen in Figure 52 fires cost the Norwegian society NOK 5.5 billion on average the last 5 years. For the first two decades of the millennium, the losses were on average 1.5/1000 of Norway's gross national product.

For engineering purposes, the financial losses would have to be estimated for each scenario in Eq. 4 (see page 89).

One could argue it is a matter of politics to decide whether property protection should be regulated by government or privatised through insurance. Without regard to how it is regulated, cost-benefit would be a highly relevant performance criteria for property protection, more relevant than the specification of a maximum gross area per fire section in the guide to the Norwegian building regulation.

Examples in Norwegian Legislation

As seen in section 3.10, the Fire Prevention Regulations mandates the upgrade of older, existing buildings to a level of fire safety equivalent to the building regulations of 1985 or later, with the following moderation:

Oppgraderingsplikten gjelder så langt den kan gjennomføres innenfor en praktisk og økonomisk forsvarlig ramme.

The obligation to upgrade applies as far as it can be carried out in a practical and economically feasible manner.

There are no economic parameters in the legislation, but the paragraph invites the analyst to include the cost-benefit of the upgrade and allows for excluding upgrades which have little effect compared to their cost.

TEK17 section 8-8 paragraph 4 lays down requirements for infrastructure for charging of electric vehicles for parking spaces mandated by the Planning and Building Act. In paragraph 5 some exemptions are given, and interestingly, sets financial a cut-off point for where the requirement does not apply. For general renovation of existing buildings, the current building legislation comes into force on the entire project, but for electric vehicle charging infrastructure, the requirement is wavered if compliance represents more than 7 % of the total renovation cost.

5.7.5. Proxies

Fictitious quantities with no direct relation to fire science, with the objective to rank or score certain aspects of a building. These are parameters without any meaning outside a given methodology, like risk matrices and risk index methods.

The main benefit of proxies is that they can reduce variability between different practitioners and serve as means for comparison of different alternatives. Additionally, they can be used to simplify matters for ease of communication, or to provide early-stage estimates.

Proxies may have short-comings regarding new technology and novel designs, as the methodology usually specifies ratings, weighting, etc for the properties and systems under consideration.

5.8. Discussion

5.8.1. Summary

In chapter 5 we have reviewed different ways of quantifying aspects with relevance to fire safety:

- Specification
- Component Performance
- Environmental Performance
- Threat Potential Performance
- Risk Potential Performance
- Other Miscellaneous (Maximum Allowable Damage, Probability of Failure, Time to Critical Events and Cost-Benefit)

Although these concepts allow for quantification of fire related aspects, only a few are applicable as measures of fire safety performance for a building, relevant for legislation. One would have to identify the desired outcome of quantification in order to assess the applicability of the performance types discussed. As stated in the introductory sections of this thesis, there is a need to increase confidence in performance-based fire safety engineering, where one of the potential strategies would be to increase regulatory control, whilst still obtaining the design freedom associated with performance-based design. Thus, a performance-criteria should regulate fire safety, without undue restriction of solutions, technology, or fire strategy.

Specification and component performance fail to meet these criteria and will have to be seen as prescriptive. The consequences of legally binding specification and the status of pre-accepted performance levels is further discussed in subsection 8.3.

Environmental performance and threat potential performance are similarly not seen as fit for regulating the fire safety performance of the building as a whole. These criteria must be seen in context of the full analysis, as such making these types of performance more relevant to guidance documents on the conduction of fire safety engineering. The implications of stricter regulation of verification methods are discussed in section 8.5.

Risk potential performance and cost-benefit are concepts which sufficiently can encompass enough variables to represent a viable performance criterion for fire safety in buildings. As will be seen in the following chapters of this report, one fixed performance criterion may still leave a significant variation between different practitioners, unless stricter regulation is enforced on the verification.

5.8.2. Desirable Benchmarks

114 persons from different disciplines and backgrounds (30 % fire safety engineers, primarily from USA) were asked to rank different forms of benchmarks to be used for verification of the adequacy of design in a survey [96]. All alternatives are shown in Figure 53, although some technically do not require quantification of performance. A regulator, practitioner, reviewer, and a contractor may have conflicting views on what a desirable benchmark is, as these different roles will be affected in different ways.

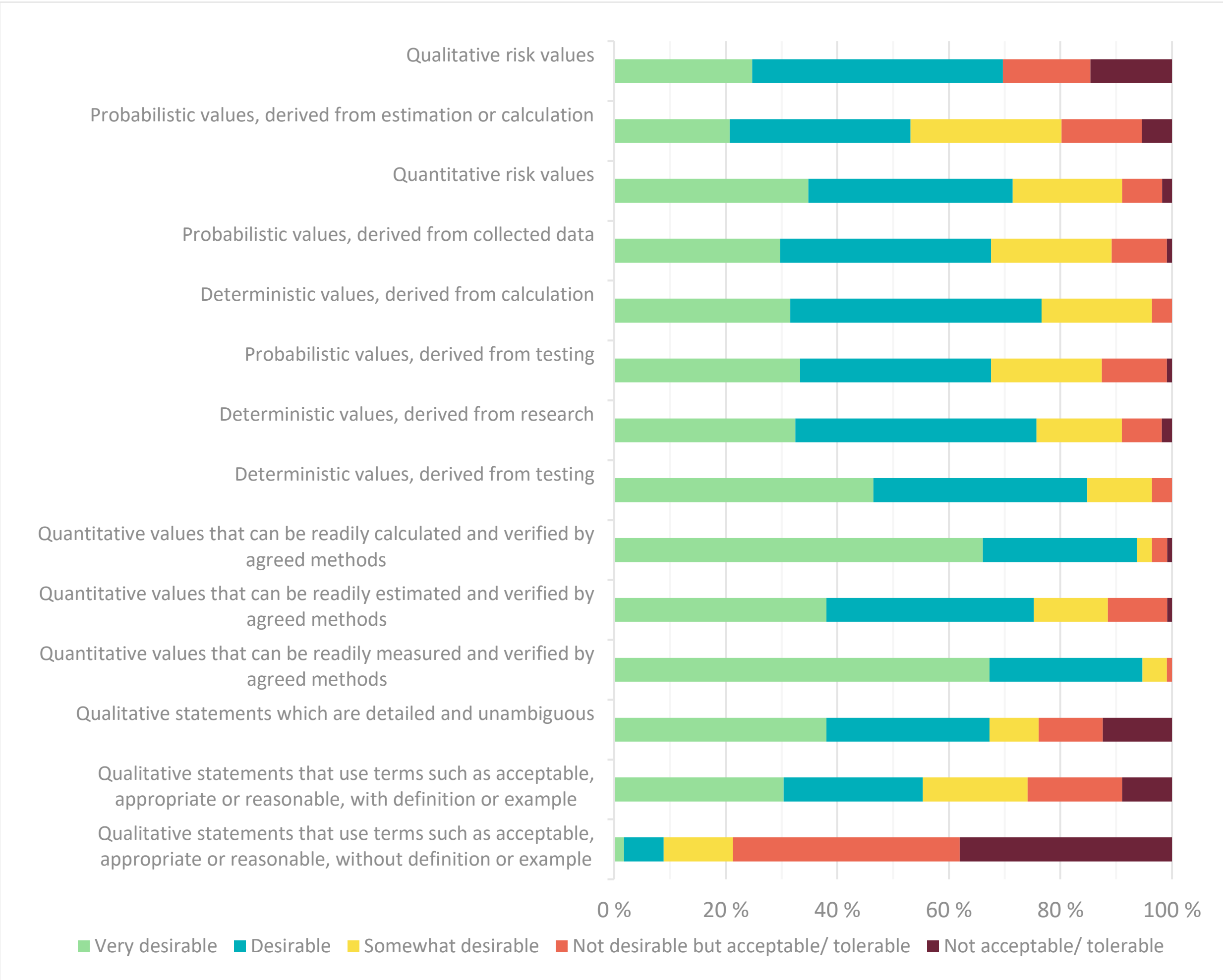


Figure 53 Results from a survey, where 114 persons responded to the question "Please indicate the desirability of different forms of benchmarks to demonstrate compliance / verify performance" [121]

A general observation from Figure 53 is a preference towards clarity and unambiguity. Qualitative statements lacking definitions or examples are found inadequate. In Table 9 the results for each benchmark are given a score, where the percentage from the survey is multiplied with a number from 0 to 4, representing the 5 categories, so that a score of 400 would mean 100 % found the benchmark to be very desirable.

Table 9 Ranking of different types of benchmarks, based on [121]

Type of benchmark	**Score**
Quantitative values that can be readily measured and verified by agreed methods	361.15
Quantitative values that can be readily calculated and verified by agreed methods	355.37
Deterministic values, derived from testing	327.73
Deterministic values, derived from calculation	304.54
Quantitative values that can be readily estimated and verified by agreed methods	300.95
Deterministic values, derived from research	297.36
Quantitative risk values	295.51
Probabilistic values, derived from testing	287.38
Probabilistic values, derived from collected data	285.59
Qualitative risk values	279.32
Qualitative statements which are detailed and unambiguous	269.04
Qualitative statements that use terms such as acceptable, appropriate or reasonable, with definition or example	250.94
Probabilistic values, derived from estimation or calculation	248.66
Qualitative statements that use terms such as acceptable, appropriate or reasonable, without definition or example	93.81

The two highest scoring benchmarks clearly state that one can readily verify compliance. For other quantitative metrics mentioned, the responder's background may influence preference, based on available verification methods.

5.8.3. Completeness of Metrics

It is crucial for the metric to encompass all aspects of the risks intended to be regulated by the requirement – even more so if it is made legally binding. A legally binding (or otherwise high status) performance criterion is susceptible to misuse (see subsections 8.2.7 and 8.5.4).

When comparing the pre-accepted solutions and performance levels to the potential metrics in chapter 5, some examples fit well, and verifying alternatives to the pre-accepted approach seems feasible. Other aspects, however, have an unclear connection. If a given aspect in the guide to the building regulations are found to not influence the calculated fire risk, one can conclude that 1) the metric and verification method is incomplete and does not fully describe all consequences of the deviation, or 2) the pre-accepted performance level or solution is unnecessary.

If cost-benefit criteria were to be more actively used, one would also have to clarify whose cost and whose benefit should be considered. For property protection, both the cost and the benefit belong to the owner, but when considering the need for or protection of a fire fighter lift, a different perspective is required.

Certain aspects of fire safety may have an unclear quantification potential – either because there is a lack of predictive modelling tools, or because the effort involved in quantifying the relevant phenomena is disproportionate to the scope of the analysis. In these situations, specification and component performance have a place, potentially supplemented with qualitative analysis as discussed in section 6.4.

5.9. Conclusion on Quantification

For the purpose of regulating performance-based fire safety design, specification and component performance is deemed too rigid, and will reintroduce the issues of past building regulations, which performance-based design was meant to cure. Environmental and threat performance has a central role in fire safety engineering, but cannot be used as a metric for the fire safety performance of a building, without being seen in context of an analysis considering fire frequency, fire scenarios, managerial procedures, emergency preparedness, etc.

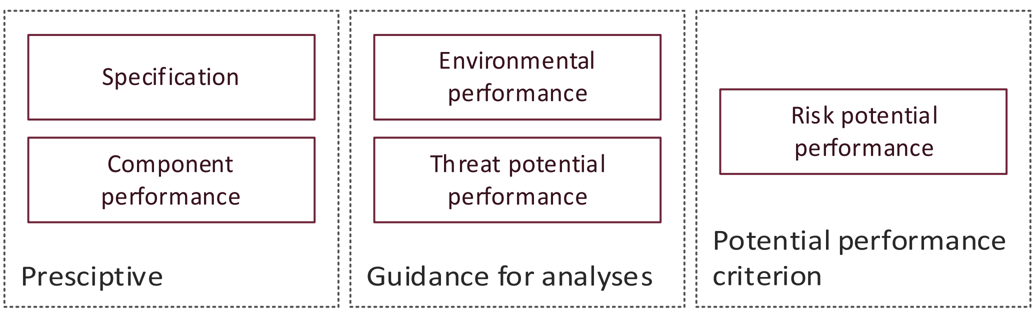
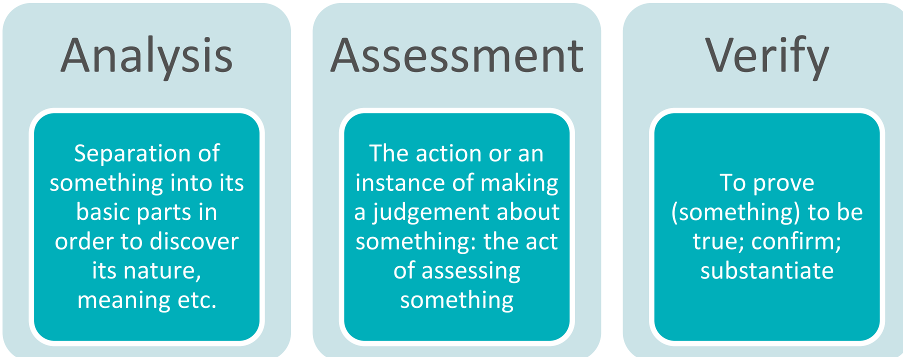


Figure 54 Summary of reviewed types of performance

6. Verification Concepts – How to Verify

Some key terms, as defined by Australian Building Code Board [122]



6.1. Introduction

Where chapter 5 has discussed different potential metrics for fire safety, chapter 6 explores how these metrics can be applied, primarily for design of buildings.

There are applications to analytical models beyond demonstrating compliance. The designer may have a need to dimension or size certain systems or components (smoke extraction or egress components), informing decisions between different design options, for insurance, or other. In this chapter, the term verification is focus, meaning the process (or the result of the process) of demonstrating compliance with functional requirements. This process does not seek to give detailed descriptions of what will happen in case of fire, but it aims to demonstrate that the safety in case of fire is addressed appropriately [123].

6.1.1. Categorisation of Verification Methods

Several attempts have been made to structure the different approaches to verification, where most seem tend to discriminate on whether the performance criteria are numerical or not (qualitative or quantitative.

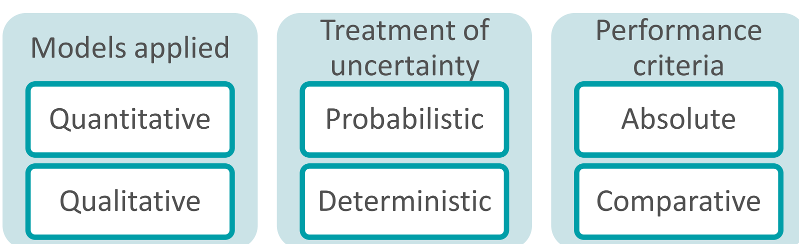


Figure 55 Typical categorisation of verification methods

Furthermore, distinction is made between probabilistic and deterministic approaches, and whether the performance criterion is an absolute value, or a reference building deemed to give satisfactory fire safety (comparative). Both ISO 23932-1 and BS 7974 have proposed the following structure to illustrate how these concepts can be combined for any verification need.

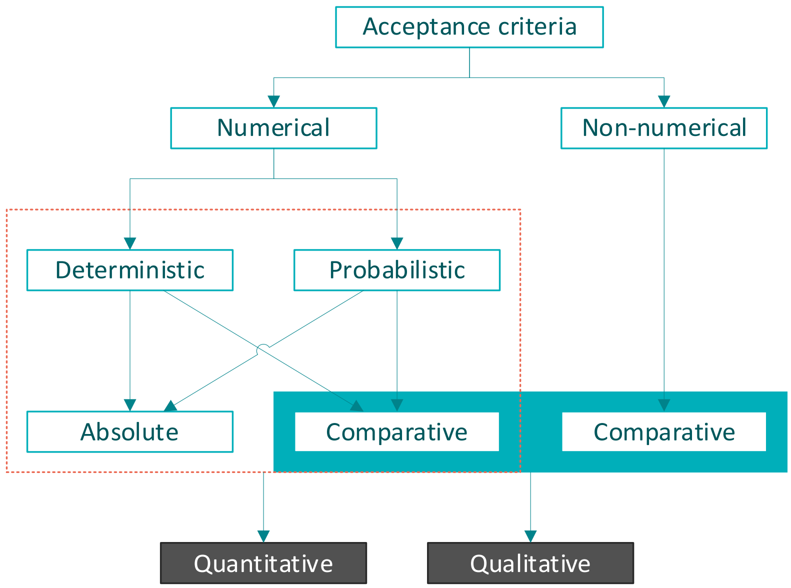


Figure 56 Categorisation of different acceptance criteria [7, 34]

These concepts are widely adopted and can thus not be neglected in chapter 6. When applying these criteria in fire safety engineering, the criteria themselves are not sufficient for categorising the verification methods. Based on the Figure 56, one is led to think that a non-numerical approach must be comparative – which is not the case.

For the discussion of verification methods other factors than the criteria are vital. As seen in Figure 57, one can categorise based on the degree of regulatory guidance is being applied – both for the fire safety concept (to what extent the design deviates from pre-accepted performance) and for the analysis.

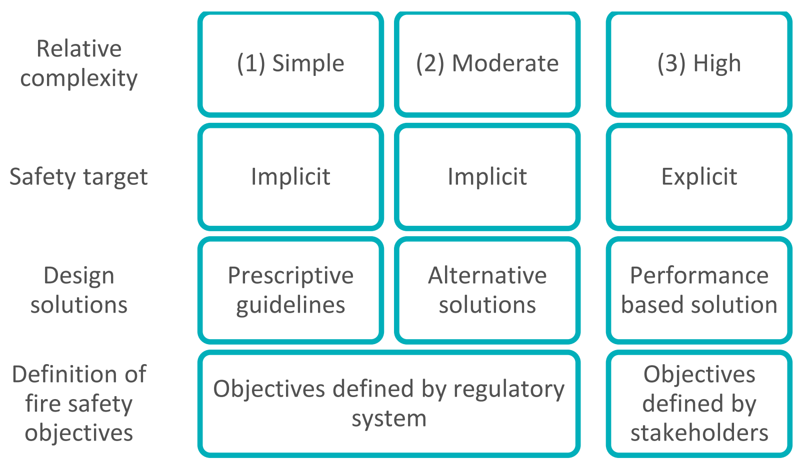


Figure 57 Ranking of verification methods based on complexity [124]

If a prescriptive or comparative approach is taken, the fire safety performance will be only explicitly assessed, as it is compared to (or is in accordance with) designs assumed to result in adequate safety.

When comparing practices internationally, it is also necessary to be aware of how differences on a systemic level affects the verification. If all input parameters for a predefined verification method are provided and mandated, the verification process will be dramatically different than if the only legally binding requirements is functional requirements.

As seen from a survey amongst European jurisdictions, reproduced in Figure 58, there is significant variation in the question of which actor is responsible for identifying appropriate design fires. From a regulator's perspective, there is no immediate need to impose detailed regulation of design fires on designers, if all design fires are to be determined or signed off by local authorities.

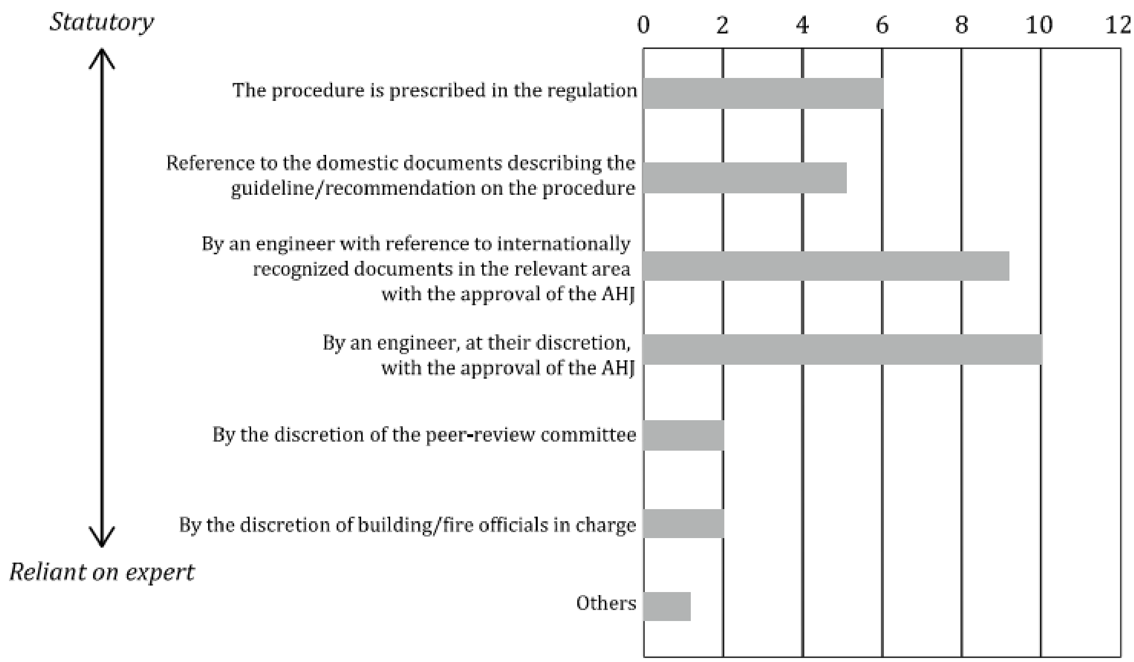


Figure 58 Answers of a survey to the question: How are the design fires determined in a performance-based fire safety design project? [3]

Similarly, authority oversight, approvals, third-party reviews, and sanctions are mechanisms which will have an influence on the domain in which the verification is conducted. These mechanisms are parts of what in this thesis is called a support structure, which entails the practitioners' competency, accountability, ethics.

Finally, verification is inherently linked to the requirements to which the analysis shall demonstrate compliance. Consequently, certain verification methods are rendered irrelevant by how the mandatory requirements are phrased. As discussed in chapter 5, the type of performance required can dictate the possible verification methods. Some requirements are global in their nature, whereas other are more specific, to the point where the verification will revolve around a single component. Similarly, some verification methods aim to give an exhaustive treatment of all objectives (e.g., risk analysis), whilst other methods have a scope limited to one or only parts of one objective (e.g., fire brigade intervention modelling).

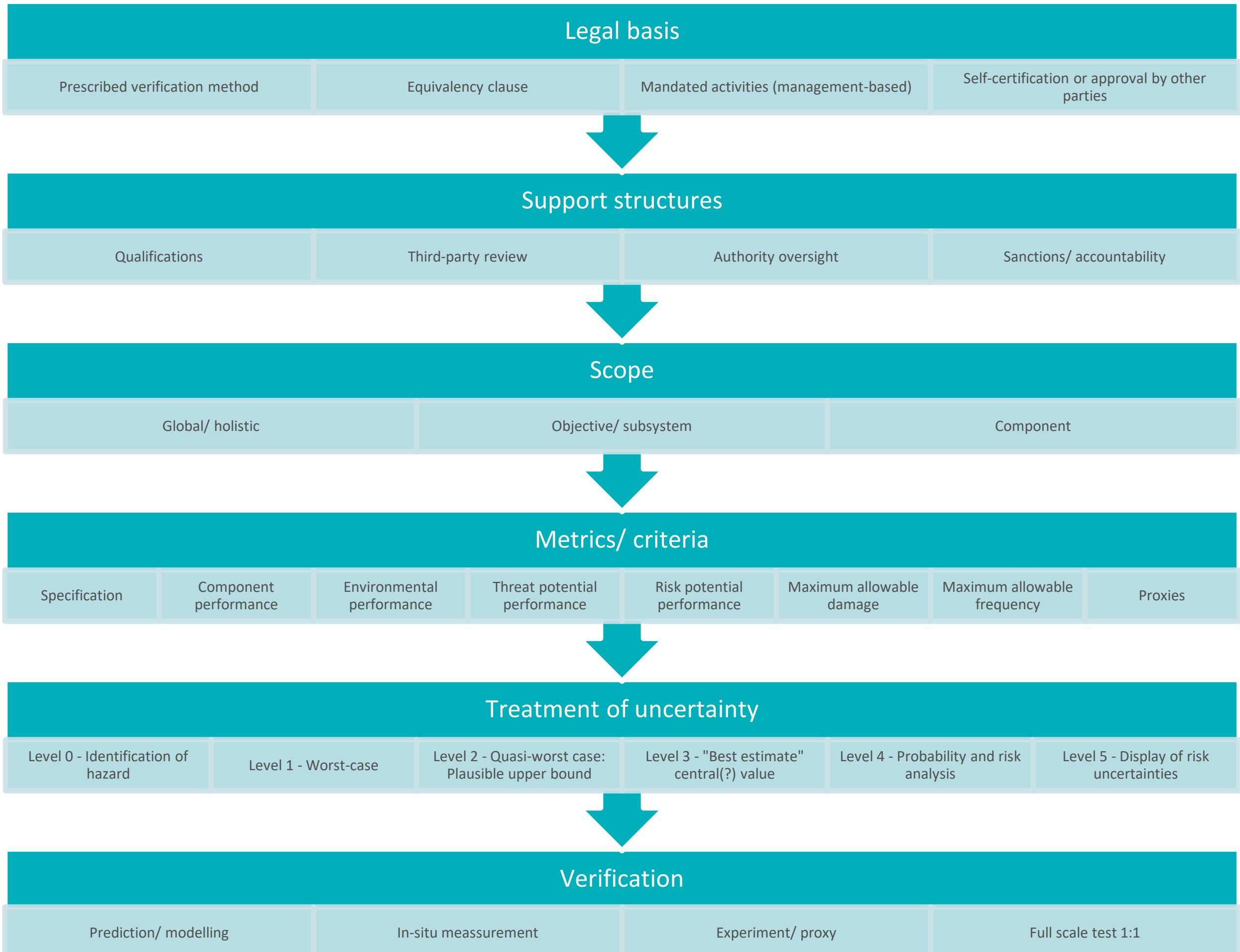


Figure 59 Further categorisation of verification approaches

6.1.2. Formal Requirements

Section 2-2 of the Norwegian building regulations set some overarching requirements for analyses demonstrating compliance with the functional requirements. In addition to requiring that the analysis must “*show that the performance levels comply with the functional requirements in the Regulation*”, the following requirements are given.

> *(3) If compliance with the Regulation's functional requirements is verified by analysis, it must be demonstrated that the method of analysis applied is suitable and valid for the purpose. The assumptions used shall be described and the reasons for using them given. The analysis shall state the necessary safety margins.*

In the guide [73], reference is given to standards for verification methods deemed acceptable, but the use of these standards is not mandatory.

6.1.3. Guidance Documents

As part of the process of quantifying the Australian National Construction Code (NCC), Arup undertook an assessment of 5 internationally available guidance documents for fire safety engineering [125]. The intention was to identify the guidance document most compatible with the Australian building legislation, so the assessment is not universally valid. 17 criteria were established under the following groups:

- Key assessment criteria
    - Scope, structure and application
    - Overall process and major components
    - Methods of evaluation
    - Variability and uncertainty
    - Documentation
- General assessment criteria
    - Compatibility with Australian context
    - Additional issues.

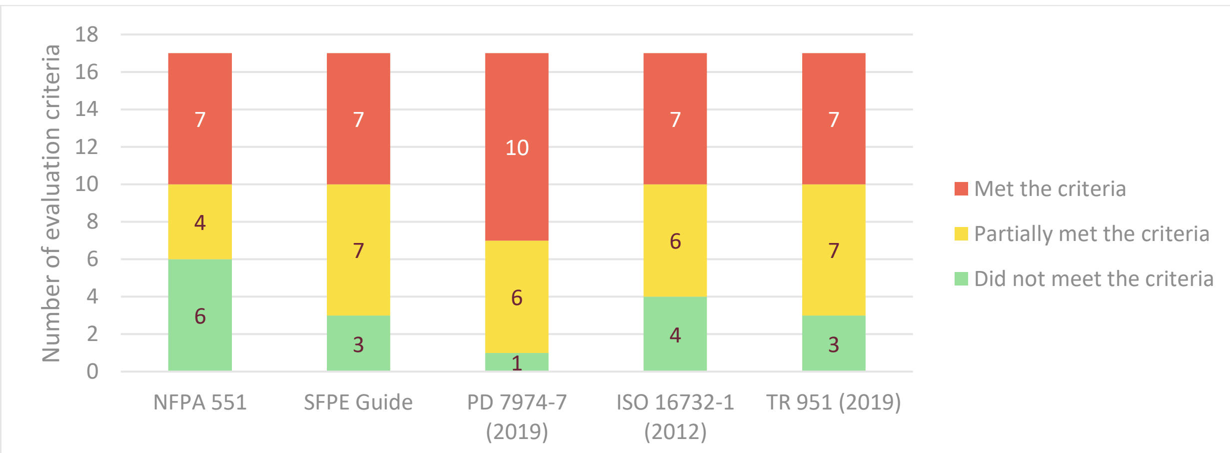


Figure 60 Summary of evaluation of five different international guidance documents [125]

From 15 years' experience in the Norwegian building, some other sources of guidance are relevant to mention:

VTEK17 [73] is not giving much guidance on how to perform an analysis but gives some supplementation to the formal requirements referred in subsection 6.1.2. Reference is made to NS 3901 [42] and INSTA 950 [1], deeming analyses in accordance with these documents acceptable.

SN-TS/INSTA 950 [1] is the result of an inter-Nordic collaboration, leading to a technical specification on comparative analysis. Being made by and for the Nordic market, it provides a reasonable benchmark, providing tenability criteria, guidance on design fires, and other information beyond the concepts of comparative analysis.

NS 3901 [42] is a national, Norwegian standard from 2012, with two alternative routes: Comparative analysis or risk assessment. The scope is wider than demonstrating compliance in new builds, giving more attention to processes than suggesting quantitative criteria or input parameters. There is a qualitative description of four fire scenarios which shall be considered.

HO-3/2007 [126], although formally withdrawn, the document has high relevance, being the most detailed description of expectations to fire safety design analyses coming from the Norwegian building authority. The document addresses municipal supervision of design, but is very useful for practitioners, giving a pragmatic approach alternative solutions – where the fire safety strategy mainly is according to pre-accepted performance levels, but one or more deviations trigger the need for an analysis.

BBRAD [127] is a guide to analytical fire safety design published by the Swedish building authority, Boverket. This guide is widely referenced in Norwegian projects, as it provides quantified properties like maximum heat release rate, growth rate, including a recommended approach in sprinklered buildings. Although the scope of this document is to demonstrate compliance with Swedish building regulations, not the Norwegian, it is assumed that these recommendations are relevant to Norwegian projects. The use of this and similar documents available from Denmark [128], New Zealand [129], and jurisdictions is discussed in subsection 8.5.3.

6.1.4. Validity and Accuracy of Models and Data

The analytical approach to fire safety design requires predictive models to quantify the likelihood, consequences, or risk of fire. Thus, a central question emerges: What is the method's ability to predict the behaviour of the product or system under real conditions? To a varying degree, these models require simplifications, assumptions, or the use of proxies to obtain results. Ideally, one should simplify as much as possible, but not beyond the point where the model no longer is able to give reasonable predictions [88]. Where is this cut-off point?

BS 7974 points to the following as main sources of uncertainty:

- Limitations of empirical relationships.
- Necessary simplifications in the modelling.
- Input parameters.

Limitations of empirical relationships is a term including the lack of scientific models to accurately represent the phenomenon. This can be due to lack of understanding, or it can be driven by the random nature of the phenomenon or one of the involved aspects. Within fire science, randomness is considerable contributor to uncertainty, as seen when experiments are repeated, even in highly controlled environments. Furthermore, there are shortcomings of the available models' ability to model human behaviour, under-ventilated fires, glass breakage, the effects of suppression systems, and many other key features of a fire safety strategy.

Necessary simplifications make quantification possible within an acceptable time frame/ cost, but the resulting uncertainty may be considerable. Within enclosure fire dynamics, a common simplification is the two-zone assumption, where the upper and lower layers are individually treated as homogenous. For enclosures where the fire is large relative to the volume, this assumption represents reality well, whereas it is known that less buoyant fire scenarios cannot be modelled under the same simplification. Similarly, the immense number of possible design fire scenarios and egress scenarios will in most situations have to be reduced to a manageable amount to allow for quantification. One can also find a dilemma where the analyst must choose between high resolution (level of detail per scenario) or giving a balanced representation of the variance in possible scenarios.

Input parameters

The Dalmarnock fire tests [63] and more than one round robin performed at Lund university [62] have clearly demonstrated how different practitioners will assess differently the appropriate input parameters for fire safety engineering, even where there is an abundance of information available. This challenge must be seen as an addition to the challenge of data scarcity, where fire frequencies, reliability/ efficiency data for fire safety systems, human behaviour in fires, and many other central phenomena are inadequately measured, monitored, and shared [130, 12].

6.2. Treatment of Uncertainty

For fire safety engineering treatment of uncertainty is an essential concept. The degree of uncertainty for design is also substantially different from the uncertainty experienced in fire investigations or research. In this section, an introduction to the concept of uncertainty will be reviewed in the context of verifying fire safety performance.

6.2.1. Types of Uncertainty

Many terms are used to describe the different types of uncertainty, but according to the SFPE Handbook [20], it is increasingly common to mainly use two main categories, as discussed in the following.

- Aleatory Uncertainty (also called variability, randomness, or stochastic uncertainty [115])
- Epistemic Uncertainty (also called fundamental or knowledge uncertainty [115])

Aleatory Uncertainty

Uncertainty where the source primarily is the random nature of the phenomena being studied is called aleatory uncertainty. For fire safety engineering, this would include turbulence, time of day for occurrence of fire, successful operation of a fire safety systems on demand, walking speed of occupants, etc.

Epistemic Uncertainty

Uncertainty mainly originating in the incompleteness of knowledge is epistemic uncertainty. This knowledge is conceptually assumed to be obtainable, but it is simply not available or complete to the analyst. The models used in verification are made to represent real events, which we only partially can model, and in some instances, we use models with known limitations or simplifications to obtain results. This ads to the epistemic uncertainty of the analysis.

Accumulation of Uncertainty

Uncertainty can come from the application of a calculation model, the input, or from many other sources. Before looking further into different ways of treating uncertainty, it is of use to be aware that the uncertainty may be interlinked in different ways.

Let us demonstrate by a simple example, using the point source model to estimate the radiation from a fire. We are uncertain about several parameters, so these are treated as random variables, using triangular distributions, as seen in

$$\dot{q}" = \frac{\dot{Q}\chi\cos\theta}{4\pi R^2} \qquad \textit{Eq. 8}$$

, where $\dot{q}"$ is the radiative flux [kW/m²] and other nomenclature is shown in Table 10.

Table 10 Nomenclature and values used for example in Eq. 8

Symbol	Parameter	Unit	***Distribution*** **Variables**	Graph
$\dot{Q}$	Heat release rate	kW	*Triangular* Min: 1 000 Mode: 1 500 Max: 2 000	
χ	Radiative fraction	-	*Triangular* Min: 0.2 Mode: 0.3 Max: 0.4	
θ	Angle off horizontal	rad	*Constant* 0	
R	Radial distance to target	m	*Triangular* Min: 1 000 Mode: 1 500 Max: 2 000	

The calculated resulting radiative flux is shown in Figure 61.

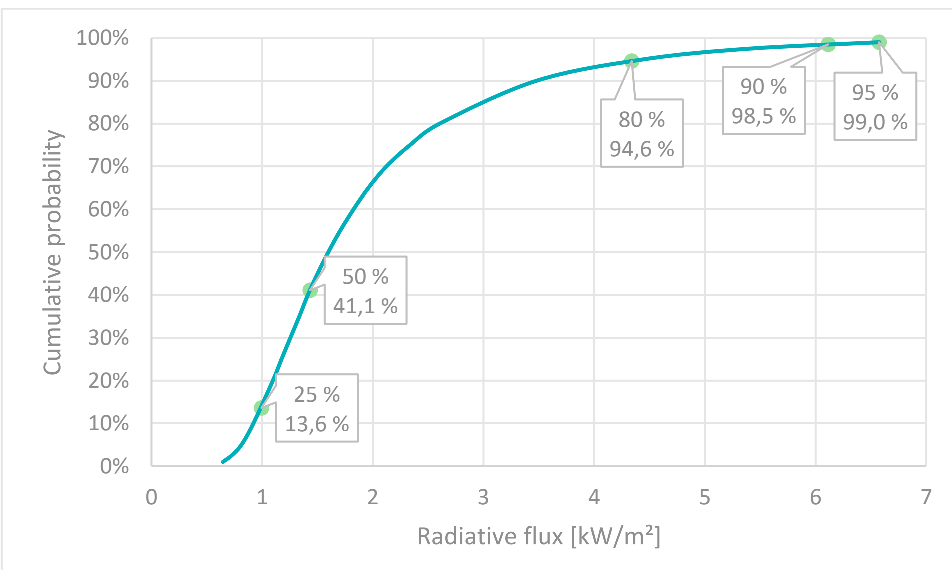


Figure 61 Cumulative distribution for the calculation of radiative flux, using the point source model of Eq. 8 and input parameters as described in Table 10

The dots and callouts in Figure 61 show points where all random parameters are set to some selected confidence levels. As a consequence of the asymmetric distribution on radial distance, the most probable value for each variable does not equate the cumulative probability of 50 % for the calculation result. Similarly, when applying the 90th percentile for each input variable, the resulting confidence level is at 99 %.

For this simple example, it is possible for the analyst to keep track of the parameters, and to see and understand how they are interlinked.

6.2.2. Six Levels of Treatment

If the first step is to acknowledge that our knowledge and ability to model future events is imperfect, the natural second step would be to find mechanisms to treat this uncertainty. A structure for different treatments has been proposed by Paté-Cornell [131], as presented in Figure 62, and discussed thereafter.

Level 0
- Identification of hazard

Level 1
- Worst-case

Level 2
- Quasi-worst case: Plausible upper bound

Level 3
- "Best estimate" central(?) value

Level 4
- Probability and risk analysis

Level 5
- Display of risk uncertainties

Figure 62 Six levels of uncertainty treatment [131]

Throughout this thesis, levels 0-3 are categorised as deterministic, whereas levels 4 and 5 are categorised probabilistic.

Level 0 – Identification of Hazard

Level 0 simply involves identifying a hazard. For fire safety, this goes beyond the chance of a fire occurring – It will involve acknowledging that certain fire safety systems may fail, or that other prerequisites defined for the analysis may fail (e.g., fire load, occupancy type). The further treatment on level 0 will typically be a qualitative analysis, or mitigating measures can be decided based on the existence of the hazard if the costs are low compared to the risk reduction.

Level 1 – Worst-Case Approach

Level 1 means disregarding probability and basing decisions on the worst comprehendible set of assumptions. Paté-Cornell points out that this approach is challenged by the fact that it almost always possible to adjust any assumption in a more conservative direction – to the point where the scenario no longer is realistic, or where the design is no longer adequate to meet the harsh scenario.

The approach, or a variant thereof, may be relevant where the potential consequences are deemed so high that low likelihood alone is not sufficient justification for the design. See subsection 6.8.5 on Maximum Allowable Damage (MAD).

Level 2 – Worst Credible Case

Paté-Cornell uses the terms "plausible upper bounds" and "quasi-worst case", but within fire safety engineering, this concept is usually referred to as worst credible case. The meaning of the phrase is nonetheless a conservative assumption, but not to the point of level 1, where it is unrealistic. Examples are "1 000-year storms", "200-year floods", and the 95th percentile, although the worst credible case usually is estimated without any quantification of its probability.

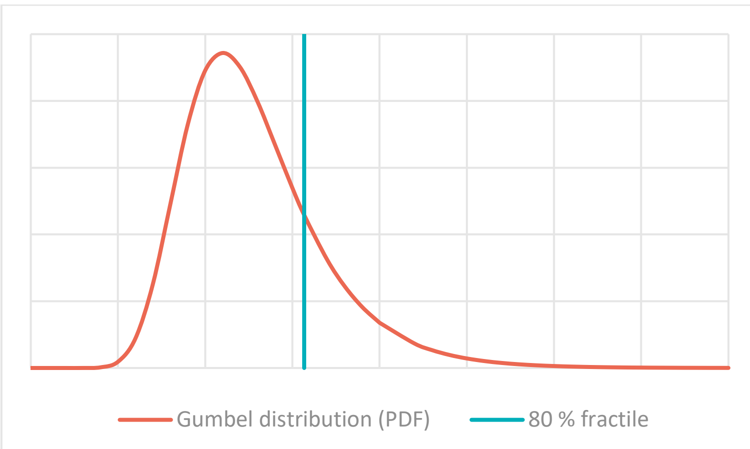


Figure 63 Type II gumbel distribution, highlighting the 80 % fractile

This approach can be seen in the calculation of fire load densities, where fire load densities for different occupancy types are described as gumbel distributions [92], and Byggforsk 321.051 propose the use of fire load factors not to be exceeded more than 20 % of the time of operation for the building [132].

Extreme value distributions are relevant for many aspects of fire safety, where the "tail" of the distribution indicate that significantly more conservative values than best estimates are possible. The challenge with the worst credible case approach, is thus, how far in the conservative direction is appropriate? As also pointed out by Paté-Cornell, there is no way of judging the conservatism applied, and it will be challenging to compare risk, seeing that the probability is not specified.

Lastly, as will be further discussed in section 8.3 and 8.2.6, what happens if an event occurs, which by the worst credible case-approach is infrequent enough to disregard it?

Level 3 – Best Estimate

Best estimate, or central value, means aiming for estimating the risk of the most probable outcome. As seen in Figure 64, asymmetrical distributions will have a mode that deviates from its mean value. Here Paté-Cornell states that the median may be more useful, as the mean is sensitive to extreme values.

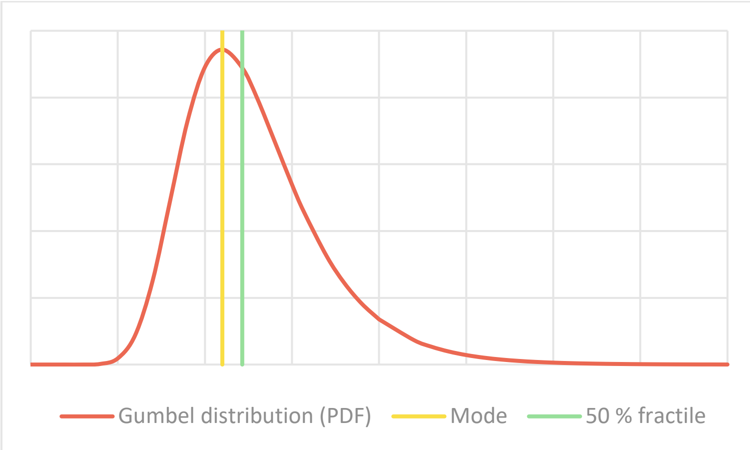


Figure 64 Type II gumbel distribution, highlighting the mode and 50 % fractile

For many risks, fire included, the most probable is that an event will not occur, like a logarithmic probability distribution of fire damage, where the most likely is no fire (no damage) and increasing fire damage will have increasing probability.

The approach can still have a place in fire safety engineering, e.g., for estimation of maximum unimpeded walking speed of a population, or the most likely outcome, given one failing barrier.

This approach is still limited by being based on single value estimations, and thus giving a non-transparent picture of the uncertainty.

Level 4 – Probability and Risk Analysis

Level 4 is probabilistic risk analysis (PRA) or quantitative risk assessment (QRA). Simplifications can be made to only include aleatory uncertainties (see subsection 6.2.1), or epistemic uncertainty may also be quantified. The analyst will define probability distributions, which are best estimates of the random variable. A simple example of which is given in the discussion of Accumulation of Uncertainty on page 107.

As opposed to previous approaches, PRA allows for communicating the span of possible outcomes, and their respective probabilities.

INSTA 951 was published to promote probabilistic approaches in fire safety engineering and can serve as a starting point for applying these techniques [78].

Level 5 – Display of Uncertainties

Level 5 involves displaying a family of curves, which either represent different hypothesis for the same variable, or different variables, where their interaction is kept separate. In INSTA 951 this is exemplified by bi-variate treatment of available safe egress time (ASET) and required safe egress time (RSET), as seen in Figure 65 – see also subsection 6.8.2.

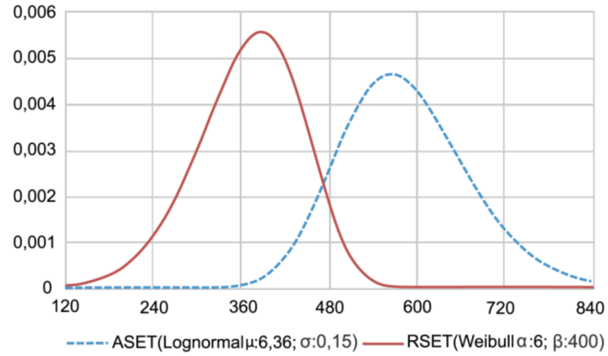


Figure 65 Example of available and required safe egress time displayed as two curves [78]

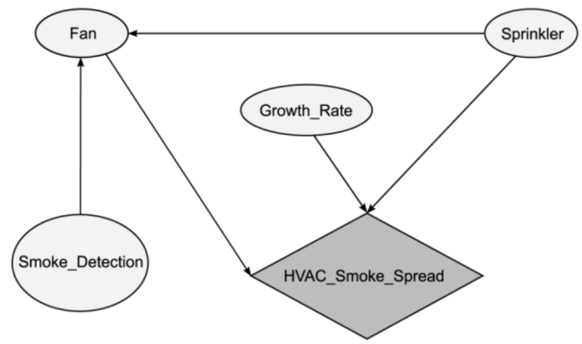


Figure 66 Influence diagram, where probability distributions can be used to represent different states [78]

Figure 66 shows a simple influence diagram for a fan operating during fire. Statistical tools like Bayesian networks may serve as useful means of treating and communicating uncertainty in fire safety engineering.

Level 5 treatment of uncertainty is referred to as “secondary probabilities”, as it deals with uncertainty in estimating probabilities, an example of which is describing the reliability of sprinklers as a normal distribution where $\mu = 0.86$ and $\sigma = 0.046$ [78]. This is a concept which is highly relevant to fire safety engineering, as reliable, fresh, local, relevant data is scarce or non-existing. Thus, the analyst may use probability distributions to allow the uncertainty to be reflected in the results. Where relevant data is lacking, simple, triangular distributions as seen in Table 10 on page 108 will be superior to assuming one single value.

6.2.3. Concluding Remarks on Uncertainty

Uncertainty is an integral component of fire safety engineering, whether it is quantified or not. Some practitioners find probabilistic approaches difficult, as they do not convey the same clear distinction between acceptable and unacceptable, as can be seen in deterministic approaches. The benefit is however the ability to communicate the uncertainty, and to be verbal about the residual risk.

Communication is another challenge when applying more complex models. A good example of transparency in uncertainty is seen in Figure 67, where complex meteorological modelling is condensed into a curve showing the predicted temperatures over time. Without any training or expertise, the reader can understand the estimates, and the associated uncertainties.

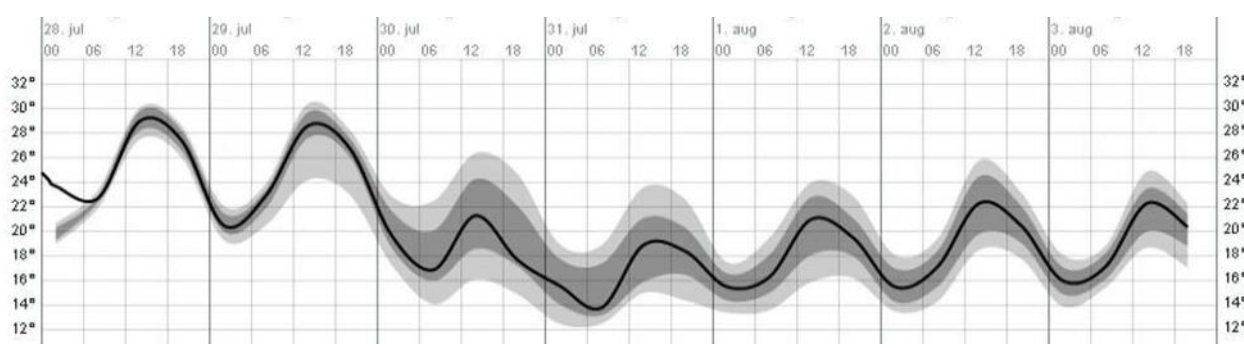


Figure 67 Example of how results can be presented, also displaying uncertainty.

As seen through the presentation of Patè-Cornell's Six Levels of Treatment, their input parameters and risk acceptance are intertwined. Consequently, regulators cannot rigorously control the resulting level of safety with performance levels alone if the designer is free to choose the level of conservatism for the design fires or other uncertain input parameters. Through chapter 6 we will see if a similar interconnection exists for verification concepts.

6.3. Pre-Accepted Performance Levels

In terms of demonstrating compliance, the application of pre-accepted performance levels is the least complex. As per TEK section 2-2, no analysis nor verification is required when the design is in accordance with the pre-accepted performance levels [5].

6.4. Qualitative Analysis

Qualitative analysis is a term used here to characterise non-numerical, or predominantly non-numerical analyses, aiming to demonstrate compliance with a functional requirement. It is defined in ISO 23932-1 as [31]:

Risk analysis approach in which areas of increased risk are identified

As we will see, they come in many forms, and can be found to be less formal or less structured than quantitative approaches.

Qualitative analysis will typically serve one or two purposes:

1. The first identification of hazards, fire scenarios, and other forms of basis for a further (quantitative) analysis [1, 42], or
2. The only analysis provided, where a qualitative analysis is considered adequate [42, 126, 133].

With the exemption of Comparative Pseudo-Analysis, section 6.4 will primarily deal with the latter.

6.4.1. When is a Qualitative Analysis Enough?

The required extent of an analysis is a returning question in building projects, and a topic difficult to effectively regulate. The Norwegian building authority have given the following advice in the guide to the building regulations' section 2-2 (relevant to all chapters of the regulations) [73]:

Formålet med en analyse er ikke å produsere mest mulig "papir", men å vise på en systematisk og oversiktlig måte hvordan funksjonskravene er oppfylt der de preaksepterte ytelsene ikke er lagt til grunn. I noen tilfeller vil en enkel faglig vurdering eller et logisk

The purpose of an analysis is not to produce as much "paper" as possible, but to demonstrate in a systematic and clear manner how the functional requirements are fulfilled when the pre-accepted performance criteria are not applied. In some cases, a simple professional

resonnement, eventuelt med referanse til rapporter eller lignende, være tilstrekkelig.	*assessment or logical reasoning, possibly with reference to reports or similar sources, may be sufficient.*

Here, the extents are not clearly described, and no guidance as to when a simpler approach is possible is given. The possibility of simplifying the analysis is however clear, provided that the analysis can demonstrate compliance with the functional requirements.

A separate paragraph of the guide to the same section of the regulations specifies the following, for safety in case of fire) [73]:

Rent kvalitative scenarioanalyser kan bare benyttes i ukompliserte byggverk der det er små fravik fra de preaksepterte ytelsene, og der fravikene i liten grad påvirker personrisikoen. En kvalitativ analyse må være underbygget av statistikk, erfaring, tilgjengelige rapporter mv. med konkrete referanser.	*Purely qualitative scenario analyses can only be used in uncomplicated buildings where there are minor deviations from the pre-accepted performance levels, and where these deviations have a minimal impact on life safety. A qualitative analysis must be supported by statistics, experience, available reports, etc., with specific references.*

Interestingly, a significantly more strict and restrictive language is being used. The message is repeated in the national standard for fire risk assessment [42] and SINTEF Byggforsk [133], with similar wording also found in HO-3/2007 [126].

It can be disputed whether it is a requirement, but at least it is good practice to support the qualitative assessments with references to statistics (e.g., loss reduction in sprinklered buildings), experience (e.g., evidence from fire investigations), or reports (e.g., articles or reports from recognised sources, where the topic is addressed). Conversely, if support is not found in sources as mentioned above, more justification is required.

All these four Norwegian guides and BS 7974 also indicate the need to consider other means of analysis in cases of complexity or where there is significant distance between the trial design and the pre-accepted performance levels or solutions.

HO-3/2007 recognises that qualitative analysis may be the only viable verification method in certain situations [126]. This is not acknowledged by the other three, where qualitative analysis is depicted more as the less capable “little brother” of quantitative analysis. For quantitative analysis to be a viable verification method, 1) the relevant phenomena must be quantifiable with available tools with acceptable levels of uncertainty, and 2) the quantification must translate into unambiguous verification of compliance with a functional requirement.

6.4.2. Expert Judgement

Qualitative analysis will in most cases involve judgement of a fire safety professional. Thus, both the competency and integrity of this professional is of utmost importance [42, 7, 134, 30].

The qualitative analysis will in most cases take the form of logical reasoning by addressing the functional requirement, by analysing scenarios (ch. 6.4.3), by applying comparative arguments (ch. 6.4.4) or a combination.

Four different forms of logic are presented in Figure 68.

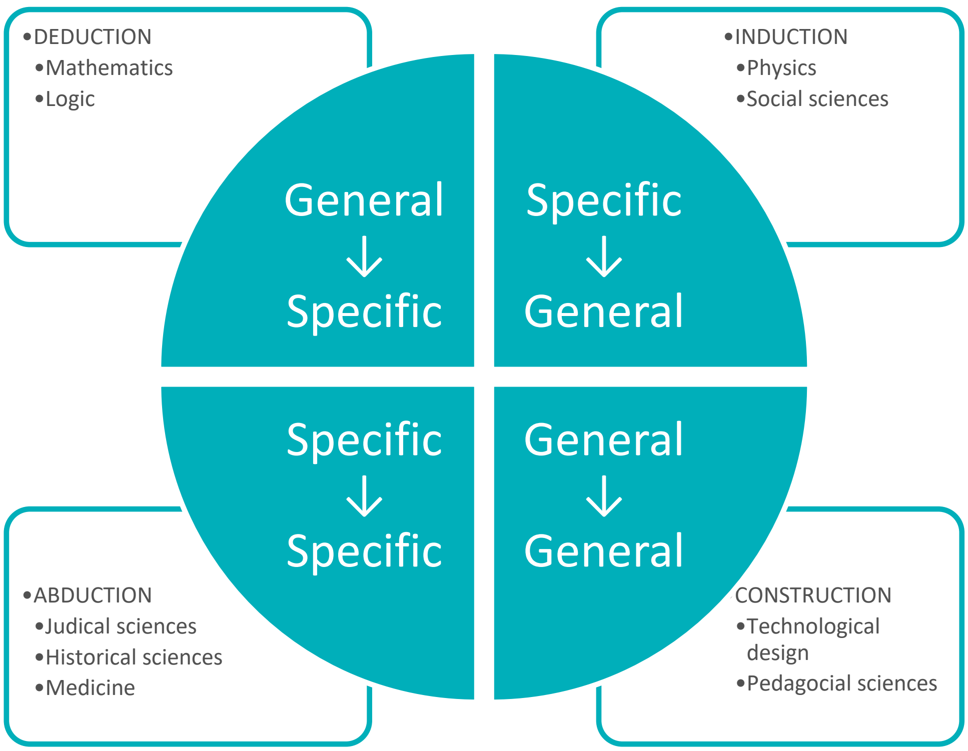


Figure 68 Four forms of logic [21]

It is worth noticing the fundamental difference between design and investigation of fires. Investigations will use abduction to find reasons for the specific outcome of a fire. For design, however, the aim is to from a goal construct a fire strategy meeting certain functional requirements. A near limitless number of alternatives may meet the goal, and thus variability is expected. Investigations, on the other hand, will aim for the one true cause of events. Stoop et.al describe the use of construction, and state the following [21]:

> *Predictions to the actual performance of an artefact have to be postponed to the phase of operations in the intended environment. There are no formal algorithms and operating procedures that define a correct and exclusive solution.*

The term expert judgement is not meant to allow for fire safety professionals to act on their gut feeling. As mentioned, they are expected to be able to support their judgement by reference to statistics, reports or other reliable sources, and as seen from the formal requirements, the assessment shall be documented in writing.

Qualitative analysis may also refer to practice in other jurisdictions [126], and by doing so rendering compliance probable, especially in case where other jurisdictions have more specific guidance than what is found nationally. One example could be means of egress from special-purpose industrial occupancies, which is explicitly described in NFPA 101 [8] as being ”*characterized by a relatively low density of employee population, with much of the area occupied by machinery or equipment*“, whilst the guide to the Norwegian building regulations make no distinction between these occupancy types and other industrial or business occupancies.

6.4.3. Qualitative Scenario Analysis

Qualitative scenario analysis or consequence analysis should include [126]:

- Specification of each deviation from pre-accepted performance levels
- Description of compensating measures
- An assessment of the consequences of all deviations with regards to
    - Life safety
    - Property protection
    - Fire service safety
    - Access for rescue, and firefighting efforts.

Seeing that there may be more than one deviation from pre-accepted performance levels, the scenario analysis may consist of more than one analysis, which in combination with the qualitative arguments shall make it clear to the reader that the functional requirements are met.

This approach is most relevant, although not exclusive to designs predominantly complying with pre-accepted performance levels, but where some deviations are made. As seen from the bullet list above, the scenario analysis will in most cases focus on how the trial design differs from the pre-accepted solution, and based on e.g., sprinkler performance statistics describe how a sprinklered building (with some deviations) is expected to perform compared to a non-sprinklered reference building.

Qualitative scenario analysis may however be absolute in nature, not being reliant on pre-accepted performance levels. An example can be the use of statistics or literature on fire service arrival times, compared to the required fire resistance of load-bearing structures. Another approach could be to describe or produce an event tree or fault tree to describe the inherent robustness of the fire strategy. Without quantifying the robustness of a reference building, the analyst may find sufficient grounds to deem the design adequate.

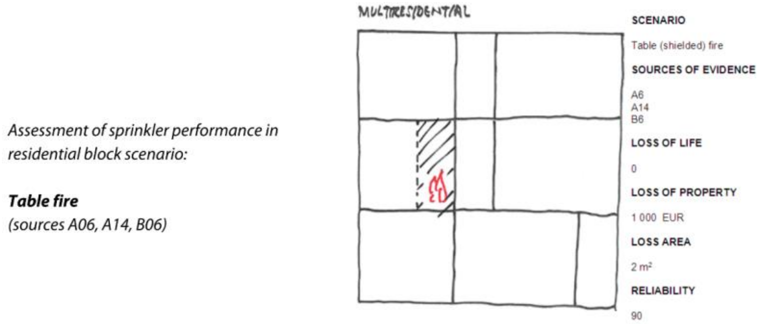


Figure 69 Example of qualitative analysis informed by literature [135]

As exemplified in Figure 69, a qualitative analysis may be a highly effective and transparent way of analysing a fire safety design, when relevant literature is found. The analyst must be able to identify these sources, and set them in a context, relevant to the design being assessed.

6.4.4. Comparative Qualitative Analysis

The principles of comparative analysis are further explained in INSTA 950 [1] and section 6.5 of this thesis, but here the focus is on qualitative analysis. For comparative qualitative analysis the key premise is that a pre-accepted performance level exists and is valid for a building reminiscent of the trial design. Thus, if the analyst can provide arguments to demonstrate that the trial design is at least equally safe, the trial design is acceptable.

In many instances it will be relevant to follow the steps of a qualitative scenario analysis, as shown in subsection 6.4.3, but this is not always required or the most rational way forward. The key to this approach is to dissect how the deviation affects the performance – not to quantify or otherwise objectively explain the overall fire safety.

6.4.5. Comparative Pseudo-Analysis

A common way of reasoning, albeit not a structured method of analysis, is applied where the trial design technically is not in compliance with the pre-accepted performance levels or solutions, but where a minuscule or insignificant change to the design would give compliance. Furthermore, this approach is used where it is obvious that the trial design will perform better than a hypothetical design in line with pre-accepted performance levels.

6.4.6. QDR – Qualitative Design Review

Although qualitative design review is mentioned in other sources [1, 136], BS 7974 gives the fullest description of the intended process and provides the most structured approach. As with other forms of qualitative analysis, QDR can form the only demonstration of compliance, but the focus here is to establish and align the basis for a more thorough analysis. BS 7974 describe the fire safety engineering process by the following steps [7]:

1. Qualitative design review,
2. Performing the analysis
3. Assessment against acceptance criteria
4. Internal peer review, quality assurance
5. Reporting and presentation of results
6. External peer review/approval.

The process is described as more involving than what is practiced in most Norwegian building projects. As seen in chapter 2, self-certification, whereas other jurisdictions have authority involvement both in the final approval and for milestones leading to final approval. NS 3901 also include stakeholder management [42], but for many building projects, verification is seen as a single-discipline activity. The steps in the QDR process are nonetheless relevant.

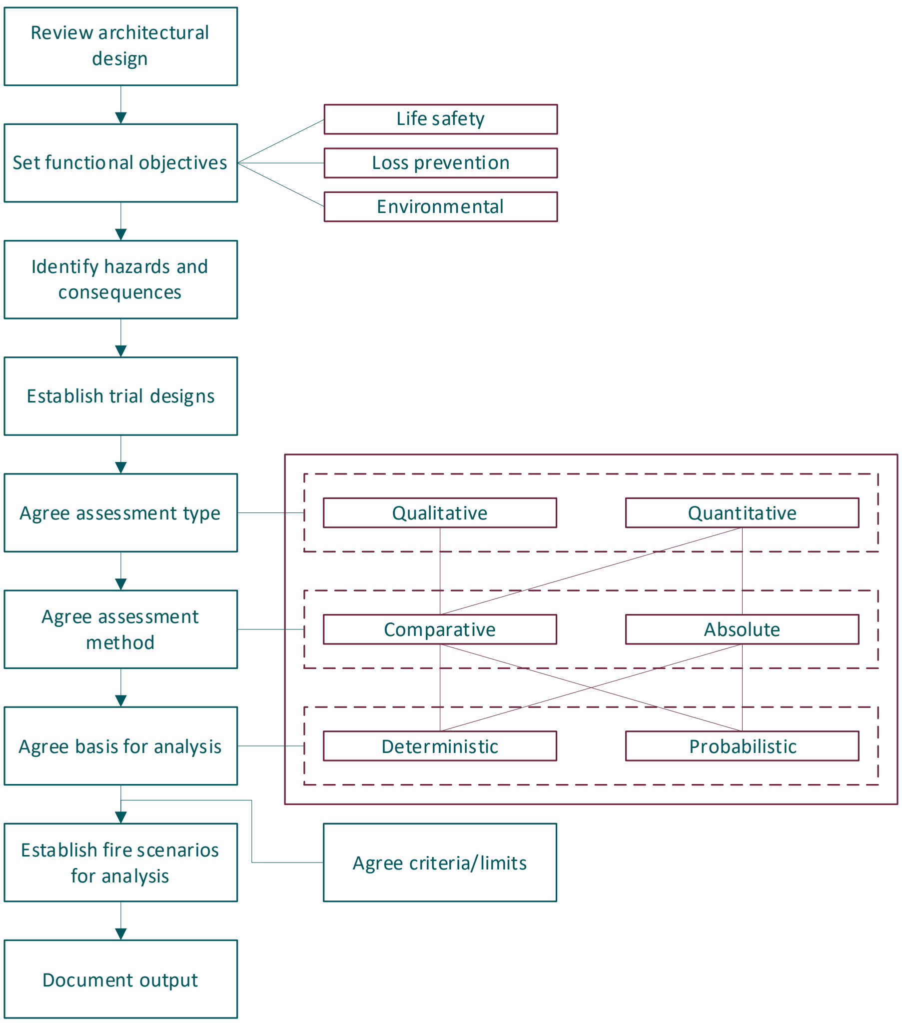


Figure 70 The process of qualitative design review, QDR, reproduced from [7]

Formalising the qualitative design review, may give several positive effects:

- Better structure and more use of cited sources as input to subsequent analyses.
- Reduction of project risk, as more of the analysis is performed at an early stage, where change is less likely to give adverse effects on cost and time schedule.
- A natural milestone to perform quality assurance and align expectations, criteria, and assumptions, prior to spending many resources on quantitative techniques.
- If communicated clearly, also non-professionals within fire safety should be able to question or express concerns about assumptions posing unacceptable constrains or limitations on the use of

the final building. This can avoid unreasonable limitations to the design, but will also reduce the pressure on the analyst, by involving other stakeholders in deciding the appropriate assumptions for the analysis.

6.5. Comparative Analysis

6.5.1. Key Concepts

As seen in section 6.4, qualitative analyses often use comparative arguments. The approach discussed in this section is however a structured analysis, primarily quantitative, where compliance is demonstrated if the trial design performs at least equal to a reference building. Key to this concept is that this reference building is in accordance with pre-accepted performance levels and solutions, or otherwise represents a known acceptable design. The reference building shall be realistic, buildable, and be as close as possible to the trial design [1].

6.5.2. Analytical Tools and Techniques

The analytical tools used for comparative analyses will vary, depending on the objective of the analysis – or where the trial design deviates from the pre-accepted performance levels. If the trial design is in accordance with all pre-accepted performance levels, except egress widths, the analysis can be limited to this, deeming all unaffected aspects of the fire strategy acceptable (e.g., load-bearing structures, and even available safe egress time).

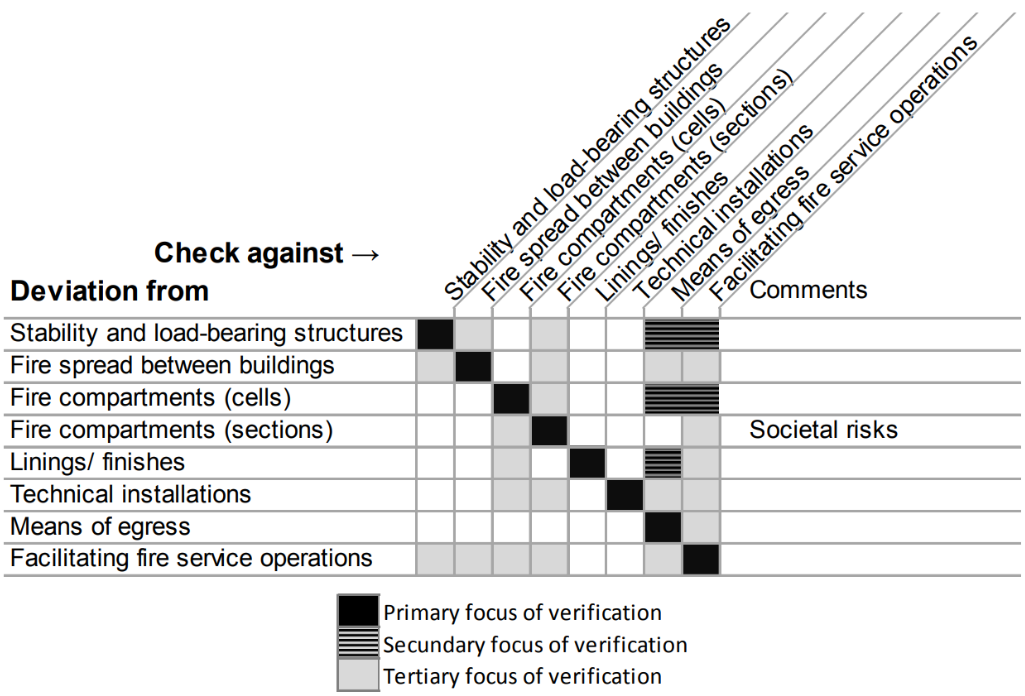


Figure 71 Matrix indicating interaction between subsystems reproduced from [1]

Naturally, a deviation from the pre-accepted performance levels will necessitate an analysis of means of egress, but as seen in Figure 71, one also must look for possible secondary and tertiary effects of the deviation, like safe access for the fire service.

The chosen performance criteria and strategy for treating uncertainties will further dictate whether to conduct the comparative analysis as a deterministic (ch. 6.6) or probabilistic analysis (ch. 6.7).

6.5.3. One or Many Analyses?

In a qualitative comparative analysis, the analyst is required to make a holistic assessment of the fire safety strategy, including all deviations from pre-accepted performance levels. The main portion of the analysis will however be on each individual deviation.

For a quantitative comparative analysis, the analyst should as a minimum include all deviations affecting the same objective(s) into one analysis. It is not uncommon to apply different verification methods to different objectives, e.g., a comparative analysis for property protection and a life safety evaluation based on deterministic analysis of available and required safe egress time (ASET RSET).

6.5.4. Risk Indices

Risk indices, or risk ranking, is a concept that has been around for decades, but not gaining much traction in the Norwegian building industry, despite advocacy from the national building authority [45]. This approach cannot be seen as a deterministic model, as it does not apply science-based mathematical expressions but must be seen as a semi-quantitative comparative approach.

The concept involves checklist where features of the building are given scores. The model provides a weighting of properties of the building, the presence and state of fire safety systems, etc.

Health authority:
Building: Victoria Hospital
Survey volume: Ward 1
Date of survey:
Surveyor:
Number of bedspaces: 30

Component		*Grade*	*Percentage Contribution*	*Score*
01	Staff	0 1 2 (3) 4 5 X	9	27
02	Patients and Visitors	0 1 (2) 3 4 5 X	6	12
03	Factors affecting smoke movement	0 1 2 (3) 4 5 X	7	21
04	Protected areas	0 1 2 3 4 (5) X	6	30
05	Ducts, shafts and cavities	0 1 2 3 (4) 5 X	4	16
06	Hazard protection	0 1 2 3 4 (5) X	7	35
07	Interior finish	0 1 2 (3) 4 5 X	5	15
08	Furnishings	0 1 2 (3) 4 5 X	6	18
09	Access to protected areas	0 1 2 3 (4) 5 X	4	16
10	Direct external egress	0 1 2 3 (4) 5 X	4	16
11	Travel distance	0 1 2 (3) 4 5 X	5	15
12	Staircases	0 1 2 3 4 (5) X	5	25
13	Corridors	0 1 2 3 4 (5) X	5	25
14	Lifts	0 1 2 3 4 (5) X	3	15
15	Communications systems	0 1 (2) 3 4 5 X	5	10
16	Signs and Fire Notices	0 1 2 (3) 4 5 X	4	12
17	Manual firefighting equipment	0 1 2 3 (4) 5 X	3	12
18	Escape lighting	0 1 (2) 3 4 5 X	5	10
19	Automatic suppression	(0) 1 2 3 4 5 X	3	0
20	Fire Brigade	0 1 2 3 4 (5) X	4	20
		TOTAL SCORE (out of 500)		350

Figure 72 Example of summary sheet for a risk index model [137, p. 67]

Figure 72 shows how the user gives a grade to the different components, and the percentage contribution to the total score is given by the model. Using the same approach, one can determine how different fire safety systems and components of a fire safety strategy contributes to the total fire safety of a building.

Design alternative	Risk index
Concrete frame (acceptance level)	2.81
Timber frame, three sections, EI 60 and R 60	2.40
Timber frame + sprinkler system, EI 30 and R 30	2.34

Figure 73 Example of comparative assessment between a reference building and two alternative solutions [45]

As shown in Figure 73, the model is intended to give a ranking to alternative trial designs – one of which can be according to pre-accepted performance levels, thus providing a benchmark reference building.

The approach is highly sensitive to the scores and weight attributed to each component, so using a Delphi panel to determine these may be beneficial [45]. The above examples are grossly simplified, and thus of limited use to fire safety engineering. If a more comprehensive model was to be established, the workload for the experts in a Delphi panel would be immense, and it would be challenging to keep the model up to date as new fire safety technology, risks, and knowledge emerges.

6.5.5. Remarks on Comparative Analysis

There are some paradoxes involved in comparative analysis. Conservatives may prefer comparative analyses, because it creates a bridge to well-known concepts, thus reducing uncertainty. Verification against absolute criteria would however give a clearer picture of the fire risk, while comparative analysis is limited to implicit description of risk [138].

Comparative analysis may also reveal weaknesses of the deemed-to-satisfy solutions. A performance criterion for a comparative analysis could be to have a safety margin (available safe egress time – required safe egress time) at least equal to a reference building in accordance with pre-accepted performance levels. The analyst could demonstrate compliance even if both building were found to have negative safety margins, provided the margin is better in the trial design. There are no incentives to further improve the design where the design meets the criterion, as further discussed in subsection 8.2.7.

6.6. Deterministic Analysis

ISO 23932-1 defines deterministic analysis as [34]:

Risk analysis approach in which the fire safety design is evaluated using a set of worst credible case scenarios.

Firstly, it is interesting to see ISO acknowledging deterministic analysis as a risk analysis approach, considering how it previously has been seen as the counterpart to risk analysis. This is however in line with the treatment of uncertainties discussed in section 6.2, acknowledging that the inherent uncertainties of fire safety design, forces the analyst to assess probabilities, whether they are quantified or not.

Quantification through deterministic analysis can also be done without the aim of demonstrating compliance. Deterministic analysis may be applied for sizing/ dimensioning of egress capacity, smoke control systems, assessing the need for fire resistive glazing etc, as much as a pure verification exercise.

6.6.1. Models, Techniques, and Performance Criteria

Depending on the objective and scope of the analysis, the analyst has an abundance of models and techniques to choose from. The chosen performance criteria for the analysis will dictate possible modelling tools. These range from simple hand calculations, spread sheets, and statistical data, through zone models, computational fluid dynamics models, and finite element methods. Relevant metrics are discussed in chapter 5, and may include global parameters, like total evacuation time, fire resistance of the main load-bearing structure, or the analysis may focus on single components, like the flow through a door or the radiative flux to a neighbouring façade.

Analogue to initiating the analysis with a qualitative analysis, it is good practice to do initial modelling with simplified tools. This allows the user to familiarise with the problem at hand, and to provide a benchmark for the more advanced tools applied later. As with qualitative analysis, the use of simplified tools may also prove adequate, if the margins found in the initial screening are convincing.

6.6.2. Scenarios

As seen in Figure 70 the process of identifying fire scenarios is placed after the choice between probabilistic or deterministic verification approach.

ISO 16733-1 proposes the following steps to identifying design fire scenarios [139]:

1. Identify the specific safety challenges.
2. Location of fire.
3. Type of fire.
4. Potential complicating hazards leading to other fire scenarios.
5. Systems and features impacting on fire.
6. Occupant actions impacting on fire.
7. Selection of design fire scenarios.
8. Modify scenario selection based on system availability and reliability.
9. Final selection and documentation.

As seen in section 6.2, the selection of scenarios may be just as pivotal for the level of safety as the performance criteria discussed in chapter 5. When treating uncertainty by Level 1 – Worst-Case Approach, it is imperative to be transparent and systematic, and to the greatest degree possible, anchor the assumptions in updated and relevant literature. A premise for successful performance-based fire safety design is the designer’s ability to apply subject-matter expertise to the context of a specific project. The process of identifying design scenarios as outlined above allows the analyst to identify hazards and vulnerabilities in the building, thus, establishing tests to disclose the performance of the trial designs.

The difficult task for the analyst is to determine the degree of conservatism to apply. Here terms like “worst credible” [34], “upper plausible” [131], and “reasonable worst case” [7] are indicative, but considering the myriad of possible fire scenarios, the cut-off limit for high consequence and low likelihood is a challenging decision. A well-structured qualitative design review process, involving stakeholders, can however reduce the pressure on the analyst, and increase awareness and ownership to the fire safety strategy for others.

Although it is in the nature of deterministic analyses to base the design on a set of worst credible case scenarios, it may be beneficial to illustrate or roughly quantify the probabilities of the design scenarios. Illustration by event trees (with or without probabilities) may ease the communication on the scenarios and makes the level of conservatism more apparent.

6.6.3. Remarks on Deterministic Analysis

Applying deterministic models[6] is no guaranty for obtaining the same result when run by different analysts presented with the same problem. The Dalmarnock and other research clearly demonstrates the scatter amongst different practitioners, even presented with much information about the fire enclosure [63, 62]. Conversely, tight regulation of these analytical processes (like specification of design fire scenarios) defies the purpose of performance-based design, where the designer shall apply the best knowledge and science available to a project specific problem.

BS 7974 summarises the advantages and disadvantages of deterministic analysis as shown below [7].

Advantages

- *Considerable data available*
- *Wide range of well-validated calculation procedures available*
- *Provides a simple yes/no result*

Disadvantages

- *Very dependent on initial assumptions*
- *Provides no measure of costs and benefits*
- *Limited benefit for loss control purposes*

Being based on scientific mathematical expressions, the deterministic models have the advantage of being able to adapt to new knowledge and new technology. Lack of data or models can be resolved by research. Although it is convenient to assess the deterministic result against a criterion, it also strengthens the assumption that a building, in itself, is either safe or unsafe. As we will discuss in chapter 7, this is perhaps not what the industry needs.

The dependency on initial assumptions is discussed for fire scenarios, but also the identification of performance criteria, choice of analytical models, input parameter values, and other factors add uncertainty to which the results may be sensitive. The more convincing and realistic the presentations of results get; it may be more challenging to have meaningful and balanced discussions on uncertainty. Renderings and 3D animations of evacuees escaping before the onset of untenable conditions may be attractive to present to stakeholders, reviewers, and authorities, although lower-resolution results could have given a better picture of the fire strategy's resilience and robustness against a variety of fire scenarios.

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[6] Deterministic model – *Fire model that uses science-based mathematical expressions to produce the same result each time the method is used with the same set of input values* [189]

6.7. Probabilistic Analysis

6.7.1. Key Concepts

As with deterministic analysis, probabilistic quantitative analysis is not a singular approach to verifying fire safety, but a family of techniques which are characterised by how uncertainty is treated. ISO 23932-1 defines probabilistic analysis as [34]:

> *Risk analysis approach in which the fire safety design is evaluated using the full range of representative scenarios.*

Thus, the general approach to the analysis does not differ much from other verification approaches, but the steps involved may be handled differently.

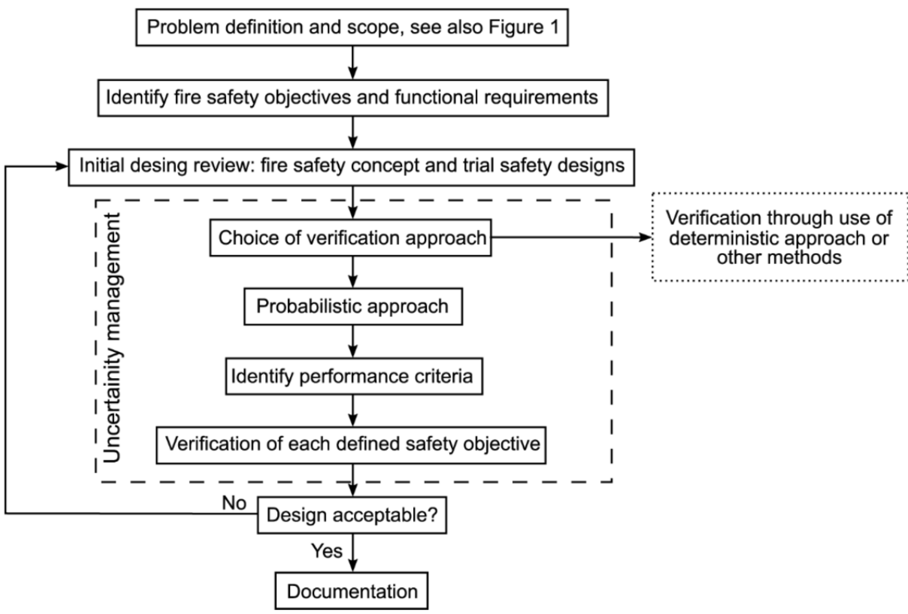

Figure 74 Flow chart of verification by probabilistic analysis [78]

Performance criteria can be comparative or absolute but are identified after the choice of verification approach is made, allowing for performance criteria fit for a probabilistic approach.

6.7.2. Techniques and Models

As described in INSTA 951, probabilistic approaches can be introduced to problems or models of a more deterministic nature [78], although this could breach the definition of probabilistic analysis found in ISO 23932-1.

Figures 75 through 77 show probabilistic concepts with direct application to fire safety engineering – Event trees, fault trees and circuit diagrams. Although event tree most likely are most in use, all techniques can facilitate in structuring different paths for an event to evolve or occur.

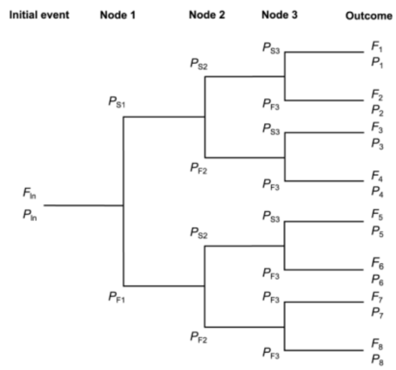

Figure 75 Event tree [78]

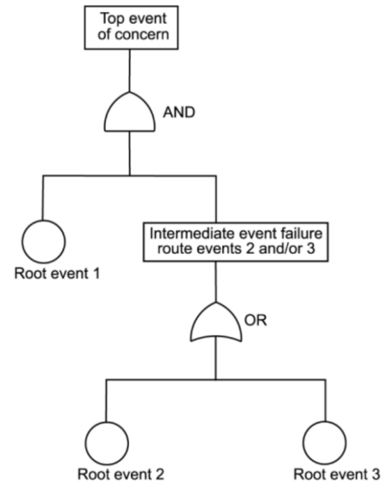

Figure 76 Fault tree [78]

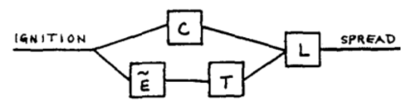

Figure 77 Circuit diagram [140]

Event trees can be used to group different outcomes or scenarios into clusters, on which further analysis is conducted, or the input parameters can be represented by continuous probability distributions. It may be challenging to treat time-dependent parameters with the above shown concepts, which are primarily based on states or yes/no gates. Critical time steps or events can however be modelled by separate branches/ nodes/ states (e.g., fire spread beyond compartment of fire origin before fire service arrival: yes/no).

Conceptually, the above shown illustrations seem relevant and applicable to fire safety engineering, although the reader must acknowledge the immense workload involved in fully probabilistic approach to fire safety analysis. Looking at the simple influence diagram in Figure 66 (page 112), each of the five nodes will have interactions between them, all of which associated with a conditional probability. An event tree with the same case would require 36 branches, for which consequence and probabilities would have to be determined. It is also worth noting that each node also may represent continuous distributions, displaying fire load, occupant loads or other parameters not being discrete or binary.

An increasing number of software tools are made available with probabilistic features, where B-Risk [141] and Pathfinder [142] being the most noteworthy. Efforts have been made to also provide Montecarlo features for computational fluid dynamics (CFD) models [143], although this has not been widely applied. CFD modelling is still computationally expensive and is therefore not a good fit for Montecarlo simulations. Furthermore, the richness in detail of CFD results make the output of these simulations difficult to obtain and interpret. For situations where the two-zone assumptions of B-Risk are valid, the computational cost, time required, and availability make the approach a viable alternative to deterministic analysis.

6.7.3. Data and Criteria

Scarcity on data and performance criteria are expressed by many to be the hinder of further application of probabilistic approaches [78]. Data for probabilistic analysis can conceptually be perceived in two alternative ways:

1. Data that represent aleatory uncertainty – the variability and respective probability for quantities as they can be observed scientifically.
2. Data that represent epistemic uncertainty – the degree to which the analyst is uncertain about a parameter.

The former stays true to the definition of probabilistic analysis, and aims to present the full range of possible scenarios. The latter lets the analyst take a more pragmatic approach to uncertainty, allowing for communicating and displaying the variability associated with the uncertainty. The estimation and fitting of probability distributions is explained in INSTA 951 annex E, and advocates the use of triangular distributions, which are easily moulded by the analyst to reflect the lower bound, upper bound, and the most expected value. These functions are also easier to modify to case specific situations, e.g., if the analyst finds reasons to estimate higher probability of a successful operation of sprinklers due to an extraordinary maintenance and service regime.

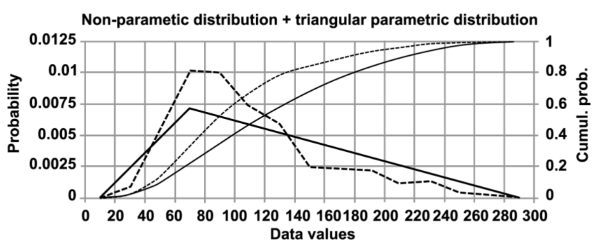

Figure 78 Fitting of triangular distribution [78]

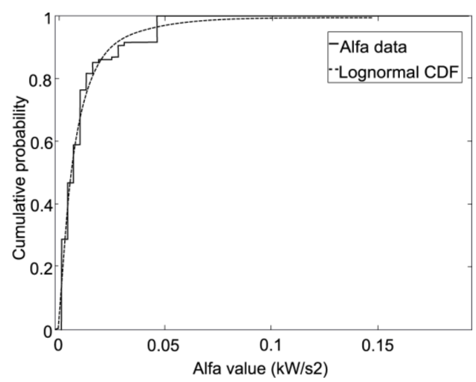

Figure 79 Lognormal cumulative probability distribution based on statistical analysis of real fire events [78]

Although a tremendous effort is required to establish databases of reliable and relevant data for exhaustive probabilistic analysis of fire safety design, the principles are applicable and useful prior to a time where all parameters are thoroughly mapped. As discussed in section 6.2, the uncertainty is also prominent in deterministic analyses, and remain embedded in the analyses from the initial assumptions are made. The continuing search for and sharing of data (ref. [78, 144]) will facilitate the further application of probabilistic analysis. As part of ongoing efforts to quantify the Australian building regulations, the Australian Building Code Board have mapped the short term [145] and medium-to-long term data needs and strategies to collect data [146].

An increasing number of sources also provide support for establishing probabilistic performance criteria, primarily on life safety [78, 128, 147].

6.7.4. Remarks on Probabilistic Analysis

The advantages and disadvantages of probabilistic analysis are summarised by BS 7974 as seen below [7].

Advantages

- *Provide comparison between dissimilar fire protection systems*
- *Provides a numerical value of risk*
- *Can quantify the probability of unlikely events with severe consequences*
- *Can quantify the risk associated with failure of one or more fire-protection systems*
- *Provides data for cost-benefit analysis*

Disadvantages

- *Availability of directly applicable data can be difficult to source*
- *Data are often out of date*
- *Time-consuming analysis*

Whether the uncertainties are treated explicitly or implicitly, they are a central topic in performance-based fire safety design. As discussed in subsections 6.2.2 and 6.6.3 deterministic analysis based on worst credible case assumptions is in its current state susceptible to user bias and subjective opinion. If this is rectified by tighter regulation or guidance, the analyst will no longer be tasked with identifying project specific treats, hazards, and mitigating measures. Thus, probabilistic techniques are an attractive alternative, allowing greater transparency for all involved parties.

Building on the pragmatic approach of INSTA 951, principles, tools, and good practice can be established while structuring and gathering of data of better quality is ongoing. The probabilistic approach can also be implemented gradually, where the analyst should estimate probability distributions, rather than worst credible cases to otherwise deterministic analysis, thus implementing probabilistic approaches as integrated sensitivity studies.

6.8. Further on Miscellaneous Approaches

Section 6.8 discusses some verification concepts not adequately covered by the above categorisation, or for other reasons need further description.

6.8.1. Partial Factor Method

In the mid-to-late 1990s, as much of the first practical experience was formed at a greater scale, much inspiration was drawn from structural engineering [32, 115]. Consequently, much more emphasis is seen on concepts like fire load, safety factors, partial factors, and other terms from structural engineering. NKB defined partial factor as [32]:

Sikkerhedsfaktor, der multipliceres/dividers med grænseverdier eller materiale parameter for at få de regningsmæssige værdier.

Safety factor, which is multiplied/divided by limit values or material parameters to obtain the calculated values.

For structural design, this involves safety factors for loads and capacities, but also reduction factors to certain load combinations. The well-established expressions for structural stability can then be adjusted by partial factors to avoid unreasonably conservative load combinations, like impact load during fire under extreme wind and snow loads.

Some concerns must be considered before the partial factor method is launched as the primary strategy for advancing fire safety engineering:

When new risks or technologies emerge, partial factors are not readily available by which adequate fire safety can be demonstrated. New aspects (risks, technologies, etc) will have to be assessed by the entity at liberty to determine new factors. Seeing that these factors are policy-driven, advances in research within natural science cannot be readily applied in design. Regardless of the analyst's available research on e.g., fire risks in energy storage systems, the right committees will have to be summoned and reach consensus before the risk can be assessed by the partial factor method.

Secondly, the factors will be intertwined with building legislation and policies and will to a great extent have to be determined in national annexes, acknowledging the differences in how building fire safety is regulated.

Lastly, fire safety engineering lacks the pedigree and tradition of structural engineering, and the discipline is far from ready to agree on mathematical expressions to cover all involved aspects of building fire safety. Thus, the approach is primarily of use in the interface with structural engineering, where Eurocodes are applied.

The use of methodologies and techniques from other disciplines and industries is discussed further in subsection 8.5.2.

6.8.2. ASET RSET

The concept involves a quantification of the time available for safe egress (ASET – typically the time from fire initiation to untenable conditions occur), measured against the time required for safe egress (RSET – the time from fire initiation or onset of evacuation, until the occupants are evacuated). The difference between ASET and RSET may be presented as a safety margin, implying satisfactory safety for occupants in the assessed scenario if the margin is greater than zero.

$$ASET > RSET \qquad \textit{Eq. 9}$$

, or

$$ASET = RSET + Safety\ margin \qquad \textit{Eq. 10}$$

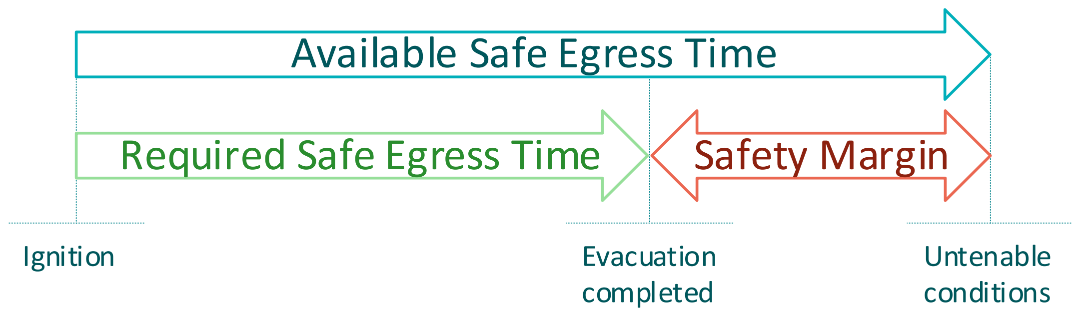

Figure 80 Illustration of Available and Required Safe Egress Time (ASET and RSET)

ASET RSET was established in the mid 1970´s by NIST, and was further developed into the early 1980´s. It is currently widely applied in fire safety engineering – Arguably the most established concept.

The concept holds similarities to structural engineering[7], where ASET corresponds to the capacity of the structure, while RSET corresponds to the loads. Thus efforts have been made to apply probabilistic approaches to the concept of ASET and RSET [115, 116, 78], treating either (univariate) or both values (bi-variate) as random variables.

Available Safe Egress Time

Estimates of the available safe egress time can be made by a variety of methods and techniques, either as a Deterministic Analysis (see section 6.6) or a Probabilistic Analysis (section 6.7). The time from ignition to the onset of untenable conditions are estimated by hand calculations, zone-models, or by computational fluid dynamics (CFD) models.

Depending on the scope of the analysis, the effect of occupant intervention, fire safety systems, or fire service intervention may be included, but most common is a worst credible case. Most guides and standards expect the analyst to assess the robustness of the design, by analysing the consequences of disabling fire safety systems, blocking exits, or otherwise remove some barriers or premises of the fire strategy [42, 1, 8, 7].

It is worth noting that ASET, as presented in Eq. 9 and Figure 80 it includes the safety margin, as seen in Eq. 10.

Safety Margin

The safety margin can either be seen as the mathematical difference between ASET and RSET [1, 2], or it can be seen as a required margin to compensate for sensitivities and uncertainties in the analysis [8, p. 411].

As an indication on the lack of relevant guidance for the required safety margin, the Norwegian building authority found reason[8] to update the illustration of ASET and RSET, exaggerating the safety margin's proportion to RSET.

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[7] Further discussion on the adaptation of concepts from other disciplines is given in subsection 8.5.1.
[8] Anecdotal information: Practitioners have measured the length of RSET and safety margin to obtain a ratio to use as justification for safety margin of their analysis.

Figure 81 Illustration of ASET, RSET, and safety margin in the 1997-2007 guides to TEK [33, 52, 53, 54]

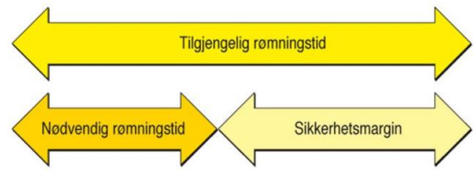


Figure 82 Illustration of ASET, RSET, and safety margin in the 2010-2017 guides to TEK [55, 73]

Generally, a reduced safety margin can be accepted if the analysis is based on conservative assumptions throughout, applying models with known small uncertainties, or if the uncertainties are already managed by applying conservative input parameters. In some situations, a margin close to 0 can be accepted where reliable and effective fire safety systems are discredited in the analysis (e.g., the design is deemed acceptable if ASET = RSET for a worst credible case fire and evacuation scenario, where sprinklers are assumed to be ineffective).

As will be discussed further in subsection 8.5.3, strict regulation of design fires, input parameters, and tenability criteria, will reduce some variability amongst practitioners, but will not give the intended control unless all factors, including safety margin, is regulated.

Required Safe Egress Time

As illustrated in Figure 83, RSET starts at the time of ignition. Time to detection is usually estimated as part of the ASET analysis, to which a warning time (t_{warn}) is added. Although the terminology implies an automatic fire detection and alarm system, both of these mechanisms may be independent of fire safety systems, where occupants sense fire cues, and warn each other.

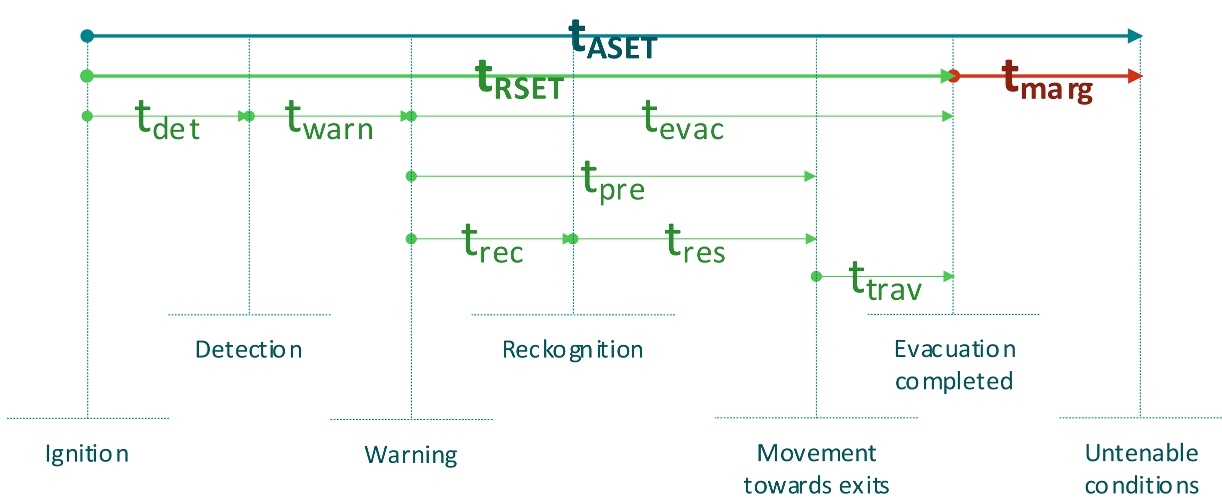


Figure 83 Illustration of time segments and events defining available safe egress time, required safe egress time and safety margin.

After warning is given, the occupants must recognise (t_{rec}) the message and respond (t_{res}) – this period is referred to as pre-movement time (t_{pre}). The occupants do not necessarily stay motionless until they start their travel towards an exit (t_{trav}), but activities like gaining information, warning others, ending ongoing processes, awaiting orders, or other alternatives to actively evacuating the premises are seen as pre-movement time. The sum of pre-movement time and travel time is called evacuation time (t_{evac}). RSET ends when all occupants have reached a place of safety.

Advantages

The concept of ASET RSET has many strengths, one of which allowing for presenting fire safety design in a direct manner, relating the fire safety of the building to representation of realistic modelling of the events – both fire development and evacuation. The concept is also scalable, in the sense that it can be applied in a simplified by hand calculations – or even quasi-quantitative, and it provides a framework to evaluating trial designs, potentially also assessing the effects of different fire safety systems, the consequences of failure of systems or fire safety management, etc. As seen in literature [115, 78], the concept is also fit for applying more advanced probabilistic or risk-based methodologies and can form a solid foundation for quantification – or could also be one of the fire safety objectives where sufficient regulation is achievable without quantification, seeing that .

ASET RSET is so widely adopted that it is shared across many jurisdictions. This is made possible by the fact that it is independent of pre-accepted performance levels, mandatory provisions, or differences in roles, responsibilities, and authority involvement.

Lastly, the concept must be said to be science-based, meaning that research advancements within e.g., premovement readily can feed into the analyses. Similarly, quantifiable performances of new technology aimed to reduce the required safe egress time (e.g., improved notification to occupants) or increase available safe egress time (e.g., new smoke exhaust technology) can fit into the established concept. Conversely, new, or novel risks can also be analysed by how they affect ASET, RSET, or both.

Disadvantages

In a 2010 *Fire and Materials* article, Babrauskas et al addressed the weaknesses of the ASET RSET concept and concluded that the concept is flawed [148]. His main concerns were:

- Treatment of uncertainty.
- Humans do not act mechanistic and robot-like, as assumed in calculations of RSET.
- The concept underpins the illusion that one number can be a representative measure of fire safety.
- There are no incentives to further improve safety when ASET>RSET.

Although this thesis acknowledges all these points as issues, it is worth questioning whether the issues give ground for disregarding the concept.

Uncertainty – The greatest disadvantage of the concept is the amount of time and computational power required to provide an adequate understanding of the full range of fire and evacuation scenarios – or if worst credible case scenarios are acceptable – where is the defining line between reasonably conservative and negligible. This uncertainty is integrated in any fire safety analysis, whether expressed in available and required safe egress time, or in other terms.

Simplified evacuation approaches are a consequence of the uncertainty about human behaviour in fires, and the criticism would be more constructive if it pointed towards methods of improving the modelling.

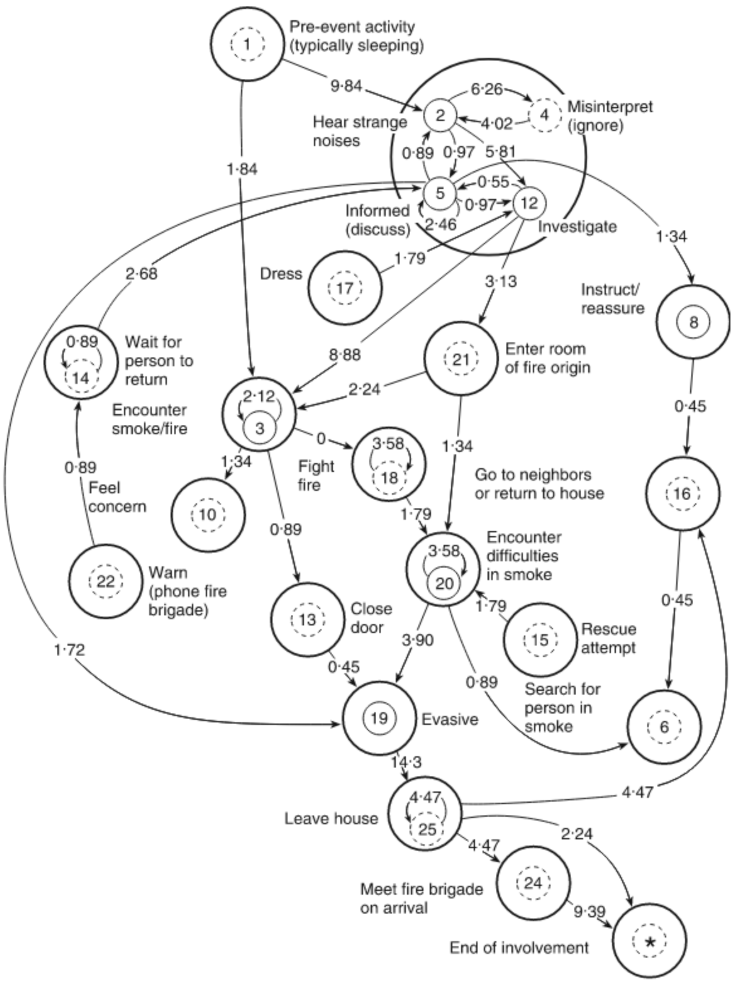


Figure 84 Human behaviour in domestic fires [20]

Figure 84 shows how the SFPE Handbook explains human behaviour in domestic fires [20]. As described on page 130, the pre-movement time includes time spent on all activities between receiving warning and commencing evacuation. Thus, a debate could have been directed towards better estimates of pre-movement times. After the publication of the article, advancements have been made within human behaviour in fires, although much research still is needed. In this context it is also worth noting the work of Lovreglio et al, publishing a comprehensive database of pre-movement times in 2019 [144].

Babrauskas et al further directed attention to how the industry tends to spend analytical resources on the wrong questions. This is further addressed in section 7.6.

One number to encompass fire safety has been discussed in chapter 5 – neither golden numbers nor prosperous metrics are identified which will to an adequate degree guarantee a certain fire safety level. Again, this is not specific to ASET RSET, but to fire safety engineering in general. Among the available concepts for quantifying and describing the performance of buildings, ASET RSET must be seen as one of the discipline’s most mature concepts.

Incentives to improve fire safety beyond compliance is discussed in section 7.3 as one reason for reducing or removing the focus on verification – not only for ASET RSET, but for fire safety engineering.

6.8.3. Fire Brigade Intervention Modelling

Building on the successful concept of the engineering timeline for available safe egress time (ASET) and required safe egress time (RSET), an equivalent concept is established for fire service intervention, to allow for demonstrating compliance with functional requirements for facilitating fire and rescue service operations.

$$ASIT > RSIT \qquad \text{Eq. 11}$$

, where ASIT is the available safe intervention time and RSIT is the required safe intervention time.

The approach used in Australia can be seen to be more specified, where data is provided by the Australasian Fire and Emergency Service Authorities Council (AFAC) [149], whereas the British approach found in PD 7974-5 is more process oriented, relying on alignment with local fire brigade during the qualitative design review [111].

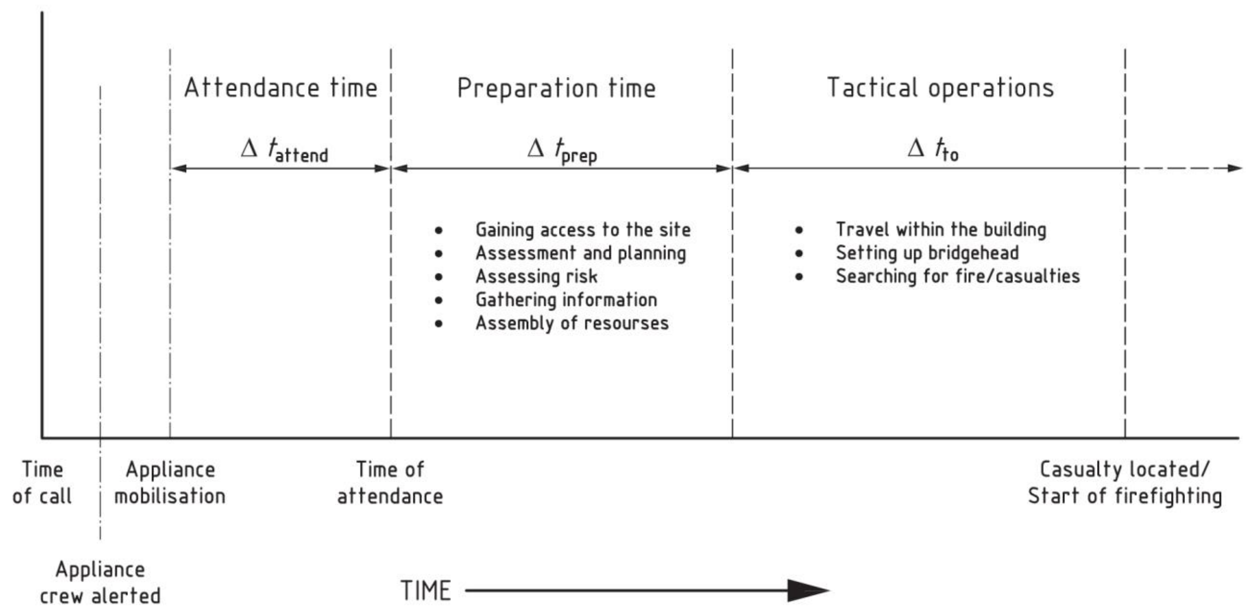


Figure 85 Engineering timeline for fire service intervention [111]

As for ASET RSET, the approach involves estimating how much time is available to perform fire and rescue operations during relevant fire scenarios in the building (ASIT), compared to the time required to perform the assumed fire and rescue service operations.

6.8.4. A Comment on Risk Analysis

Since the 2003 version of the guide to TEK97 [53], risk analysis has been referred as a recommended verification method. It is worth noting that a shift has been seen in how risk and risk analysis has been understood and used in the fire safety engineering industry [65, p. 26], with the publication of ISO 23932-1 as a pivotal point in 2018. Here the term risk analysis approach is defined as follows [34].

method for comparing estimated risk and tolerable risk using some form of risk measure, which includes quantitative analysis, deterministic analysis and probabilistic analysis

This stands in contrast to traditional understanding of risk analysis being the estimation of frequencies/ probabilities and consequences. The more inclusive understanding of risk analysis means that all analyses conducted in fire safety engineering must be seen as risk analysis, as the probability component of risk is inevitably embedded in the analysis by uncertainty.

6.8.5. Maximum Allowable Damage (MAD)

Introduction

In the 128th volume of Fire Safety Journal, Jaime E. Cadena et.al. proposed an approach for quantifying fire safety performance, called Maximum Allowable Damage (MAD) [150]. The paper argues that shortcomings in precision, certainty, robustness, and completeness render deterministic analyses inadequate for fire safety engineering. Furthermore, a warning is given against unintentional misuse of probabilistic risk assessments (PRA) when used "mechanistic" as means of demonstrating compliance. With reference to the Hackitt report [151], and also resonating with the work of Bjelland [152, 44], risk assessments are proposed as tools for assessing risk and identifying mitigating measures – not for verification.

The Process

As illustrated in Figure 86, the process consists of five steps.

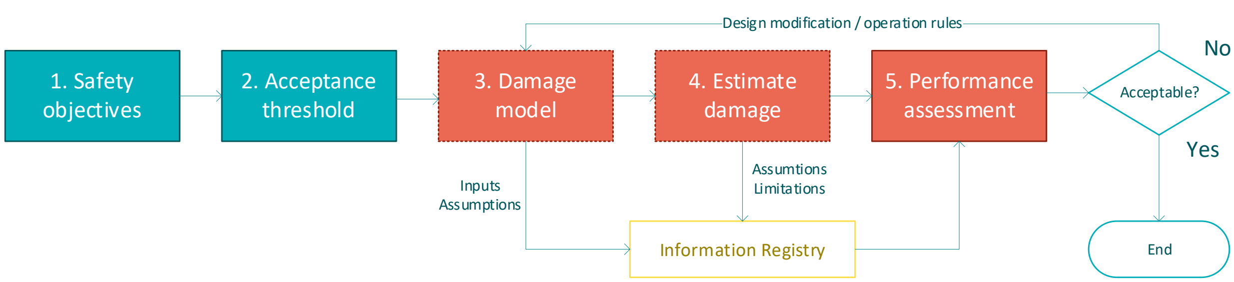


Figure 86 Maximum Allowable Damage (MAD) methodology process, as described by Cadena et.al. [150]

1. The fire safety objectives are identified and stated. Objectives should reflect the desired outcome, but in a way that allows for defining acceptance thresholds as a function of fire damage.
2. Defining the threshold of maximum acceptable damage. Damage beyond this threshold is considered unacceptable.
3. Constructing a model that captivates the involved phenomena.
4. Applying the model from step 3 to estimate the damage caused by fire, for the selected set of conditions and fire scenarios.
5. The obtained results from step 4 are evaluated against the acceptance threshold from step 2. Entries in the *Information Registry* inform the analyst on the sensitivity and trustworthiness of the analysis (see more on [uncertainty management] below).

A key feature of the approach is how likelihood is treated. Firstly, probability of fire occurring is set to 1. Furthermore, the probability of failure for key fire safety measures may be set to 1, to provide the designer with information on the "worst possible performance of the system".

Uncertainty Management

Although the same principles could be applied for other verification concepts, Cadena et.al. describes a systematic and transparent treatment of sources of uncertainty throughout the analysis. For each point in the process where assumptions, limitations, or simplifications are made, an entry is made to the *information registry*. In addition to the resulting list of assumptions, a rating is given for the strength of knowledge and insensitivity.

Weaknesses

As mentioned by the authors, the Maximum Allowable Damage (MAD) concept can be seen as "too conservative". The fire frequency is neglected, the selected fire scenarios are severe, and the effect of key fire safety systems and measures are neglected.

No guidance is given for the degree to which the user should apply this conservative approach. Even as a basis for assessing the maximum damage from fire, the frequency and conditional probability will be close to negligible.

When discounting fire safety systems and measures, their value in the fire safety strategy is unknown, and the user would need other means to justify the need for them and to demonstrate their role in the fire safety strategy, informing system design, maintenance, and control.

Strengths

The concept can provide a useful framework for critical infrastructure, load-bearing capacity for high-rise buildings, business continuity, and other situations where low likelihood alone is no justification for a massive damage potential. The concept is presumably best fit in combination with an event tree, demonstrating the robustness of a design.

The strongest feature of the Maximum Allowable Damage concept is the way uncertainty is treated. The described approach with *Information Registry* is transferable to most other analyses performed in fire safety engineering and can be further developed and tailored to virtually any verification concept.

Table 11 Visualisation of key assumptions according to principles in [150]

		Insensitivity		
		Low: Theoretical grounds for increased damage in case of changes leading to MAD breaches	**Medium**: Theoretical grounds for increased damage in case of changes	**High**: Theoretical grounds indicate an increase in damage is not reasonable
Strength of Knowledge (SoK)	**High**: Recent references, strong and relevant theoretical grounds, and agreement between analysts	A1,A2	A4,A6	A0,A3,A9
	Medium: Neither high nor low		A5	
	Low: Poor theoretical grounds, supporting references or low consensus between analysts	A10,A11	A7,A8	

6.9. Discussion

6.9.1. Qualitative Analysis – Ranting or Rational Use of Experts?

As seen in literature, verification by qualitative analysis is only applicable to simple cases and minor deviations from pre-accepted performance levels (see also section 6.4). Generally, one is led to believe that quantitative analyses are of a higher quality.

Considering the immense uncertainty involved in fire safety engineering, one could imagine that qualitative techniques were superior to quantitative models. If the analyst is uncertain about what fires to expect in a building, the analysis will not be stronger by providing high-resolution quantifications on a limited number of scenarios. If qualified actors applied reasoning and expert judgement, citing peer-reviewed or otherwise reliable literature, the assessment could be better fit to clarify how the design is fit for purpose. As underlined in the guide to the building regulations, the purpose is not to produce as much text as possible, but to present rationale for the decision, creating links between the fire safety concept and the functional requirements. This links should be strengthened by reference to literature.

6.9.2. Proxies and Simplified Methods

The use of risk indexes methods, or other simplified methods intended to reduce variability amongst practitioners may be a useful approach for traditional buildings, where there are only minor deviations from the pre-accepted performance levels. This is analogue to how structural engineering is treated, as illustrated in Figure 87.

Imperative to this approach is that the simplified approach is known to yield conservative results, giving incentives to apply more sophisticated tools if the simplified approach do not cover the need.

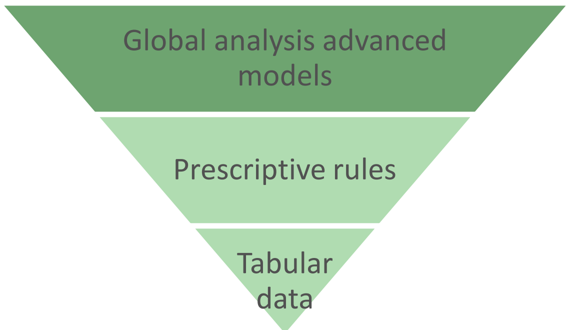


Figure 87 Different approaches to structural design with increasing flexibility (bottom up) and complexity [92]

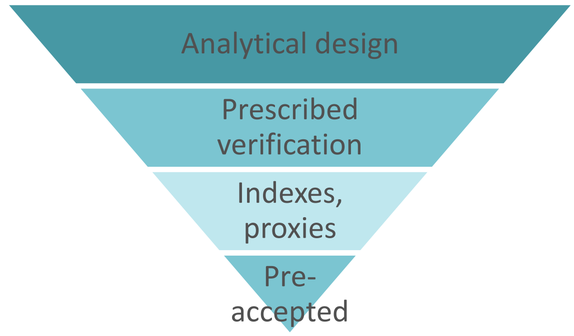


Figure 88 Different approaches to fire safety design with increasing flexibility (bottom up) and complexity

Simplified methods will typically have a limited scope, so it is vital for the analyst to be aware of the limitations and respect the field of application. New technology and novel designs may not be covered in the simplified approaches, and more comprehensive tools are needed.

6.9.3. Prescribed Verification Methods

Where verification methods are prescribed, they are deemed to satisfy the building regulations, and there are no incentives for applying new knowledge or identifying and managing risks not covered by the verification method. Strict and tight regulation of verification methods will eventually turn into proxy, where the accuracy of the models or the realism of the result does not matter.

New Zealand [129], Sweden [127], and Denmark [128] all have detailed guides on the verification process and provide input parameters and criteria which require no further justification.

This is discussed further in subsection 8.5.3 Standardisation and Repeatability vs. Flexibility and Accountability

6.9.4. On the Effects of Third-Party Review

The use of third-party review can take many forms and must be seen in context with the technical regulations, the required qualifications of practitioners, accountability, and responsibilities.

For prescribed verification methods, the third-party review can focus on ensuring that the method is accurately followed, and that there are made no errors. In cases where verification is more loosely regulated, the third-party reviewer can be invited to exercise more discretion. With loose regulation and application of general guidance, the main focus is to present the analyst with the problems to solve, rather than stipulating how they should be solved. Third-party review would in these cases add more value by being invited to assess the appropriateness of the assumptions, simplifications, tools, and parameters used.

6.9.5. Consistent Level of Crudeness

The term "Consistent level of crudeness" has been used in the context of fire safety engineering as an appeal to awareness of sensitivity. When considering the significant uncertainty in the input parameters and calculation methods, designs should reflect this by applying conservative and robust solutions.

One can however argue that the discipline of fire safety engineering suffers under an inconsistent level of crudeness. A couple of examples follow:

The computational capabilities have increased tremendously over the last two decades. When comparing the time required for CFD[9] analysis of fire development, the increased computational capacity is consumed by an increased expectation for resolution. Academia and software developers are not to blame for continuing the chase for better agreement between simulation results and experiments – Science shall strive for ways of predicting and recreating fire relevant phenomena as well as possible. For design purposes, however, the increased level of detail is futile, in view of the lack of confidence of the input parameters.

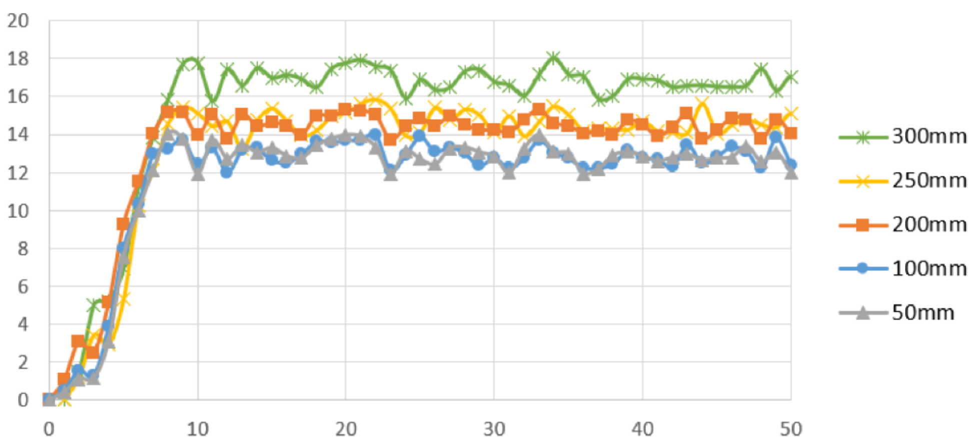


Figure 89 Volume flow (m^3/s) through an opening as a function of time, simulated with 5 different grid resolutions [128]

Similarly, there is an abondance of data and studies on the flow of people through doors, corridors, and stairs. Tables and probability distributions are available for different demographic's unimpeded maximum travel velocities – often given with multiple decimals.

Three decimals are given for the fire growth rate in [128], yet the pre-movement time is set as a fixed number of minutes. For offices a pre-movement time of 2 minutes is given when alarm is given by a simple tone, reduced to 1 minute in the case of voice alarms.

[9] Computational fluid dynamics

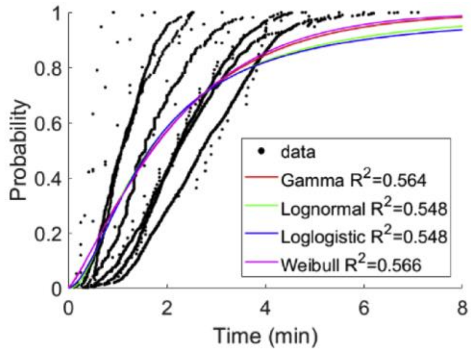


Figure 90 Probability distribution for pre-movement times in business occupancies [144]

A comprehensive study is undertaken by Lovreglio et al to produce a database of pre-movement times to be used in egress simulations [144]. The example in Figure 90 shows a spread between 7 minutes and close to 0. Based on this, one can argue that the prescribed values of 1 and 2 minutes in the Danish guide are not conservative. One can also question what incentives Danish practitioners have to introduce this knowledge into their projects, when the prescribed pre-movement times are less restrictive.

Still, the high fidelity of input parameters specified are inconsistent with the guide's treatment of safety margin:

Der er ikke specifikke krav til størrelse af sikkerhedsmarginen i grund- og svigtscenarier, men den skal afspejle bygningens anvendelse, indretning, brandsikringstiltag, driftstilstand mv.	*No specific requirement is given for the safety margin in the base scenario and robustness scenario, but it should reflect the building's use, layout, fire safety measures, operational conditions, etc.*

This generic text will allow for considerable variability between different analysts.

The lack of consistency in the domain of fire safety engineering may be seen as an indication of the discipline's adolescence. For some situations, one finds loose regulation and generic guidance, where no predictive models are available (e.g. facilitating fire and rescue services). For other situations, stringent and structured procedures are provided, well-founded in fire science, but with limited application for design.

6.9.6. Ability to Model All Relevant Phenomena

The field of fire safety engineering is widespread, with many of interfaces to other disciplines. Figure 91 illustrates the key technical competencies for a fire safety engineer according to SFPE [153].

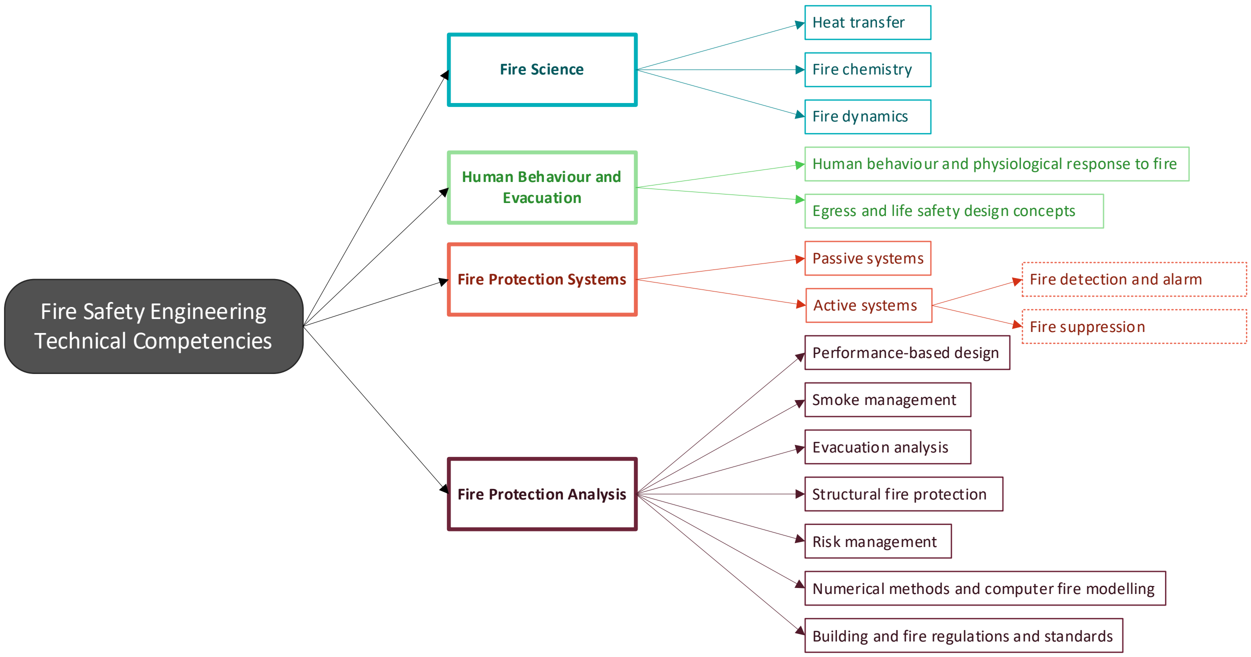


Figure 91 Fire safety engineering technical competencies, based on [153]

Both SFPE and IAFSS have published lists of suggestions for research within the domain of fire safety engineering and fires science [11, 12]. From a technical standpoint SFPE points at the lack of practical models for pyrolysis of complex materials, extinction and reignition, sprinkler suppression, under-ventilated combustion, glass breakage, and human consequences.

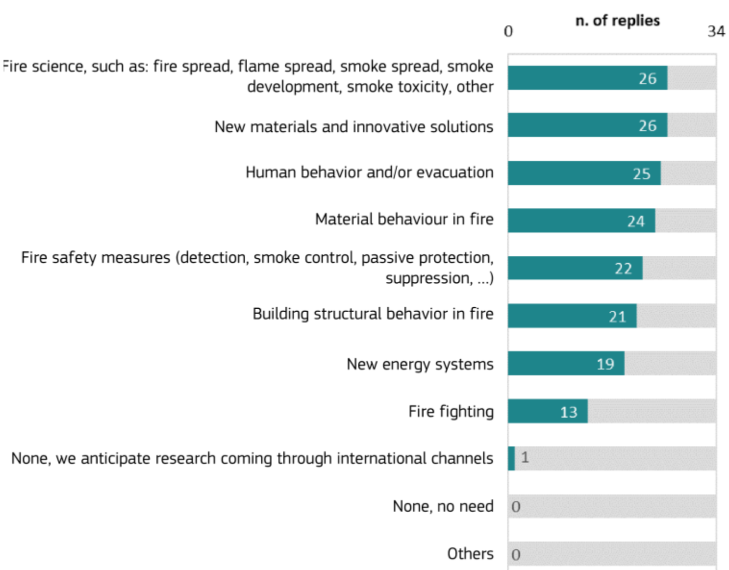


Figure 92 Survey responders' view on research needs for fire safety engineering [58]

The European survey referenced in Figure 92 confirms the need for better modelling capabilities and understanding of fundamentals of fire science, but also points to the need for better understanding of new materials/ technology and human behaviour in fires.

6.10. Summary

Chapter 6 has provided an overview of the fundamental approaches to verifying fire safety performance. They range from expert judgement and qualitative assessments to highly advanced quantitative models capable of producing high fidelity results.

Key to this topic in a design context, is however the uncertainty, as presented in section 6.2. The modelling, high or low fidelity, is embedded with uncertainty stemming from a lack of understanding and knowledge about the future, and imperfections in the available tools' ability to model reality. Thus, applying safety factors, making conservative assumptions, or explicitly stating the uncertainty is essential.

The available verification concepts for life safety are the most mature, although it is recognised that our understanding and treatment of human behaviour in fire is limiting. Other objectives and subsystems are less mature, and comprehensive verification concepts are lacking.

Meacham summarises the dilemma of verification [65]:

> *The framing of PBD for fire safety as strictly a deterministic problem, based on a very small number of nonrepresentative scenarios and limited size design fires, is inappropriate and contributes to challenges in obtaining agreement on design verification. However, a push for quantitative risk assessment methods, when there is a lack of data, and lack of understanding of the concepts, is inappropriate as well.*

7. On the Need for Verification

7.1. Introduction

Through chapter 3 and 4, we have now an understanding of how fire safety is treated in current performance-based regulations, and what the concept of performance-based design is. Through chapters 5 and 6 we have seen that it may be challenging to mechanistically calculate or measure fire safety in a reliable, predictable, and fair manner.

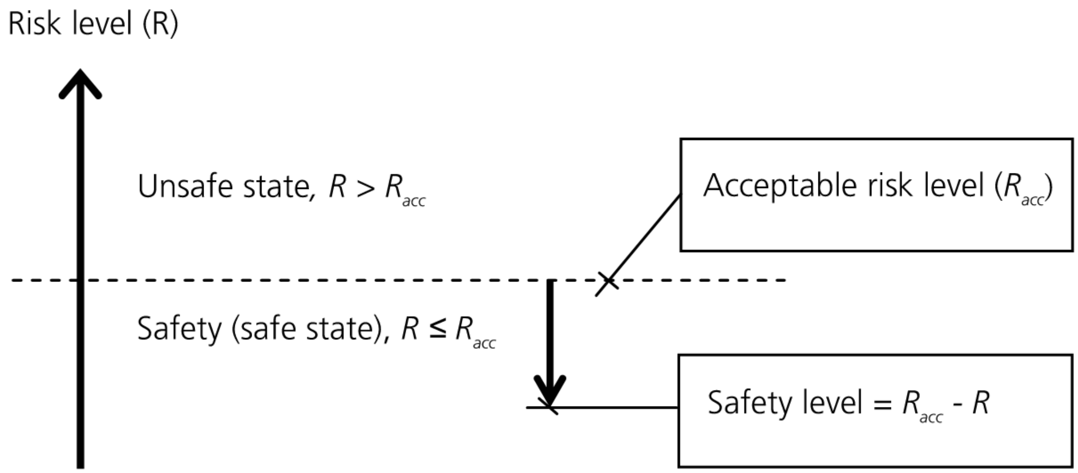


Figure 93 Relation between the concepts of risk and safety [154]

Although the above figure clearly illustrates the relation between risk and safety, it also implies the existence of a clearly defined (or definable) line between safe and unsafe. Acceptable and not acceptable risk. Chapter 7 aims to explore these concepts, dissect whether they are feasible for fire safety engineering, or if other schools of thought could be more beneficial.

An official Norwegian report from 2012 addressed the inadequacy of current verification practice [87, p. 23]:

Mange forskere argumenterer for at beslutningsprosessene, blant annet med involvering av mange aktører med ulikt ståsted og kunnskaps-grunnlag, er viktige i vurderingene av hva som er 'godt nok' (sikkert nok). Ekspertbaserte analyser (statistikk og lignende) og overordnede politiske eller rettslige føringer er ikke tilstrekkelig som grunnlag for å avgjøre hva som skal være

Many researchers argue that decision-making processes, including the involvement of multiple stakeholders with different perspectives and knowledge bases, are crucial in determining what is deemed 'good enough' (sufficiently safe). Expert-based analyses (statistics and the like) and overarching political or legal guidelines are not sufficient as a basis for determining an acceptable

et akseptabelt sikkerhetsnivå (eller tolererbar risiko).	*level of safety (or tolerable risk).*

Although this chapter explores alternatives to the pursuit of verification, it must be clear to the reader that such a change in paradigm must be the result of regulatory changes. Under current legislation, the line in Figure 93 also separate legal from illegal designs, and documentation of compliance in writing is mandatory whenever pre-accepted performance levels are not applied.

7.2. Why Verify?

Subsection 3.3.6 gives an overview of the required features of a functioning performance-based building code. With relevance to verification, the legislation should give the following:

- Certainty of outcome.
- Minimise disputes.
- Certainty of compliance.

For any given project, the purpose of verification may also vary – beyond demonstrating compliance.

- Dimensioning/ sizing of smoke control systems, egress components, etc.
- Cost-benefit-optimising.
- Providing basis for performance-based detail design in other disciplines (e.g. structural fire safety design).
- Inform owner, users, etc about residual risk, as basis for maintenance, service, and operations.
- Inform insurer and owner about resiliency and potential loss of property, business continuity, public trust or other.

Regulator's Perspective

For regulators, the verification is a way of assuring that politically determined safety levels are implemented in buildings. This further allows for surveillance, review, control, and potentially sanctions where deficiencies and non-compliances occur.

Practitioner's Perspective

Under the current regulatory framework in Norway, demonstrating compliance with functional requirements is therefore mandatory – either by applying pre-accepted performance levels, or by analysis (verification). Thus, the burden of proof is on the regulated party – the designer is required to verify. Acknowledging this fact, it should also be recognised that the regulated has a right to demonstrate compliance, which may be more relevant for fire safety than other disciplines, as phrased by Alavarez et al [57];

> *The concept of risk does not appear to be acknowledged by the regulators, which can lead the FPE [Fire Protection Engineer] to be legally exposed in case of a rare catastrophic event even though the building design seemed robust and appropriate to all the involved stakeholders.*

Some events have a frequency so low that it is not socioeconomically viable to design buildings to fully meet all criteria for these scenarios. Although the likelihood is low, the event may occur, and the designer should be able to present a justification for the design, which also a posteriori could be evaluated in light of the knowledge available at the time of design.

After an event, investigations and evaluations may direct attention to design alternatives which would have given a reduced fire loss. There are also examples, where the post event investigations reveals that the fire developed differently than described in the designer's analysis (e.g. the probability of fire spread between vehicles in a carpark [106]). Law addresses this challenge of fire safety design [123]:

> *A common misconception is that the role of the fire safety engineer is to predict in detail what will happen in the event of a fire. This is not the case. The fire safety engineer must produce a design which achieves adequate safety levels.*

Here, the pressing question is of course: What is adequate safety? This is discussed in section 8.3.

By verification, the fire safety level is more explicitly addresses, and thus, helps to level the playing field among practitioners, and reduces the risk of misinterpretations. Furthermore, a more explicit approach to fire safety may provide more useful feedback loops, where statistics and data from real fires can inform regulations, guides, and new designs.

It also helps ensure a level playing field and reduce the risk of misinterpretation. Without verification methods, a "race for the bottom" may occur, where the consultant is favoured who produces the fire safety strategy with the least impact on cost, construction time, or other factors of importance to the client.

7.3. Why Not?

Does "Adequate Fire Safety" Even Exist?

When reviewing literature on systemic thinking, verification of fire safety, as performed in today's building industry is regarded an exercise in futility. Bjelland et al argue that [44]:

> *fire safety and safety margins are emergent properties of socio-technical systems that need to be managed rather than verified. The search for objectivity and mechanistic decision criteria is futile and diverts attention from the main purpose of engineering: to guide decisions during the whole design process and thus enable safe operation.*

Thus, one argument for not verifying fire safety, is that fire safety a static property of a building that cannot be measured and verified in a meaningful way in isolation.

Incentives to Improve Fire Safety Beyond Compliance

Adequacy furthermore implies a pass-fail criterion, where no further risk reduction is required. For one, this means that most of the information disclosed in the analysis is condensed down to a pass-fail question, rather than being fed into the operation and management of the building [57].

Secondly, the use of pass-fail criteria gives no incentives to improve fire safety beyond the point where compliance can be demonstrated – even if further risk mitigation can be achieved without undue cost or disadvantage.

Simplifications and Unacceptable Uncertainty

Babrauskas et al declared RSET/ASET – identified as the most mature fire safety verification concept in chapter 6 – a flawed concept [148], arguing that the inherent uncertainty in predictive modelling of fire safety renders them less useful for verification, and that a better approach would be to do comparative studies of safety margins, opting for the alternative yielding the highest affordable margin between available and required safe egress time.

The same perspective can be seen in the investigation of fires, such as Sola carpark fire [106] and Lone municipal residential building [155]; Fire safety engineering under the current Norwegian Planning and Building Act is being presented as a process of optimising fire safety, while no such optimising is required by legislation, nor ordered by most clients.

7.4. What are the Alternatives to Verification – If any?

As discussed by van Coile et al [124] a fire safety design may be considered adequate if:

> *an objective, diligent and competent fire safety professional would consider the spectrum of possible consequences (and their associated probabilities) associated with the design to be acceptable to normal societal stakeholders.*

To follow this line of thought, it would be imperative to ensure the objectivity, diligence, and competency of the fire safety professionals performing these assessments.

Although it may be seen as drastic to leave a concept of verification, it is worth considering the state of verification at the time of implementation of functional requirements, as seen in chapter 2. Many credible institutions of the time openly stated that verifying compliance with functional requirements are difficult or even impossible – and still do. Appreciating this deficiency, it was vital for the system supporting the implementation functional requirements in 1997 to ensure the above-mentioned traits of the professionals. In Norway this was treated as the three major dependencies described in section 3.11:

- Competencies (regulated by GOF, now by SAK10)
- Surveillance (regulated by SAK10)
- Third-party review (regulated by SAK10)

These factors and other supporting mechanisms are discussed further in section 0.

A formalised step away from verification, would most likely involve a step towards more management-based regulation, as described in subsection 3.4.2.

7.4.1. Systemic Thinking

Being introduced as a counterpart to the traditional safety engineering approach of verification, systemic thinking represents an obvious candidate to replace verification. As seen from the introduction given in section 3.15, progress is being made in the conceptualisation of treating fire safety in the context of socio-technical systems.

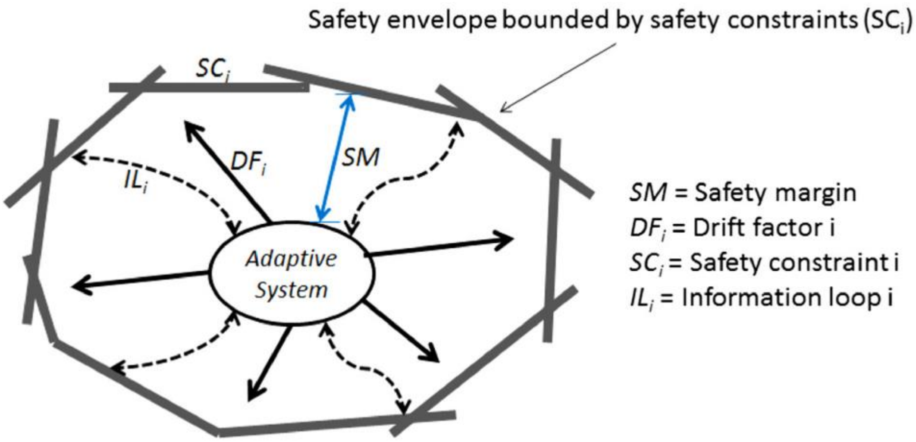


Figure 94 Illustration of buildings, as an adaptive system, being kept in a state of safety by safety constraints [44]

The approach is most easily understood imagining an industrial manufacturing process, where the safe operation of a process requires the pressure to remain within a certain range. The safety margin would then equate the difference between the current pressure and the criteria for unsafe pressure. Drift factors are phenomena, events, and systems affecting the pressure, potentially reducing the safety margin. By monitoring the pressure, information loops can be created, giving the operator or the system feedback, ultimately allowing for the activation of safety constraints, like, reducing the temperature, pressure relieve valves, fire suppression systems, emergency shutdowns, etc.

Considering the challenge of multiple legislations mentioned in section 3.10, comparisons can be drawn to road safety or consumer product safety, where the ultimate safety obviously is a sum of the item, the environment in which it is being used, the user, and how it is being used [152]. Extrapolating these examples, one can consider the manufacturing of vehicles or consumer products, and recognise that these products are regulated, including safety requirements to the product and its constituent parts. Thus, a systemic approach can be taken to the global fire safety problem, whilst still regulating the various actors and components of the system differently. This approach is assumed to be more complex, and an agency taking full ownership to the totality would be essential.

Adaptive Systems

Bjelland et al states [44]:

> *It is in the nature of complex socio-technical systems to change. The development of a socio-technical control structure allows systems to change in a safe manner. Providing for safety is not a one-off task (verification), but a continuous control task which implies a continuously changing safety margin between safe operation and the limits of safe operation.*

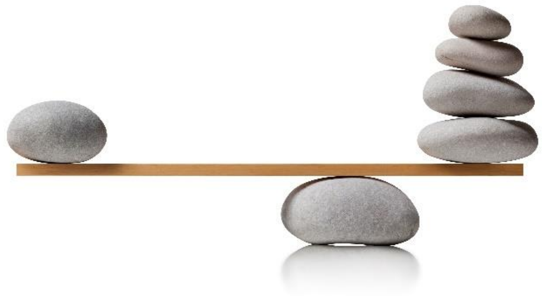


Figure 95 Static balancing static objects

Figure 96 Tightwire walker with balancing pole

Above, two illustrations of balance are given, analogue to a system being in a state of safety. Figure 95 symbolises a static system, where balance established initially, and is maintained until sufficient external forces are applied. This is meant to represent a verified fire safety design, where all focus is placed on technical properties of the building, which are the only "moving parts". Depending on the design, the task of demonstrating and establishing balance can be easy (robust, well-known measures), or it may be a task involving more fine-tuning (high uncertainty, sensitive analysis, small margins)

An adaptive balance is illustrated in Figure 96, where balance is maintained by constantly making small adjustments. To increase the momentum of the adjustments, a long pole is used as a tool. For fire safety, this would be information loops and control constraints mitigating changes to the fire risk. This could be the changing ability of self-rescue among residents in a residential building, the changing fire characteristics and sizes of vehicles in an underground carpark, construction work, but also more abrupt changes like the failure of a fire detection and alarm system, or sudden snowfall, etc. All of these changes will challenge the fire safety design's robustness and require vigilant observation of information loops in the system.

A substantial difference from the current verification-based regime, is that maintaining the system in a safe state is treated coherently through the life span of the building. Verification based on technical requirements to the building will be expected to consider robustness, but the fire safety management and monitoring of fire safety during operation, is under a different jurisdiction (as seen in section 3.10).

Maturity

Although more than a decade has passed since conceptualisation of socio-technical systems within fire safety engineering was made, the required change in paradigm is not yet fully in motion. Meacham suggest the following steps to further advance the application of socio-technical system thinking for fire safety engineering [67]:

1. Recognition and acceptance of performance-based fire safety design as a socio-technical system challenge.
2. Revisit design goals and objectives, in a systemic context.
3. Establish tools and criteria for defining the safe state of systems.
4. Reframing fire scenarios to obtain information rather than verification.
5. Embrace innovative fire safety technology (safely).
6. Place equal emphasis on continued fire safety in use and design.

7. Recognise and address risks associated with actors with inadequate qualifications or preparedness.
8. Inclusion of more stakeholders in establishing and achieving fire safety performance goals.

As pointed out by Meacham [67], the approach allows for applying established analytical methodology, although in a new framework. Although the implementation of systemic thinking truly is a shift in paradigm, the advancements within the discipline over the last decades can be utilised.

7.4.2. ALARP

ALARP is an acronym for As Low As Reasonably Practicable, defined as [147]

where all reasonable measures are taken in respect of risks to reduce them further until the cost of further risk reduction is grossly disproportionate to the benefit

The term, ALARA, "as low as reasonably achievable" can also be used. Nonetheless, the concepts of risk analysis and cost-benefit as discussed in chapters 5 and 6 are highly relevant, although they are not used to show compliance to a definitive minimum required performance level. Thus, ALARP can be used in a management-based approach to regulating fire safety, which also is aligned with the concepts' origin, being introduced as a required assessment occupational health and safety in the UK in 1974, under the phrase "*so far as is reasonably practicable*", later shortened to SFAIRP.

Seeing the above definition in isolation, there is no lower minimum performance requirement, thus one could argue the approach is allowing for inherently unsafe designs, in which further risk reduction is extremely costly, or otherwise challenging, the risk reduction is minimal, but still the residual risk would be higher than "*acceptable to normal societal stakeholders*".

This challenge is solved by the definition used by INSTA 951 [78] (author's underlining):

Principle that all reasonable measures will be taken in respect of risk which lie <u>in the tolerable zone</u> to reduce them further until the cost of further risk reduction is grossly disproportionate to the benefit

PD 7974-7 does however include a discussion on acceptance criteria addressing this, building upon the work of Hopkin, van Coile, et al [138, 124]

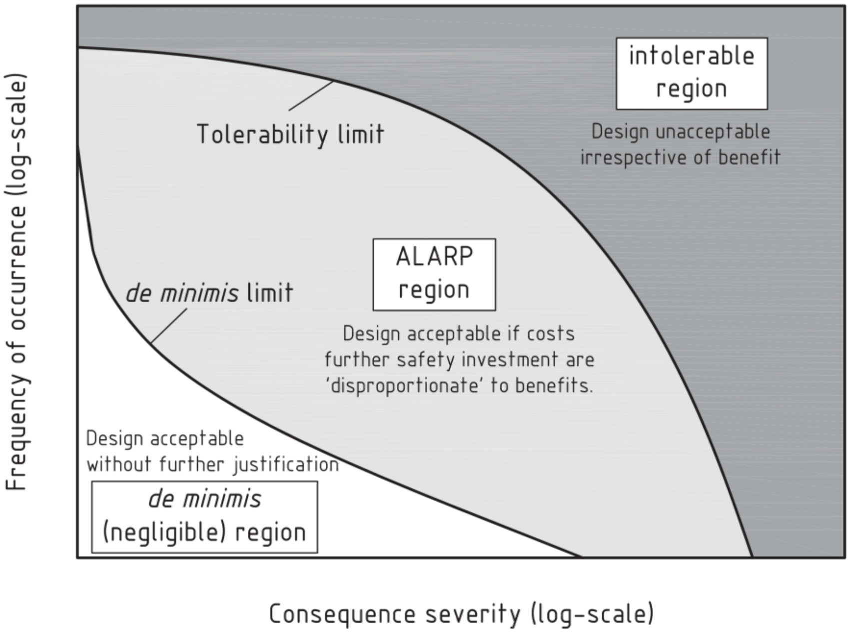


Figure 97 Three regions of risk: De minimis, ALARP and intolerable [147, 124]

As illustrated in Figure 97, it is recognised that the risk may be intolerable, irrespective of the benefit of the design or cost of risk reduction. Conversely, the de minimis limit designates designs where the risk is so low that no further justification is required. Between these zones, is lies "*the tolerable zone*", where the ALARP principle is applied.

Being in use for close to 50 years, ALARP is an established concept, albeit rejecting the verification approach in favour of a systematic ALARP approach to fire safety would require more guidance and regulation of the process of determining the "degree of disproportion" between cost and risk reduction. Furthermore, the de minimis region must be defined, assuring a minimum level of safety – effectively requiring the same process as if all aspects of fire safety regulations were to be quantified in the context of verification.

Thus, ALARP cannot be seen as an alternative to verification, but rather a mechanism which can be used to prevent a "race for the bottom" and to ensure fire safety engineers implement risk reducing measures where they are obtainable.

7.4.3. Risk Analysis

As mentioned in section 3.9, risk analysis is already a central concept in analytical fire safety engineering, but in the current regime, it is used to verify compliance, rather than a tool for disclosing vulnerabilities and informing the design. Seeing how there is a lack of formal milestones for fire safety engineering (like QDR – Qualitative Design Review as seen in subsection 6.4.6) prior to the commencement of construction, the risk analysis can be conducted after all design decisions are made, as an isolated verification procedure.

Risk analysis is however a well-established concept in general, and specifically for fire safety engineering, and the approach allows for treatment of the considerable uncertainty involved. Thus, replacing the current verification with risk analysis could be seen more of an evolution than a revolution (like systemic thinking). Contemplating the 2003 version of guidance given to the Norwegian building regulations, it can be argued that a slight change in practice and regulation would suffice for risk analysis to replace verification [53]:

- The risk analysis shall encompass the planned use of the construction works.
- Assumptions and premises involving the fire service should be aligned with the local fire brigade.
- Risk analysis is relevant where the trial design is based on managerial procedures by the owner or user of the construction works.

As seen from the above bullet points, previous versions of the guide to the building regulations have allowed for a more holistic approach. Recognising the loose guidance and regulation of risk analyses, the approach can resemble a management-based regulation of safety in case of fire, where the analyst involves stakeholders in establishing performance criteria. As seen in 3.11, considerable support structures accompanied the loose regulation of risk analyses, ensuring "*objective, diligent and competent*" fire safety professionals.

7.4.4. Expert Judgement

As seen in chapter 6, expert judgement is instrumental to an analytical approach to fire safety design, even when quantitative analysis is applied. For verification purposes, one can question the benefit of quantifying this judgement. In many cases calculations, simulations, statistical analysis, or other quantification techniques may be required to provide sufficient basis for a decision, but allowing for expert judgement to replace a mechanistic verification could allow for a more direct application of the analysts experience and competencies.

With this approach, it is obviously critical to ensure the objectivity, diligence, and competency of the fire safety professionals. Different means of regulating practitioners are discussed by von der Fehr et al [30], although the discussion must be revisited in the context of rejecting verification.

It is worth comparing fire safety engineering to other processes in society where professionals are trusted to decide safety related questions. Within medicine, a general practitioner can prescribe medical treatment without a written analysis verifying demonstrating adequate confidence in the efficiency or acceptability of the risk involved in the treatment. Here, licenses and qualifications, coupled with scrutiny give grounds for allowing the general practitioner to exercise discretion.

Where functional requirements are used in law, there is a margin of appreciation. Lawyers will then use previous cases where the court has exercised discretion and thus set precedence. For the court to rule in a question of interpretation of functional fire safety requirements, the most probable occasion would be a fire where the affected parties claim the performance-based fire safety strategy to be inadequate. These cases occur infrequently, and if they occur, they may regard a withdrawn version of the building regulations, non-compliances, or will of other reasons be of limited value for future design. It is nonetheless a highly inefficient way of establishing a common understanding of the regulations.

In this respect, an independent building technology advisory board (byggteknisk nemnd) was proposed in Norway in the mid-2000s, inspired by the Australian "Building Appeals Board" [18, 156].

Building Technology Advisory Board

Through two official Norwegian reports (NOU), the use introduction of a building technology advisory board was considered. After a review of the current system based on functional requirements and self-certification, the committee had a lack of confidence in the system's adequacy [18, p. 110]. The following was therefore proposed [156, p. 59]:

> *In Norway there is no body that assesses actual solutions and determines whether the technical solutions satisfy the requirements set out in the technical regulations. This is particularly unfortunate for innovative project designers who wish to test new solutions. The Building Legislation Committee proposes that a building technology advisory board with a high level of interdisciplinary expertise be established to provide advisory expert opinions on technical solutions for buildings and installations upon application by project designers.*

In addition to rule in disputes and queries from specific projects, the board would create precedence and align understandings and interpretations of the functional requirements, serving the purpose of a court ruling within law.

19 comments were received on the first public query, all of which were positive to the proposed board [156, p. 149]. Comments were however mainly received for municipal building authorities, and practitioners were under-represented.

By 2008, the challenges of interpreting the functional requirements were still acknowledged, and in a survey 10 % of municipal building authorities reported that uncertainty regarding compliance with the functional requirements occurred often – even more so for safety in case of fire [157, p. 41]. Despite of this, it was decided to not establish a building technical advisory board, with the following reasons:

- A building technical advisory board was deemed inefficient in solving the identified challenges of the building legislation.
- Cases raised to the board were expected to delay progress in ongoing building projects.
- The establishment and operation of the board was expected to be costly, even with it being financed by handling charges/ fees.
- Uncertainty regarding the liability and accountability of the board, when it has ruled in favour of a solution later found to be inadequate.
- Consider the limited pool of experts in the Norwegian building industry, it would be challenging to find board members without ties or interests in the cases lifted to the board.

The Ministry concluded that the challenges identified in the building legislation were better addressed by other means. Specifically, third-party review. Additionally, it was proposed to increase the understanding of the functional requirements by providing information and guidance to the users.

7.4.5. Abandoning Performance-Based Building Regulations

By abandoning reintroducing prescription-based building regulations, the need for verification would cease to exist – or at least be drastically reduced. An evaluation of the building regulations based on functional requirements was conducted in 2019, concluding that no significant change in quality of the built environment (positive or negative) can be attributed the transition from prescription to functional requirements [51]. The evaluation further found that the functional requirements to the greatest extent facilitated innovation and flexibility within fire safety engineering – a necessity to meet sustainability considerations.

7.5. Support Structures

As seen previously in this thesis and illustrated in Figure 98, there is a close relation between the need for regulating verification, and the degree to which the fire safety professionals can be trusted.

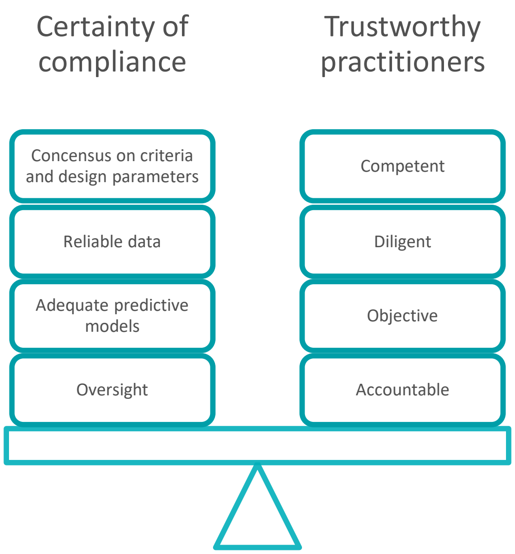


Figure 98 The relation between certainty of compliance by verification and the degree to which practitioners can be trusted

If there is no reason to trust practitioners, all aspects of the verification should be vigorously regulated. Conversely, if the verification methods are unable to give adequate certainty of compliance, one will have to ensure the trustworthiness of practitioners. In reality, a balance will have to be found.

7.5.1. Certainty of Compliance

As seen in chapter 6 compliance can be verified in many ways. If there is a shortage in trustworthy fire safety practitioners, the loosely regulated verification methods would have to be replace with more strict stipulations of the process, the data, and the models that are to be applied. As seen through chapters 5 and 6, no metrics and verifications are identified that can adequately represent all the phenomena involved in fire safety design in a science-based manner. Thus, substantial simplification would have to be made to sets of calculations and procedures to cover the span of possible designs. In leu of trustworthy fire safety practitioners, examples as seen in New Zealand [129], Sweden [127] and Denmark [128] are most likely too loosely formulated still. Thus, other control structures must accompany the verification.

The above-described approach still relies on a mechanistic verification, where specification and certainty of compliance is assumed more important than flexibility and the ability to handle new risks and technology.

Assuming the verification methods are adequately specified, oversight and scrutiny can further increase the certainty of compliance. This can be done by authority involvement (approvals, controls, or surveillance), third-party review, sanctions, or a combination thereof.

If there are shortcomings in the verification methods, the third-party review loses some of its meaning. If the conducted analysis is not fit to demonstrate compliance with the functional requirement, one could argue that TEK section 2-2 is not met, and that the analysis is inadequate. This does however not fit with the regulators´ own description of functional requirements, where it seems accepted – almost intended to have the requirements formulated in a way where objective proof of compliance cannot be produced.

Reintroduction of municipal control (bygningskontroll) was considered in 2005, but rejected in favour of third-party review [156].

7.5.2. Trust

The trust in practitioners is a concept which is difficult to measure or monitor. It is however of great importance – and even more so if the requirements regarding demonstration of compliance are relaxed.

The 2022 report on reimagining the ICC performance code concludes that "*peer review and competency of involved professionals is critical to successful use of performance-based codes and design*" [134]. This also resonates with the Norwegian regulators' understanding [45, 6].

Regulating competencies alone, would make the profession susceptible to foul play, where the designer signing off the cheapest solution would prevail. Thus, it is crucial to also ensure accountability and ethical standards amongst the practitioners. Third-party review can have a role in increasing the trustworthiness of fire safety professionals, but the type of review would have to be adjusted to how the verification (if any) is conducted. If a mechanistic and specified verification as discussed in subsection 7.5.1, the review could be limited to verifying that the specified methods and data are applied correctly. However, if the verification is abandoned in favour of expert judgement, the third-party reviewer should be given the chance to exercise his or her own judgement, thus challenging the designer. In the latter case, the third-party reviewer would most likely have to accept more responsibility of the design – potentially to the point where the reviewer and designer would have to agree on the appropriateness of the design.

7.6. Where are the Analytical Resources Best Spent?

A wider discussion on where to prioritise society's resources on fire safety is given in section 8.6. This section deals with the question of where to apply performance-based design with all its strengths and weaknesses.

Detailed and time-consuming analysis of standardised and traditional buildings is seldom rational. The use of pre-accepted performance levels and solutions, potentially with minor deviations justified by comparative reasoning may be an optimal approach, assuming the consequences in case of fire are moderate. This category, shown in green in Figure 99, has a high frequency of accidents which can provide sufficient empirical feedback. The minor consequences may allow for simplifications and standardisation.

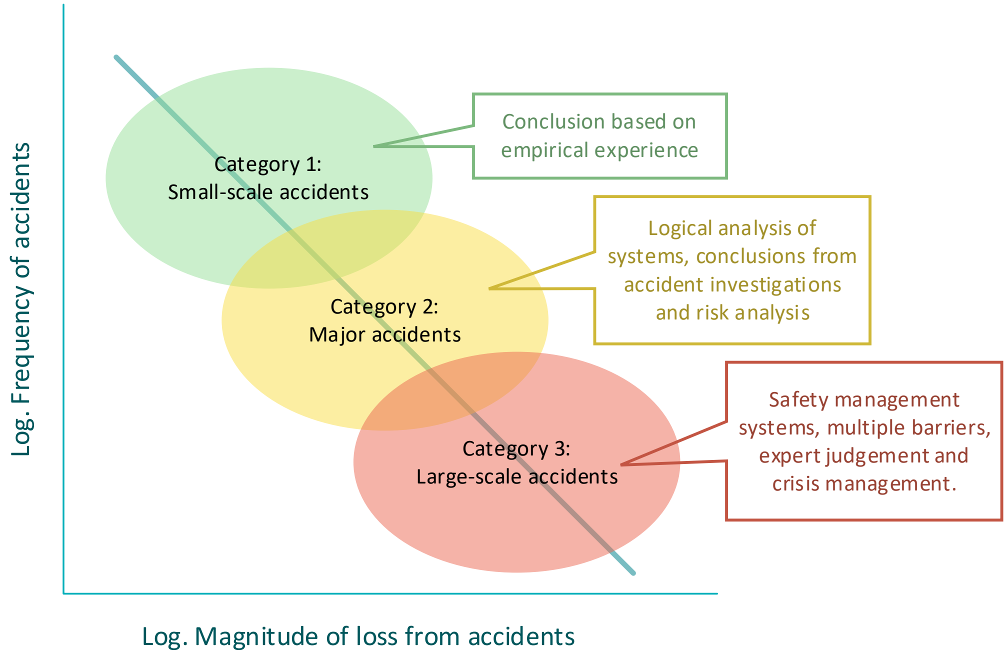


Figure 99 Management strategies for various types of accidents, based on [154]

Category 2 consists of accidents with a greater magnitude of loss, but also with a lower frequency. The empirical experience from these events may have more scatter compared to category 1, and conclusions should therefore not be based on empiricism alone. Accident investigations may inform a risk analysis in this category, but the analyst may have to interpolate, extrapolate, or draw parallels to other building types or other jurisdictions to gain a better understanding.

Lastly, infrequent, large-scale accidents, in category 3, may not be seen in national statistics, and will also include one-off or first-off projects. Lundin draws attention to management and expert judgement rather than concluding on the basis of empirical data or risk analysis for this category [154].

For Norway, it is mainly low-rise residential buildings that will be placed in category 1. As will be discussed further in section 8.6, out of the 513 fatal building fires in Norway over a 10-year period, 16 were institutions (3.1 %), 27 were commercial/ industrial (5.3 %), 2 were garage (0.4 %), and 7 other building types (1.4 %). The remaining fatal building fires occurred in residential buildings. The empirical basis for pre-accepted performance levels and solutions are discussed further in subsection 8.3.4

The onset for category 2 is difficult to define, but based on the fire frequency, many building types within the scope of the pre-accepted performance levels of VTEK lack empirical data support, and thus should be subject to an analysis.

Buildings classified as fire class 4 would be obvious candidates for category 3. Here the consequences of fire are very serious, and the frequency is very low.

7.7. Still Need for Predictive Methods, Metrics, and Thresholds

Let us imagine the fire safety design process for a venue for sporting events and concerts, where no verification of compliance is required. A reduction in occupant number would reduce the required safe egress time and would also reduce other risks associated with high person densities, like stampede. On the other hand, a reduction in occupant number would reduce the revenue for ever future event held at the venue – potentially to the point where the project is no longer profitable. More examples exist, where further risk reduction is obviously obtainable, but not necessarily required meet society's expectations to safety in case of fire.

Similarly, systemic thinking, ALARP, risk analysis, and expert judgement would all rely on quantification of certain fire scenarios, in which predictive analytical methods, metrics, and thresholds are required. Even if performance-based building regulations were abandoned, certain buildings would require dispensation from the prescriptive regulations – most likely depending on an analysis of the consequences for the authority having jurisdiction to grant an exemption.

7.8. Concluding Remarks

Effectively, the Norwegian building regulations were management-based at the time of implementation, considering the following:

- The functional requirements were not backed by performance criteria.
- Tools and methods were not available to mechanistically verify compliance [32].
- Risk assessment has been a recommended means of verification throughout [53, 54, 55, 73].
- The regulation of verification is so loose that it mainly regulates the activity – not the performance of the building [57].
- Considerable efforts were made to ensure objective, diligent, and competent fire safety professionals [158]

The least disruptive way of reducing the undesirable effects of verification would be to revert to practicing the current legislation as summarised above. More specific guidance could have made this clearer to practitioners and authorities, but essentially non-mandatory, as key to this approach is to fully utilise competent and accountable practitioners. Such a change, potentially coupled with guidance on ALARP procedures, could have paved the ground for more substantial changes in line with systemic thinking on a longer term.

Although systemic thinking seems to be a strong candidate for the further advancement of the fire safety engineering discipline, more research will have to be made before such a change in paradigm can take place. As will be discussed further in section 8.6, substantial regulatory change is most likely required before the fire safety engineering community can take a holistic approach to the design.

8. Discussion

8.1. Introduction

The intent of this thesis is not only to philosophically discuss how a phenomenon like fire safety can be measured and verified. The thesis is meant to give an insight into the matter, allowing for improvement in the regulations, guidelines, and practicing of performance-based fire safety engineering. Therefore, the discussion in chapter 8 will go further on the following topics;

Sect. 8.2 Status For Performance-Based Fire Safety Design, where a discussion is given on the state of affairs for fire safety engineering. The ability of current legislation to adopt and adapt to knew risks and new experience is discussed.

*S*ect. 8.3 *Further On the Reliance on Pre-Accepted Performance Levels* – as a consequence of lack of confidence in the functional requirements, both regulators and preactitioners have become reliant on pre-accepted performance levels. Too reliant?

Sect. 8.4 What is an Adequate Level of Fire Safety?,A discussion of what adequate safety means, and who are at liberty to set the bar for acceptable risk.

Sect. 8.5 On the Available Predictive Modelling Tools. What are the consequences of chapters 5 and 6 for design?

Sect. 8.6 *Better Return on Society's Investment in Fire Safety.* A critical view on the current regulatory framework, where calls are made for holistic design, while the regulations, guides, and standards present barriers to a wider perspective.

8.2. Status For Performance-Based Fire Safety Design

Section 8.2 discusses the status of performance-based fire safety design, with an emphasis on the Norwegian building regulations.

As seen below, 30 out of the 34 EU/EFTA member states and regions represented in a European survey state that some form of fire safety engineering (performance-based design) is allowed in their jurisdiction [58].

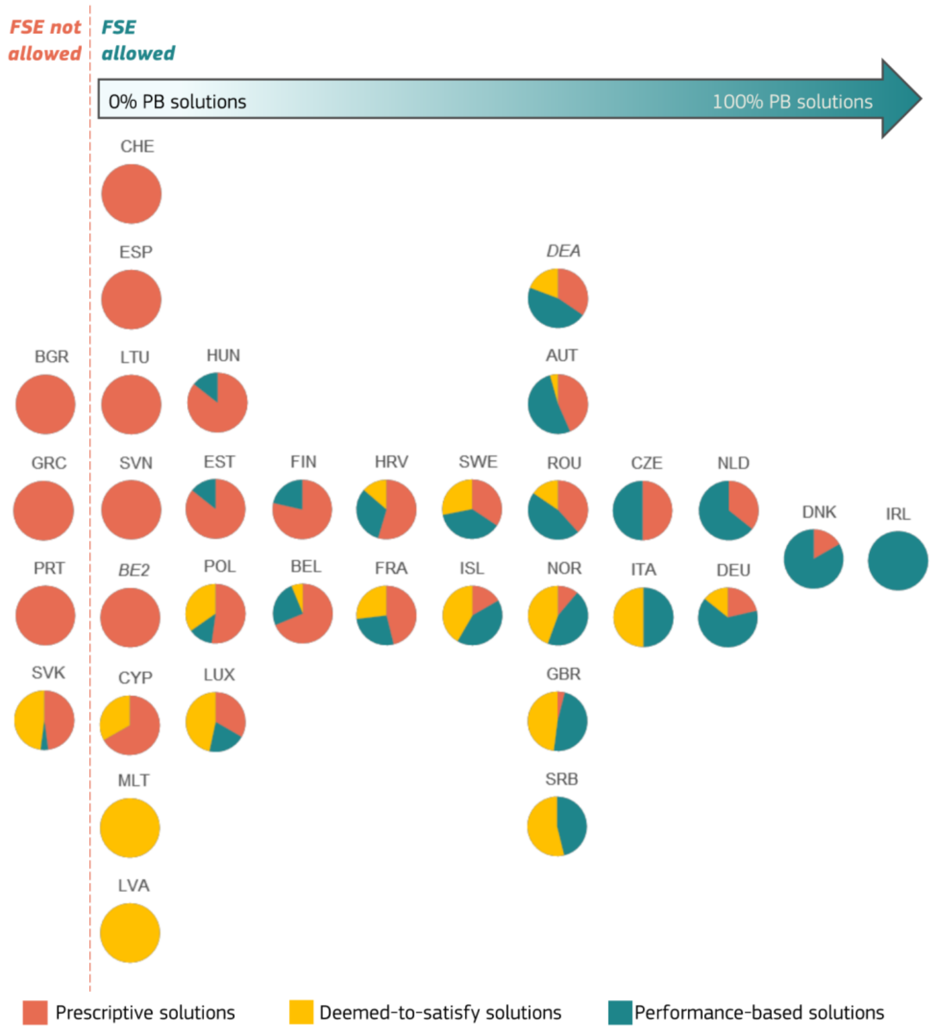


Figure 100 The degree to which performance-based approach is applied in different EU and EFTA member states [58]

Although performance-based building regulations and fire safety design now is widely adopted, increasing attention is drawn to the framework's shortcomings [57, 58, 44, 28].

8.2.1. International Birds-Eye-View

When taking stock of the state of performance-based fire safety design of 2021, Dr Brian Meacham refers to the Gartner hype cycle shown in Figure 101.

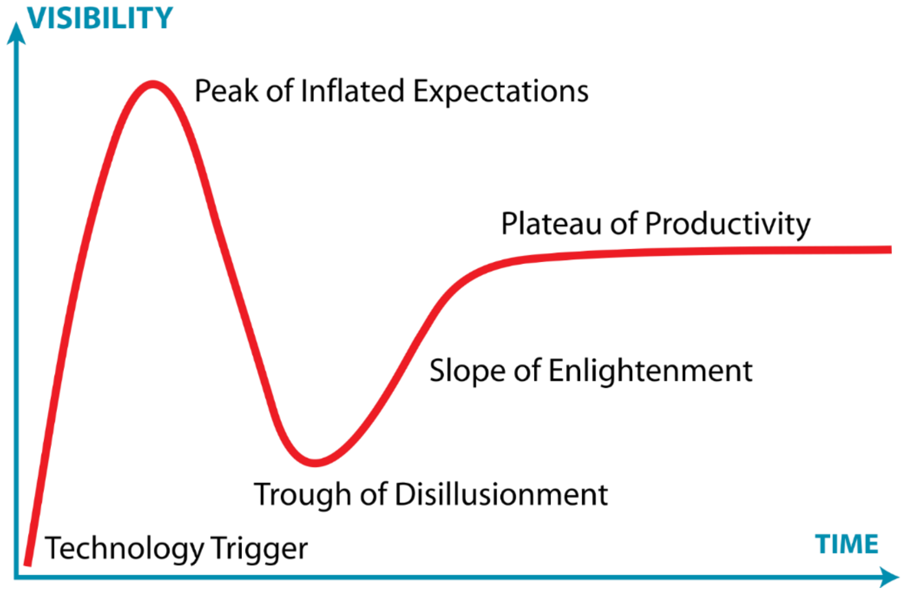


Figure 101 Gartner hype cycle [65]

Meacham argues that the different stages of technology introduction reflect the following stages of performance-based fire safety design [65]:

Technology Trigger

The development of computational tools and introduction of performance-based regulations of the 1980s and 90s, coupled with the publication of the SFPE Handbook and the application of ASET-RSET among other key concepts.

Peak of Inflated Expectations

Meacham argues that the peak occurred between 1990 and 2005, where an abundance of information was available through the Internet, and where the industry could benefit from an explosive growth in computational capability at a moderate cost. Performance-based design was being introduced to seismic and other disciplines, and the discipline of fire safety engineering could be seen to enter a more mature state.

Trough of Disillusionment

The onset of this reduced progress is estimated to around 2005, with a low point around 2010-2012. The introduction of “prescribed performance” and “verification methods” is seen as a countermeasure to the lack of confidence emerging from a period of scrutiny from building and fire authorities. The process-oriented and non-mandatory guidance gave room for variation, which also reduced the confidence in performance-based fire safety design.

Slope of Enlightenment

Optimistically, Meacham place performance-based fire safety design anno 2021 on the slope of enlightenment. This optimism is anchored to the emergence and momentum of systems thinking, and the fact that several jurisdictions are working towards the next generation of regulatory frameworks, where performance-based fire safety design is a key component.

From a Norwegian standpoint, the headlines from Meacham’s summary seem fitting, although the highs and lows are not as extreme, compared to e.g. Sweden, Australia and New Zealand. This can most likely be attributed to clarity of responsibility, where the Norwegian fire safety engineers are signing off their own design, accepting responsibility for its adequacy. In Sweden, on the other hand, the builder is solely responsible.

Furthermore, third-party review has been widely used, ensuring a self-regulating fire safety engineering industry, coupled with supervision from the municipal building authority.

8.2.2. Adequacy of Verification Methods

General state of verification

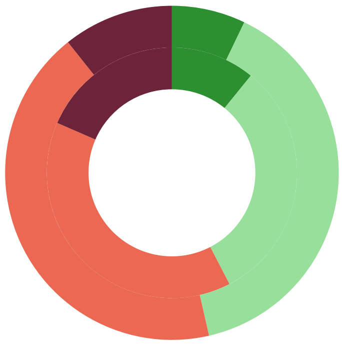
In 1994, NKB summarised the state of verification methods as follows [32]:

Udvalget har fundet, at international standardisering endnu ikke er så fremskreden, at den giver de nødvendige værktøjer og hjælpemidler, som projekterende, udførende og kontrollerende har brug for til ved analyse og beregning at kunne dokumentere, at funktionsrettede regler er efterlevet.	*The committee has found that international standardisation has not yet progressed to the point where it provides the necessary tools and aids needed for designers, constructors, and reviewers to document compliance with performance-based requirements, through analysis and calculation.*

27 years later, despite publications of numerous standards, guidelines, articles, technical reports, and handbooks, SINTEF Byggforsk declared the following [159]:

Man kan ikke uten videre bevise at et funksjonskrav er oppfylt – prosjekterende må først velge en ytelse som er god nok til at funksjonskravet er oppfylt. Funksjonskrav må derfor omsettes til akseptable ytelser før man kan bevise om funksjonskravet er oppfylt eller ikke.	*One cannot directly prove compliance with a functional requirement – the designer must first choose a performance-level suitable for fulfilment of the functional requirement. Functional requirements must therefore be deducted to acceptable performance-levels before one can prove if the functional requirement is fulfilled or not.*

The same lack of confidence in verification methods is seen in a recent survey, as seen in Figure 102 and Figure 103 [134].



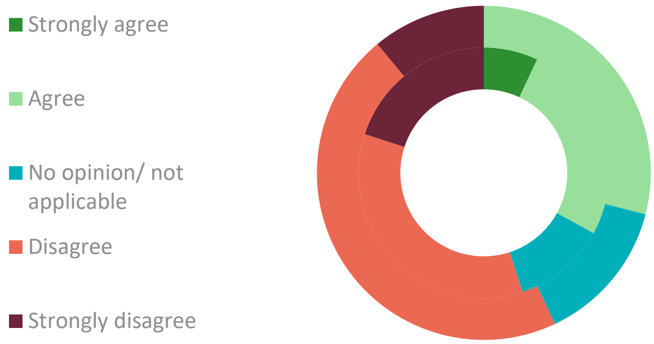


Figure 102 Response to a question 23[10] on the adequacy of expertise, competency and supporting frameworks. (Inner circle: USA, N=106. Outer circle: Non-USA, N=35) [134]

Figure 103 Question 11[11] on the adequacy of the available building code supporting performance-based fire safety design. (Inner circle: USA, N=106. Outer circle: Non-USA, N=35) [134]

Considering the consensus on the inadequacy of the functional requirements and the supporting framework, it is remarkable to note how little change has been made to the functional requirements since their introduction in 1997. Designers, reviewers, authorities, and others have gained substantial experience over these 25 years, which could feed back to future revisions, increasing the relevance and certainty of compliance with functional requirements.

Regardless of the chosen strategy to further develop the building regulations (either more or less verification), inviting to more active participation from the users and stakeholders of building regulations could increase the applicability and ensure better understanding.

Authority Guidance on the Use of Analytical Design

By the time of the introduction of performance-based building regulations, the anticipated share of analytically based design was low. The first two version of the guide to the regulations stated that analytically based design was demanding, and thus best suited for only large buildings and designs deviating substantially from traditional designs [33, 52]. Nonetheless, guidance on analytical design was said to be within the scope of the guidance document, although other sources were required for substantial support for analyses, like NS 3901:1998. It is however worth noticing that the above understanding of analyses, would form the guidance provided both in national standards and guidance documents produced by the national building authority.

As of the 3rd version of the guide [53], after 6 years of experience with performance-based building regulations, the guide described three ways of complying with the functional requirements:

1. Pre-accepted performance-levels,

[10] "In general, I thing the expertise, capability, data, tools and methods are currently adequate to support robust performance-based design for most or all aspects of building design"

[11] "I think that the performance-based building code that is being used or that is available to be adopted and used in my country or jurisdiction, and the necessary regulatory infrastructure to support its use (i.e., acceptable compliance documents and means of verification; adequate support mechanisms for review and approval of PB designs; appropriate system for practitioner qualifications; appropriate insurance structures; etc.) is adequate, appropriate and can be used with a high degree of confidence and comfort."

2. Analytically based design, and
3. A mix, where the majority of the design is based on pre-accepted performance levels, and where the need for analysis is limited to and defined by the deviations from pre-accepted performance-levels.

In addition to introducing the term mixed model (blandingsløsning), the 3rd version of the guide acknowledged that this mix was the predominant model used [53]. Furthermore, the guide indicates that comparative analysis is the most practically viable option for demonstrating compliance.

This substantial shift in understanding, compared to the first two editions, where analytically based design was assumed relevant only for the largest and most complex projects, did however not encompass an increase in guidance on comparative analysis – not until 2007, when the national building authority issued a guide for municipal surveillance [126].

As of 1 January 2013, third party review was mandated for fire safety design project class 2 and 3. A guidance document was published to advice reviewers in their work, and consequently some more information was made available on what the national building authorities deemed necessary for demonstrating and documenting compliance with functional requirements [160].

8.2.3. Pre-Accepted Performance Levels and Functional Requirements

With a low confidence in functional requirements (from the regulators and the regulated), the reliance on pre-accepted performance levels increases. This takes form of more application of prescriptive approaches to design, but also serves as barriers to application of performance-based principles to projects and problems less covered by the pre-accepted performance levels.

Further discussion on pre-accepted performance levels follows in section 8.3.

8.2.4. Still Need for Performance-Based Regulations?

Section 3.13 describes the expected benefits of performance-based building regulations, and as such constitutes reasons for maintaining regulations with functional requirements at the legally binding level.

A review of the expected benefits from a 2023 perspective has not reviled a reduced need for the flexibility provided by performance-based building regulations. On the contrary, the increasing complexity and rate of disruptive change have led to questioning whether the traditional performance-based provides sufficient support [66].

In addition to a continuation of technological development seen in the 1990s, sustainability is a strong driving force in society today. The force is of a magnitude, where society seems to be willing (actively or inadvertently) to accept higher fire risk. If fire safety engineering remains constricted by the building tradition of the 1970s, it is unclear how a safe implementation can be achieved of new energy sources, energy storage systems, new materials, new construction concepts, repurposing of existing buildings, reuse of building components and materials.

8.2.5. Ability to Learn from Fires and Apply New Knowledge

As seen in section 3.13, decoupling the building regulations from technological development and allowing for application of new knowledge are two of the expected benefits of a transition into performance-based building regulations.

Learning from Fires

Although it is imperative to learn from past events, it is also necessary to critically review and revisit the pre-accepted solutions. As described by Haythornwaite [161], there are two types of “bad law”:

> *Laws passed quickly in response to some incident, accident or event (sometimes called ‘knee-jerk regulation’). As a matter of policy, all such laws should include review and sunset clauses. As so few of them do, they should now be systematically reviewed and reassessed to see whether they are still needed and relevant.*
>
> *Laws that reflect past circumstances and, when looked at from today’s perspective, look increasingly anachronistic, cumbersome or irrelevant. For example, much of our current weights and measures legislation may fail this test when seen against current priorities in consumer awareness, business responsibility and reputation management.*

For large fires, the frequency is very low, and it may be difficult to separate “knee-jerk regulation” from learning from fires. An example here is the risk of fire spread between buildings, which since 1969 has been deemed acceptable if there is a separating distance of not less than 8.0 m. The fire at Lærdalsøyri occurred during strong winds, following a longer dry period in the winter of 2014. Fire spread was recorded across a soccer field, more than 200 m [110].

Obviously, the separating distance between buildings cannot be more than 200 m in urban areas, but the evaluation of the fire points to the fact that radiation has been the main concern regarding fire spread between buildings, whilst flying embers was the dominating mechanism of fire spread at Lærdalsøyri. A question is raised as to if the occurrence of strong winds and longer periods of draught are more probable in the future, and if the risk of fire spread thus is increasing.

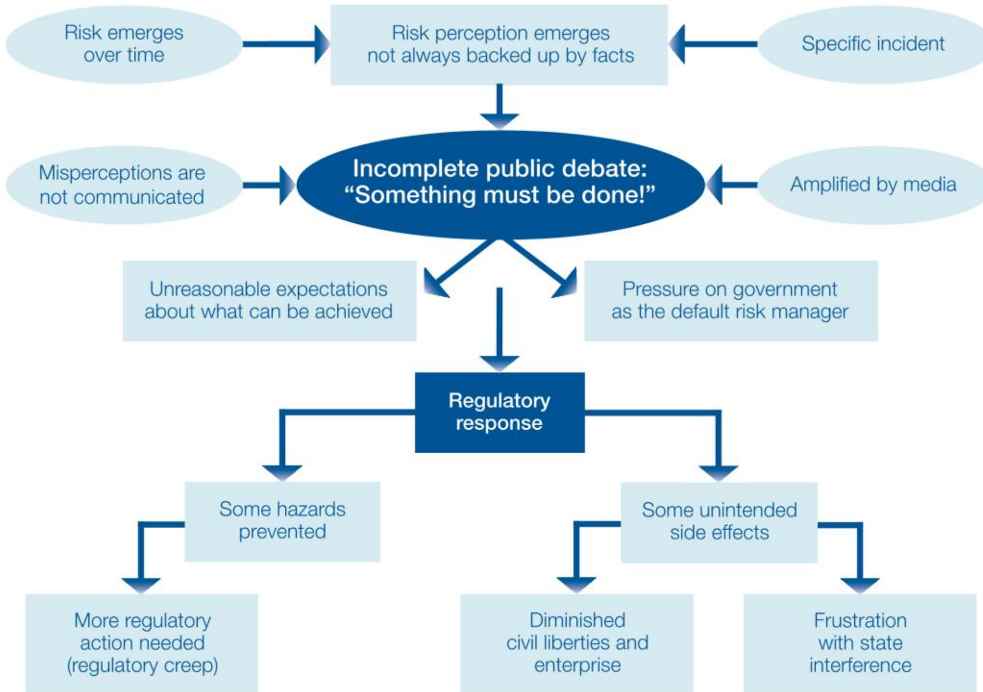


Figure 104 Regulatory response to risk [161]

As seen in Figure 104, authority response to fires may cause regulatory creep, meaning a gradual increase in the required safety levels, similar to the game "helium stick". Inadvertently, the safety level (and cost) increases without due holistic view. Having a rich toolbox of predictive models and a holistic framework for assessing fire risk, such events can be placed in a context, and informed decisions can be made to prevent similar losses in the future, or simply acknowledge that the socioeconomic consequences of mitigating the risk is not justifiable.

Leveson states [66]:

> *Blame is the enemy of safety. Focus should be on understanding how the system behavior as a whole contributed to the loss and not on who or what to blame for it.*

Although it is important to evaluate fires, it is important to respect the different approaches needed. After a fire, there is one specific chain of events that represent *the truth*, thus requiring abduction. During design, on the other hand, neither the fire event nor the outcomes are specific (construction, see Figure 68 on page 115).

Furthermore, it is necessary to take into consideration that fires are low frequency – high consequence events. Some fires are so infrequent that it is correct to ignore their occurrence in design, which also would require the same holistic understanding in the aftermath of such improbable fires.

Implementing lessons

In the aftermath of the fire in Grenfell Tower, London 2017, the Norwegian building authorities found that Norwegian buildings could be vulnerable to the same type of fire. Thus, a draft of revised pre-accepted performance levels was sent for public comment the spring of 2018 [103]:

Etterforskningen av brannen i Grenfell Tower er ennå ikke avsluttet, og det finnes ingen offentlig granskingsrapport fra hendelsen. Direktoratet har imidlertid fått foreløpige resultater fra etterforskningen fra engelske bygningsmyndigheter. Det finnes også mye informasjon tilgjengelig fra pålitelige kilder på internett.

Basert på den gjennomgangen direktoratet har gjort foreslås det endring av preaksepterte ytelser for utvendig kledning på yttervegg (fasade).

The investigation into the fire in Grenfell Tower has not yet been completed, and there is no public investigation report from the incident. However, the National Building Authority has received preliminary results from the investigation from the English building authorities. There is also a lot of information available from reliable sources on the internet.

Based on the review DiBK has carried out, it is proposed to change the pre-accepted performance levels for cladding on external walls (façade).

Anecdotal information indicate that the Ministry finds it difficult to alter the pre-accepted performance levels in the guidance document, if the functional requirement in the regulations is unchanged. Such an understanding can be seen as reasonable, considering that B-s3,d0 is the authorities' understanding of products and materials that have properties which will not "*make an unacceptable contribution to the development of a fire*" [4]. By altering the pre-accepted performance level to A2-s1,d0 one would have to admit that the previous versions of the guide were inadequate, declaring the existing building stock with external cladding in accordance with these performance levels unacceptable.

On the other hand, the understanding above can also be applied to the relation between the Planning and Building Act and the technical regulations. The regulations shall be pursuant to the Planning and Building Act, and as such one can argue that no change can be made to the regulations without changing the act. Clearly, such an understanding will constitute a barrier to the development of the building legislation, and the inability to adapt to new risks and knowledge will effectively become a societal problem.

This discussion defies the purpose of performance-based building regulations, and effectively undermines the functional requirements, as will be discussed further in section 8.3. Reverting to the original philosophies presented in chapter 0, pre-accepted performance levels are nothing but examples which are found acceptable with the current knowledge. New knowledge and new risks may call for changes to the guide.

Application of new technology

Similar to the implementation of new knowledge and lessons from past events, the application of new technology is one of the expected benefits of performance-based regulations. If pre-accepted performance levels fail to reflect the current building tradition, fire safety designers will hinder application of new technology, unless they are willing to accept the risk of a performance-based approach (see subsection 8.2.6).

The design of schools is an example studied in a master's thesis from 2022 [70]. Here, it is apparent how the current design of open plan school buildings conflicts with the presumptions of pre-accepted performance levels and solutions, based on the tradition of establishing separate education rooms connected with corridors – a practice abandoned decades ago.

Similarly, new fire safety technology should be allowed to be implemented with ease in a performance-based regulatory framework, assuming the performance and reliability is adequate. As seen in chapter 4, functional requirements of the regulation are biased towards certain technologies, deteriorating the flexibility of an analytical approach. The same bias in pre-accepted performance levels is not critical, if the legally binding functional requirements are more inclusive.

Consequences

The outcome of the above-discussed mechanisms is a static building regulation, which eventually may be less adaptive than prescriptive regulations. If the change of pre-accepted performance levels requires a revised functional requirement in the regulations, the performance level could have been placed on a legally binding level.

Over time, the lack of updates to the regulations and guides may result in a situation where the distance between pre-accepted performance levels and current design renders the guide less useful – both as pre-accepted performance levels and as a reference building for comparative analysis. In such a situation, only the functional requirement would regulate fire safety performance of buildings.

Ultimately, the reduced ability to implement new knowledge and technology will leave the society exposed to fire risks not known or understood in the past building regulations. Considering the rate of technological change and development in the built environment, the situation is pressing.

8.2.6. Litigation Risks for Practitioners

It is widely acknowledged that performance-based design involves accepting more risk for the designer [156, 159, 57]. On one hand, this risk is a useful mechanism creating incentives to design safe buildings and to provide proper documentation. On the other hand, the risk must be seen in proportion to the legislation and uncertainty in the design stage.

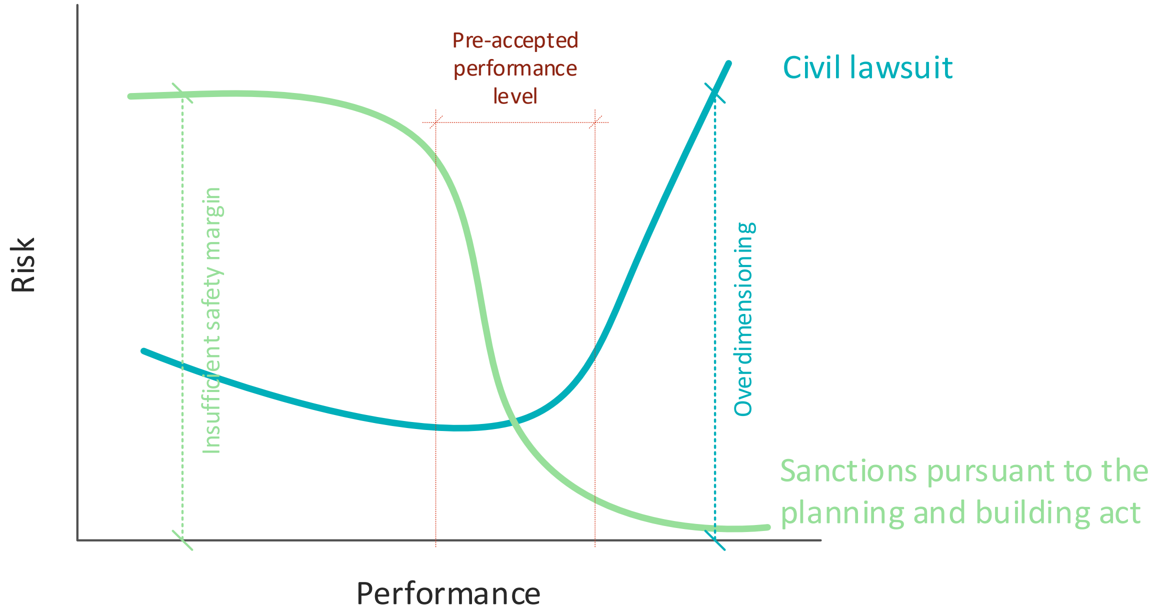


Figure 105 Illustration (on arbitrary scale) of how the designer's litigation risk is affected by fire safety performance.

As illustrated in Figure 105, a very low performance (e.g. low fire resistance) leaves the designer (rightly) legally exposed to sanctions pursuant to the Planning and Building Act, since the required safety margin is not provided. Here, the designer is also likely to be faced with a civil lawsuit if the contractor and/ or owner suffer losses because of the design error. Conversely, the designer is exposed to civil lawsuits if the performance level is overly conservative, inflicting undue cost on the contractor and/ or owner. The centre zone is defined by the pre-accepted performance levels.

Meeting Society's Requirements for Fire Safety

In building regulations based on functional requirements, it is not possible to directly prove compliance with the regulations [159]. Although such a concept does not exist, the pre-accepted performance levels can be misconceived as 100 % safe [123], whilst performance-based design is seen by some as more risky – a risk which must be carried in part by the designer. Alavarez et al [57] states:

> *The concept of risk does not appear to be acknowledged by the regulators, which can lead the FPE [Fire Protection Engineer] to be legally exposed in case of a rare catastrophic event even though the building design seemed robust and appropriate to all the involved stakeholders.*

Considering the margin for interpretation in the functional requirements, the legal exposure to designers is uncertain, and not many court rulings are available to provide precedence.

Safety Nets

As seen from the principles of performance-based regulations in subsection 3.3.6, it must be possible to ensure certainty of compliance as described by NRC [27]:

> *To include a provision as a safety net for the regulator to use as justification when something goes wrong is not acceptable to code users and undermines the credibility of the code.*

There are examples found in Norwegian building legislation and guides, like the following quote (safety net underlined by the author) [73]:

Under forutsetning av at nødvendig tid til rømning og sikkerhet for slokkemannskaper er ivaretatt, kan parkeringshus med mer enn 1/3 av veggflatene åpne oppføres med brannmotstand R 15 A2-s1,d0 [ubrennbart materiale].

Assuming that the necessary time for evacuation and the safety of firefighting personnel is ensured, car parks with more than one-third of external wall area open may be constructed with a fire resistance rating of R 15 A2-s1,d0 [non-combustible].

Here, the relevant functional requirement states that the load-bearing systems shall "*maintain adequate load-bearing capacity and stability for a minimum of the time necessary to escape and rescue persons and domestic animals in or on the construction work*". Thus, the reservation in the guide renders the pre-accepted performance level useless if the designer is required to make an individual assessment of its appropriateness. As seen in subsection 3.11.1, carparks can be placed in project class 1, where there are relaxed requirements to qualifications for the designer, and compliance by applying pre-accepted performance levels shall be possible.

The legal exposure to the designer of a structure collapsing 15 minutes into a fire is uncertain.

One can also argue that the functional requirements can be used as a safety net. Especially for designs in project class 3, the responsible designer is expected to be a competent and trained professional, capable of making independent assessment of the safety in case of fire. Thus, in the aftermath of a fire, the designer may be faced with charges for not advising more conservative performance levels and solutions, or more general criticism, where it is pointed out that "design beyond compliance is allowed" [82, 106].

Finally, fire class 4 can act as a safety net, as seen in the carpark fire at Stavanger airport Sola, January 2020. Despite a separating distance of approximately 35 m, the post fire evaluation argued that "*the multi-storey car park should have been placed in Fire class 4 ("brannklasse 4"), since it was adjacent to important infrastructure for society*" [106]. If fire class 4 had been chosen, the application of any pre-accepted performance levels would have required justification by the designer, whilst for other fire classes pre-accepted performance levels are deemed acceptable, in accordance with TEK section 2-2.

Risk of civil lawsuits

The following shows excerpts from a contract between a contractor (anonymised) and a fire safety engineer in a Norwegian building project:

[Entreprenør] anser overdimensjonering som prosjekteringsfeil iht. NS8401 pkt. 13.

[The Contractor] deems over-dimensioning to be a design error as per NS8401 clause 13.

PRO skal i rimelig utstrekning […] vurdere og påpeke alternative løsninger for oppdragsgiver.	*The responsible designer shall to a reasonable extend assess and propose alternative solutions to the client.*

Contracts like this example are introducing litigation risks even where pre-accepted performance levels are applied, seeing that designers in project class 3 are in a position to find alternative solutions, more favourable to the client.

Considering the lack of specific guidance on performance-based design, and TEK17 section 2-2 mandating a margin of safety (to manage uncertainties as seen in section 6.2), contractual clauses as seen above leaves little to no room between the civil and public litigation risk – thus the intersection point for the two lines of Figure 105 still represent a litigation risk.

Consequences

One must acknowledge the fear of liability and lawsuits as a barrier to innovation [61]. If practitioners experience undue legal exposure when deviating from the pre-accepted performance levels, the intended flexibility of performance-based building regulations is lost.

Similarly, the fear of civil lawsuits will act as a barrier to implementing risk reduction beyond the pre-accepted performance levels. A non-specific requirement for safety margins, and community expectations to risk reduction stands in stark contrast to the client's perspective, seeking cost-optimisation. This can in turn create a "compliance culture", as described in next subsection.

8.2.7. Compliance Culture

Compliance culture is a term used for communities or industries where passing the test is all that matters – even if the test is used outside its field of application, if the assessor is aware of other weaknesses or flaws not identified by the test, etc [89].

A compliance culture within fire safety engineering can be relevant in more than one aspect.

Whenever the design is in accordance with pre-accepted performance levels, the designer can assume compliance, and there are no incentives to further reduce risk beyond compliance. Furthermore, in a compliance culture, the actors will not actively seek to identify and mitigate risks for which there are no pre-accepted performance levels.

In the context of analytical design, a compliance culture may occur where detailed stipulations are given for the verification (prescribed/ specified verification methods). Here, the designer has no reason to spend resources on identifying hazards or risks that are not covered by the verification method. Even if there are factors indicating the need to consider more onerous fire scenarios, design fires, or other assumptions than given by the verification method, the analyst would not do it in a compliance culture.

8.2.8. Summary

Through section 8.3 we have seen a supplementary discussion to the discussions of metrics in chapter 5, verification concepts in chapter 6, and support structures and alternatives to verification seen in chapter

7. In summary, the fire safety engineering community is still in a state of adolescence, where key aspects and holistic frameworks still are missing.

As discussed, also minor adjustments to the current regime can have significant impacts – for better and worse. The current Norwegian building regulatory framework demonstrates an inadequate ability to adapt to change, implement lessons from fire, and gather and act upon feedback.

Signs are seen indicating an increasing fear of legal litigation, which can further diminish both the expected benefits of performance-based regulation, and ultimately the fire safety of the built environment.

Meacham's summary resonates with the authors observations of the Norwegian fire safety engineering community [65]:

> *Given the current status of fire safety engineering, and especially performance-based design for fire safety, it can be argued that fire safety engineering is a healthy adolescent. Unfortunately, this has not changed since 1999, when it was observed that "research has begun better addressing the needs of practice, the essential elements of a framework and vocabulary have been developed, and many practitioners appreciate where and how the current methodologies can address their problems. However, the field remains largely uncoordinated, it lacks a comprehensive framework where the limits of effectiveness are well understood, and some applications are rather naively formulated."*

8.3. Further On the Reliance on Pre-Accepted Performance Levels

It may seem contradictive to draw attention to pre-accepted performance levels in a thesis on quantification and verification of fire safety performance. The pre-accepted performance levels are however relevant of several reasons:

- They are widely applied and should cover most projects – either for direct application, or as basis for comparative analysis.
- They are instrumental as examples of acceptable designs, providing substance and context to the functional requirements.
- Mitigating the legal concerns as described in 3.12 may require a change in how the pre-accepted performance levels are handled. Caution must be exercised to avoid undue limitations in design flexibility.

As seen in the previous section, and in chapter 6, the currently available verification methods are not fit for providing proof of compliance with functional requirements, and as such, both regulators and practitioners must rely on pre-accepted performance levels.

Thus, section 8.3 gives a discussion of some elements of pre-accepted performance levels and their relevance to performance-based design.

8.3.1. Examples or Minimum Requirements

Two different understandings can be applied to the status of the pre-accepted performance levels:

1. They are examples of solutions and performance levels which in sum will comply with the functional requirements of the performance-based building regulations, or
2. They are minimum requirements, implying that any deviations from the pre-accepted solutions or performance levels must be compensated (trade-offs).

At first glance, the two understandings can seem closely related, or even overlapping. The following example is meant to clarify the difference:

The pre-accepted performance level for egress capacity is 1 cm per person. Section 12-7 of TEK17 (architecture) requires ceiling heights to be not less than 2.4 m for continuous occupancy. The first alternative to status of pre-accepted performance levels would allow the designer to assess the benefits of a ceiling height greater than 2.4 m and allowing an egress capacity less than 1 cm per person (either by doing a comparative analysis of available safe egress time, or by doing an analysis of ASET vs. RSET). The second alternative would treat 1 cm per person as a minimum requirement, with no regard to the ceiling height.

The wording of the regulation (TEK17) section 2-2 primarily points out that there are two alternative routes of documenting compliance – by applying pre-accepted solutions/ performance levels, or by analysis. The guide, VTEK does however contain phrases supporting the second understanding (guide to section 2-2):

Analysen skal dokumentere at de alternative ytelsene som er	*The analysis shall document that the chosen alternative*

valgt er likeverdige med de preaksepterte. Det vil si at de alternative ytelsene samlet sett må gi minst samme kvalitet og sikkerhet som om de preaksepterte ytelsene var fulgt.

performance levels are equivalent to the pre-accepted. Meaning that the alternative performance levels as a whole must result in at least the same quality and safety as if the pre-accepted performance levels were applied.

The first sentence calls for equivalence, increasing the focus on comparative analyses, and implying that the pre-accepted performance levels are minimum requirements. The second sentence does however allow for a more holistic view, pointing out that the required quality or safety can be achieved by different means.

As will be seen in subsection 8.3.3, the communication from the national building authority has varied over time.

8.3.2. Resulting Safety Level

Key to the relevance of pre-accepted performance levels for fire safety engineering is that they are a source of information on tolerable risk, in leu of explicit performance criteria or verification methods fit for demonstrating compliance with functional requirements.

Groupings and Classes of Construction Types

For ease of use, most pre-accepted performance levels and solutions are grouped and categorised, so they apply to certain hazard classes, fire classes, or their application relies on thresholds for fire load, occupant load, building height, etc. Consequently, the resulting level of safety will be stepped as indicated in Figure 106.

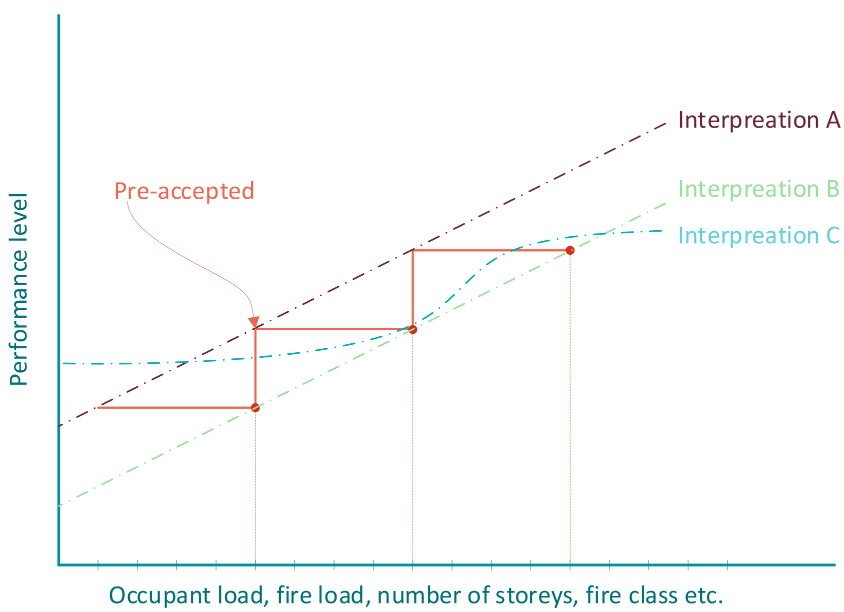


Figure 106 Pre-accepted performance levels and potential interpretations, reworked from [31]

For analytical purposes, it is relevant to know what the minimum acceptable performance level is. Let us consider the fire resistance of a fire wall based on the fire load. The pre-accepted performance level is REI 180-M A2-s1,d0 for the range 400 - 600 MJ per m² total surface area. For fire loads less than 400 MJ/ m² REI 120-M is acceptable, whilst fire loads 600 - 800 MJ/ m² calls for REI 240-M. Interpretation B in Figure 106 is applied, assuming that the performance level is acceptable for the entire interval, meaning it is overdesigning buildings where the fire load is 600 - 790 MJ/ m². Lundin gave a similar illustration, as reproduced in Figure 107 [157].

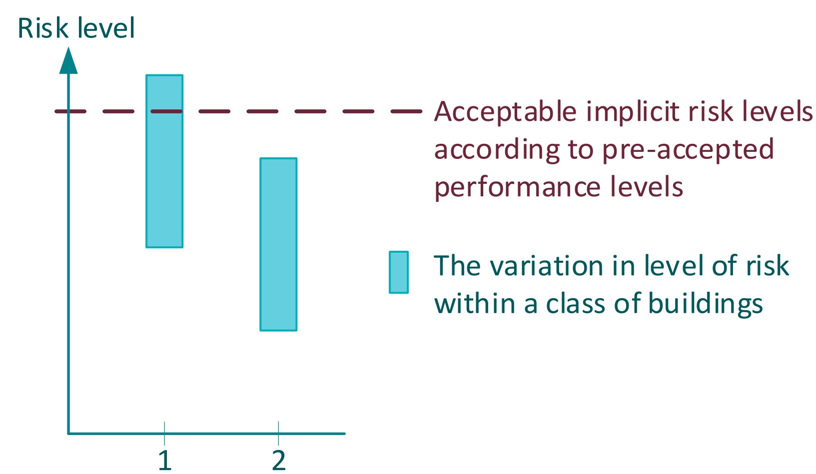


Figure 107 Two interpretations of the risk levels of class of buildings [154, p. 140]

Lundin considered that a possible interpretation was that the average risk of the class of building was deemed acceptable (interpretation 1 in Figure 107). If that was the case, some pre-accepted would fail to meet the mandatory fire safety level – defying the purpose of pre-accepted performance levels. The second interpretation is in line with the exemplar fire wall above, where the level of risk and the variation within all classes are deemed acceptable.

Residual Risk

Although obvious to most professionals, the pre-accepted performance levels do not represent zero risk. A more open attitude regarding residual risk and shortcomings of the pre-accepted performance levels could have contributed to a higher status for the functional requirements.

In the third version of the guide to TEK'97, the following text accompanied the pre-accepted performance levels for acoustic conditions [53, p. 128]:

> *Når forskriften benytter uttrykket «vesentlig støyplage» mener en slike virkninger av støy som statistisk sett gjør at mer enn 20 % av brukerne er misfornøyde med lydforholdene.*

> *When the regulation uses the term "significant noise disturbance," it refers to such effects of noise that statistically result in more than 20% of users being dissatisfied with the acoustic conditions.*

This explicit description of the performance levels' imperfection is useful for aligning expectations to the performance but is also informative when a performance-based approach is applied.

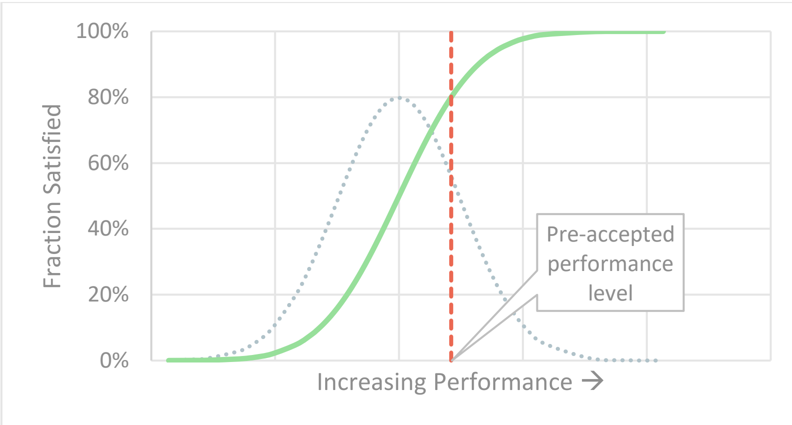


Figure 108 Illustration of the correlation between performance levels and the fraction of users being satisfied, assuming normal distribution. Pre-accepted performance levels for acoustics are indicated with a red dashed line, resulting in 20 % being dissatisfied.

Equivalent descriptions or explanations would be of great use for fire safety performance levels - even if similar quantification was possible. For one, this would serve a purpose of making clear the existence of residual risk also where pre-accepted performance levels are applied. Such a description would however be of even greater value where a performance-based approach is applied.

Let us contemplate for a moment on the design of acoustic conditions of a building. As opposed to the fire safety performance, the acoustic performance will be put to the test by occupants daily. The 20 % of users being dissatisfied may complain, or in some cases press charges through lawsuit. The designer would in these situations be well served by 1) referring to the fact that pre-accepted performance levels have been applied, or 2) substantiating that the acoustic performance is at least equivalent. By designing for 80 % of the occupants being content with the acoustic performance, the remaining 20 % are not neglected, but it is not socioeconomically viable to meet expectations of all potential users.

Fortunately, the fire safety performance of building is less frequently put to the test. Still, the comparison is valid, seeing that a cut-off must be made where further risk reduction would have been too costly. Thus, fires are expected to occur where the combination of circumstances result in an event where the consequences are greater than society readily tolerates. Post fire evaluations should focus on learnings and providing insight to the event, without introducing undue regulatory creep/ helium stick, as mentioned in subsection 8.2.5. It is furthermore important to also acknowledge the existence of residual risk – whether the design is prescriptive or performance-based.

8.3.3. Evolution of the Status of Pre-Accepted Performance Levels

In Table 12 seven quotes regarding the status of pre-accepted performance levels are given. They are dated in the first column, and a brief comment is provided in the rightmost column.

Table 12 Description of pre-accepted performance levels over time by NKB [25], the national building authority [33, 54, 126, 55] and finally by the ministry in their instructions to DiBK for 2022 [56]. Norwegian text translated by the author.

Time	Source	Description of pre-accepted performance levels	Comment
Nov 1978	NKB:34 [25]	*Nothing on this level is mandatory*	Referring to level 3 Supplement to the regulations with examples of acceptable solutions
Oct 1997	REN 1st ed [33, p. 7]	*It must be absolutely clear that the guide's pre-accepted solutions are not regulations, but descriptions of solutions that satisfy the regulations.*	Introduction to the guide. Description removed in 4th ed.
Oct 1997	REN 1st ed [33, p. 42]	*This guide provides pre-accepted solutions or performance levels which comply with the regulations' minimum requirements.*	Introduction to fire safety section of the guide.
Mar 2007	VTEK 4th ed [54, p. 10]	*This guide interprets the regulations by providing minimum performance levels to be used as basis for design and construction of construction works.*	Updated text, where the guide is the source for minimum requirements – not the regulations.
Nov 2007	HO-3/2007 [126, p. 8]	*The government's interpretation of minimum performance levels for compliance with the functional requirements are given in the guide to the technical regulations.*	Text in a guide for municipal supervision. As VTEK 4th ed., the guide sets "minimum requirements".
Apr 2014	VTEK10 § 2-1 [55]	*Pre-accepted performance levels represent the minimum of what the government deem necessary to comply with the requirements of the regulations.*	Reduces focus on interpretation of functional requirements.
Jan 2022	KDD [56, p. 5]	*Changes to pre-accepted performance levels in the guide that involve changing the level of requirements must be made through regulatory amendments.*	The Ministry deems it necessary to treat changes to the guide as a regulation.

As seen in Table 12, there has been an evolution in how the pre-accepted performance levels and solution have been presented. As indicated with double red lines, there is a significant shift in 2007, where the regulations no longer are the source of the required levels of safety. Although the wording does not change much, the implications for the status of the guide are profound: From 2007 the national building authority claims that the pre-accepted performance levels in the guide are minimum requirements.

The introductory sections of the 2007 version of the guide give a summary of the changes to the guide, mainly concerning amendments to the regulation regarding health/ environment and water supplies/ sewage installations, not fire related.

During the enquiry for the 2010 version of the building regulations, the text from versions 1 through 3 of the guide were reintroduced ("it must be absolutely clear …"), but the guide to the effectuated regulation did not reflect this (see Table 12). On the contrary, the following text was introduced in section 2-1 2 b:

Reduksjoner i noen av veiledningens ytelser krever kompenserende tiltak for å opprettholde det samlede kravsnivået som følger av forskriften.

Relaxation to any of the performance levels given in the guide necessitates mitigating measures to attain the level of performance pursuant to the regulations.

The legal implications of this shift are presented in section 3.12 and reference is made to the following sources for further reading [49, 50, 51]. As pointed out in [68], there is not warrant in the regulation to give the guide this status.

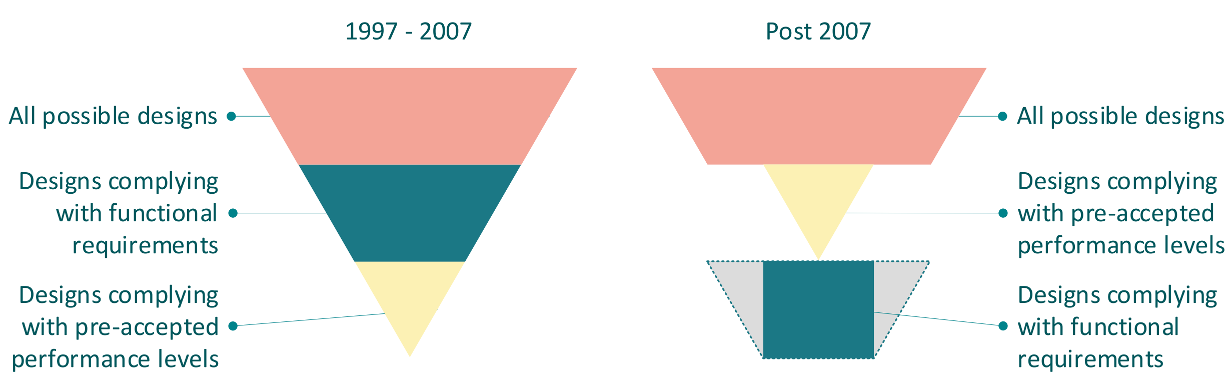


Figure 109 Illustration of the shift of status for pre-accepted performance levels in 2007.

As Figure 109 illustrates, the shift of 2007 places the status of the guide above the functional requirements of the technical regulations – which is not in line with basic legal principles. Furthermore, this wording in the guide undermines the functional requirements, reducing them only an informative backdrop to the pre-accepted performance levels. Reverting to the intentions and expected benefits of performance-based building regulations, we can see that this approach will reduce the applicability for novel designs and fire class 4 to the level of the more prescriptive building regulations pre-1997.

Finally, the shift implies (and is even stated in plain text as quoted above), any deviations from pre-accepted solutions must be compensated. If an assessment of available and required safe egress time (ASET-RSET) shows an adequate margin of safety, the above-mentioned understanding would require even further risk-reducing measures if e.g., the egress width does not equate at least 1 cm per occupant.

Referring to the anticipated outcomes of the Nordic research project mentioned in section 3.7 [36, p. 84], new analytical tools would not be sufficient to justify reductions in fire resistance where fire suppression systems are installed. If the analyst is required to show compliance by equivalency, the reference building would have fire suppression system and fire resistance in accordance with the guide to the building regulations.

8.3.4. Empirical Basis for Pre-Accepted Performance Levels

The pre-accepted performance levels are said to be based on empiricism [53]:

Ytelsesnivåene i veiledningen er i det vesentlige basert på empiri, løsninger som i praksis har vist seg gode nok. Det er også slik erfaring som ble lagt til grunn da forskriftens funksjonskrav ble formulert.	*The performance levels of the guide are mainly empirically based, solutions which in practice has been found adequate. This experience is also used as foundation for the creation of the functional requirements of the regulations.*

As will be further discussed in subsections 8.4.4 and 8.6.4, fires are infrequent events, and not evenly distributed over different building types. Furthermore, measures like sectioning walls, fire walls, and fire protection of load-bearing systems are meant to reduce the potential for a complete loss, meaning only a small portion of the fires will challenge these systems. Consequently, the experience is largely limited to the types of buildings where fires are more frequent, and to the fire safety systems involved in the early stages of a fire.

As proposed by NKB [32], much of the content of the prescriptive regulations of 1987 was transposed into pre-accepted performance levels and solutions in 1997. Thus, many pre-accepted performance levels have long traditions, beyond the performance-based regulations. As seen throughout this thesis, the performance of one component is an insufficient measure of the building's fire safety performance. Thus, a performance level with long tradition cannot be deemed satisfactory in isolation. This was clearly demonstrated in the Sola carpark fire, where a traditional approach was taken to a building where the properties of the vehicle fleet had changed substantially since the formation of the applied performance-levels and solutions [106].

Although long traditions and claims of empirical evidence increases confidence in the pre-accepted performance levels, it also forms a barrier to change. Changes to one aspect in the guide to the building regulations may impact other subsystems in ways not obvious to the regulators.

Although both terms are used for referring to pre-accepted performance levels, there is a significant difference between “deemed to satisfy” and “designs known to be satisfactory”. The pre-accepted performance levels are known to comply (as per TEK sect. 2-2), but the fire safety performance the buildings remain unknown – even where pre-accepted and traditional approaches are taken.

8.3.5. Implicit or Explicit Safety

Hopkin et al gave the following illustration of the difference between applying pre-accepted performance levels (for design or as basis for comparative analysis) and performance-based design.

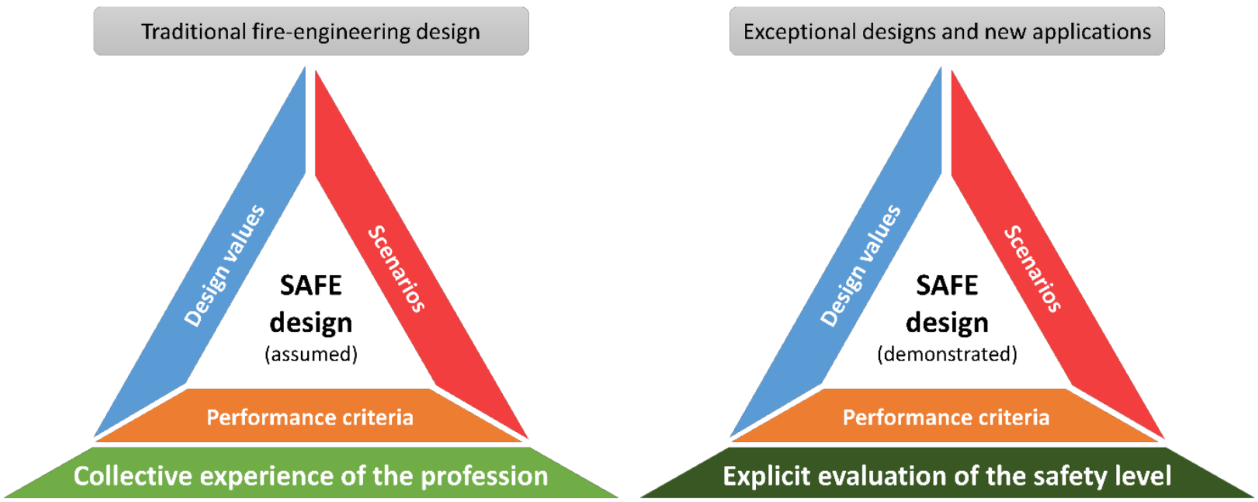


Figure 110 The difference between assumed, implicit safety in pre-accepted performance levels (left), compared to the demonstrated, explicit performance in fire safety engineering (right) [138]

Paradoxically, the implicit (assumed) safety appears more known or familiar than explicitly demonstrated safety, as many of the pre-accepted performance levels and solutions have long traditions. As discussed in the previous subsection, dethatched homes, warehouses, and few other building types are well known through real fires, whereas many other building types (for which trade-offs and performance-based design is more widely applied) the collective experience of the profession is very limited. On the other hand, performance-based design can to a greater degree give an explicit evaluation of the obtained safety level.

8.3.6. Adequacy of Pre-Accepted Performance Levels

As per TEK section 2-2, there is no need for further verification when pre-accepted performance levels are applied. Thus, the pre-accepted performance levels are deemed adequate.

The adequacy is however questioned through safety nets as discussed in subsection 8.2.6. Unexpressed expectations to reduce risk beyond compliance is another form of doubting the adequacy of performance levels and solutions stipulated by the guide to the building regulations (e.g. [162, 155]).

Lastly, uncertainty of the adequacy of pre-accepted performance levels can be introduced by how they are presented in the guide to the building regulations, as seen in the example below [73].

Rømningsvei kan inneholde mindre avgrensede rom for andre formål dersom forutsatt bruk av byggverket gjør dette nødvendig og dersom disse ikke reduserer rømningsveiens funksjon. Eksempler er resepsjon og vaktrom med inntil 20 m² gulvareal som er knyttet til korridor, og som er avgrenset slik at møbleringen ikke har mulighet for å vanskeliggjøre rømningen, jf. figur 1. Dette unntaket kan ikke benyttes som grunnlag for dokumentere andre fravik i rømningsveier.

A protected corridor may contain smaller, defined rooms for other purposes if the intended use of the building makes this necessary and if these do not reduce the function of the protected corridor. Examples are receptions and guardrooms with area up to 20 m² which are connected to a corridor, and which are defined so that the furniture has no possibility of making escape difficult, cf. figure 1. This exception cannot be used as a basis for documenting other deviations in escape routes.

The following figure accompanies the above text.

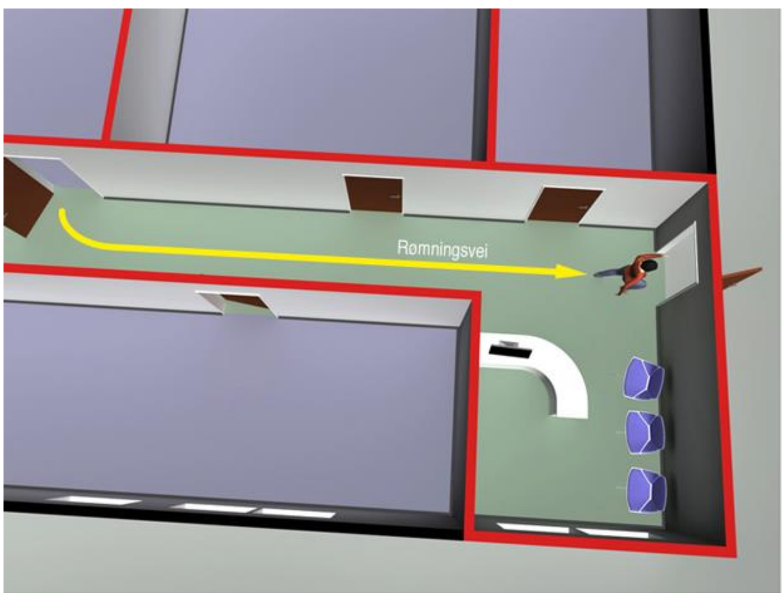


Figure 111 Illustration of a protected corridor containing a reception [73]

The above quote is nothing short of a paradox. Either

1) The described solution complies with the functional requirements of the regulations – meaning it may for basis for a comparative analysis, or

2) it does not comply with the functional requirements – meaning it should not be proposed as acceptable in the first place.

The example is a visualisation of the two roles of the guide, which do not always converge. For one, the guide shall give clear descriptions of acceptable solutions, and also provide answers to common issues, like receptions in protected corridors. On the other hand, the guide shall ease the understanding of the functional requirements, so that the pre-accepted performance levels can be applied correctly, or to provide a broader understanding of the building authorities' interpretation of the functional requirement as basis for an analysis.

8.3.7. Clarity of Intent

When assessing the consequences of deviating from a pre-accepted performance level or solution, it is imperative to have a clear understanding of what the pre-accepted performance level or solution aims to achieve. As of 2010, the format of the guide has been set up to make the link between functional requirement and pre-accepted performance level clearer. Many performance levels and solutions do however have an unclear intent – and even an unclear effect on fire safety.

The same is seen in Sweden, where a private initiative has collated what they consider the most probable intent of 72 pre-accepted performance levels and solutions [163]. The work is structured around:

- Dissection of the current wording of the guide to the building regulations,
- Review of previous versions of Swedish regulation on the topic,
- Reference to correspondence with the national building authority, Boverket,
- Comparison to other jurisdictions (typically Norway, UK, USA, Canada, New Zealand and Australia).
- Interviews.

For each topic the assumed intent is described, and the uncertainty is categorised.

Although the work is impressive, it should not be necessary. All parties benefit from clearly described intents. It is recognised that the guide constitutes decades of experience, and as such, documentation may be scarce on certain topics. A process (or roadmap), albeit time-consuming, should be initiated to improve the scientific and explicit intent and performance of pre-accepted performance levels and solutions.

8.3.8. The Need for Benchmarks and Examples

The existence of definitions and examples make a significant difference when the legally binding requirements are qualitative statements.

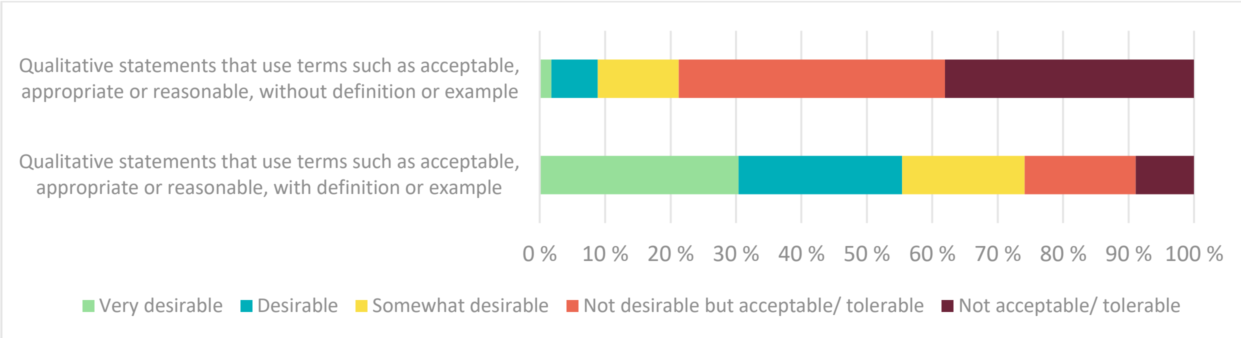


Figure 112 Excerpt of results from a survey, where 114 persons responded to the question "Please indicate the desirability of different forms of benchmarks to demonstrate compliance / verify performance" [121]

As seen in Figure 53, close to 80 % of the responders find qualitative statements not acceptable or desirable without definitions or examples. By the introduction of examples and definitions, this number is reduced to 25 %, and 55 % find this situation desirable or very desirable.

8.3.9. Conclusions

Due to a lack of confidence in functional requirements and the fire safety professionals, pre-accepted performance levels remain central in the current performance-based regulatory framework in Norway.

Consequently, the technology and building tradition of the 1980s remains the benchmark for a regulation intended for innovation and flexibility. Although the prescribed performance levels and solutions are well-known, the resulting safety level is implicit and remains unknown.

If the trust in the functional requirements and the verification is not strengthened, it is reasonable to assume that the development will continue towards a more prescriptive building regulation. Two strong driving forces are aligned:

1. Ambitions to digitalise the building regulation.
2. The legal issues, as described in section 3.12 must be resolved.

One of the least disruptive ways to mitigate would be to rise the pre-accepted performance levels to a legally binding level. Some flexibility could be retained by allowing for equivalency assessments against the pre-accepted performance levels, but the risks for "compliance culture" and misuse/ misinterpretations must be recognised.

8.4. What is an Adequate Level of Fire Safety?

8.4.1. Reflections on Fire Safety

Fire safety is not a static attribute of a building, which can be predicted, measured, or modeled in an objective manner. Even without introducing new paradigms like systems thinking, it is obvious that the fire safety is the product of a complex interaction between occupants, emergency responders, the structure, fire safety systems, and the highly stochastic phenomena fire.

Thus, the question of verification is not only a challenge to represent fire development, occupant response, material and building products response, fire brigade intervention. These phenomena must all be studied further to increase our understanding, but even in a hypothetical world, where all these models were available and perfectly validated, there would be a tremendous need for data. Again - if all this data was available, a great challenge remains – We don't know what type of fire can occur in a given building. To what degree is it reasonable to design for improbable events, even when the expected consequences are high.

This thesis is written with an emphasis on the design stage – a minuscule phase in the total lifetime of construction works.

A well-functioning framework for verification should enable seeing fire events in light of their likelihood – even after an unlikely event has occurred.

To a fire safety professional, a concept of absolute safety may be difficult to grasp. To the general public and through media, this idea may be used frequently, implying that a building is either safe or unsafe. When considering risk, it is more apparent that safety is a continuous concept, and not a binary or discrete one.

Similarly, functional requirements may use absolute, deterministic terms (e.g. fire shall not spread between buildings), although neither pre-accepted performance levels nor performance-based designs are expected to eliminate the risk.

Whether the fire safety design is based on pre-accepted performance levels, deviations, or fully performance-based approach, there is residual risk. The residual risk cannot be eliminated, but a further reduction can be considered from any standpoint. The required minimum fire safety level is the break-even point, where regulators deem the costs of further risk reduction no longer being in proportion to the reduced loss.

8.4.2. Who Can Define Performance Criteria?

Most descriptions of the fire safety engineering process point at the need for identifying performance criteria, acceptance criteria, or means of determining the adequacy of the design. The wording reveals nuances in how and by whom a design can be deemed acceptable:

- “Identify performance criteria” [78, 34].
- “Agree criteria/limits” [7].
- “Developing performance criteria” [164].

From semantics, one can see an increasing level of freedom for the designer in the above shown examples. “Identify” would imply that a criterion already exists, and that it is up to the analyst to find it.

ISO 23932-1 does not explicitly describe this and does not give any sources for performance criteria. British standard describes a process of *Qualitative Design Review* where relevant stakeholders are involved in defining criteria for acceptable risk [7], and thus, the term “agree criteria/limits” reflects this cooperative process of finding an acceptable criterion, specific to the project. Finally, the term “developing performance criteria” from the SFPE Guide, may seem open, but the guide gives further description, including stakeholder involvement, “translation of design objectives into performance criteria”, and performance criteria set by the applicable code. The SFPE Guide is also written in an USA context, where the authority having jurisdiction (AHJ) will be involved and has a chance to influence the chosen criteria.

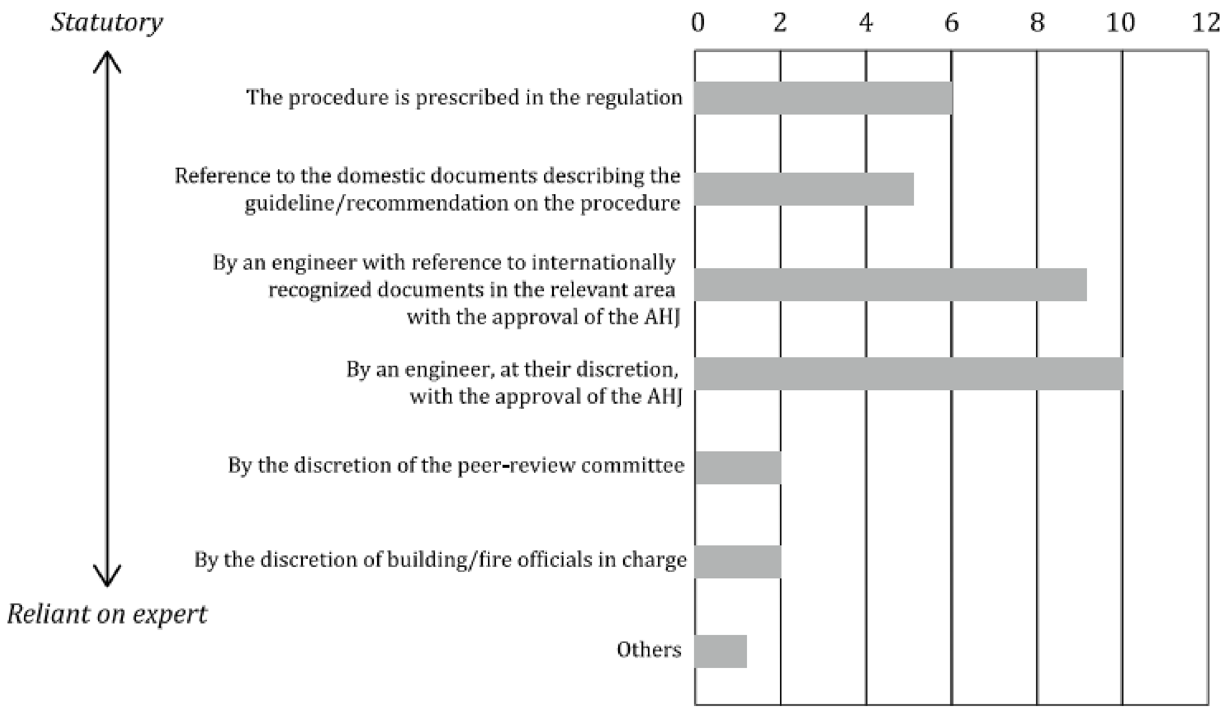


Figure 113 Survey responses to the question: How the safety criteria is determined in a performance-based fire safety design project? [3]

The challenge of providing real regulation of the final level of safety in performance-based building regulations has been known and discussed since performance-based codes have been considered. Babrauskas discussed these questions in 1998, finding that the loose regulations (and guides) failed to ensure a minimum acceptable level of safety [165]. He was not proposing to discard the concept of performance-based design, but argued that the following had to be prescribed to ensure the public’s right to safety:

- Minimum loadings
- Minimum safety factors
- Mandated fire scenarios, and
- Quantitative criteria, expressed as equations explicitly describing the pass/fail demarcation.
- And by identifying permitted and prohibited design methods for various sub-systems.

Considering the available guidance documents and verification frameworks, he pointed towards the British standards (the predecessors of BS 7974) as the only framework close to being acceptable. In short, he called for a mechanistically verification approach, as discussed in subsection 8.5.3.

In that respect, Bjelland asks "*How can authorities accept that a standardisation organisation puts itself into the regulator's driving seat?*" [152], implying that neither consultants nor standardisations are at liberty to set the bar for fire safety. This is resonating with the Official Norwegian Report (NOU) 2006:6 which states that it is "*government's responsibility to determine the level of safety for critical supplies and services*"[12] [166]. It is further mentioned that an increasing share of the critical infrastructure is privatised, and the report discusses the implications for roles and responsibilities. It is concluded that government regardless is not free from liability since the general population expects the government to adequately ensure a safe and resilient society.

The question then is whether the functional requirements truly regulate the level of safety?

8.4.3. Confidence in Functional Requirements

Verification is a process of demonstrating compliance with a functional requirement. If this can be done independently of the relevant requirement, the functional requirements are close to meaningless. Even in a regulatory environment where the practitioners "can be trusted", the level of safety should be anchored in something outside the analyst.

A project for increased application of functional requirements was proposed by the Norwegian government in 1999 [167], but substantial results of this project has not been found.

ISO has collated international examples of fire safety objectives and functional requirements [5]. Within the Norwegian industry, there has been no user involved process of improving the functional requirements after their introduction in 1997. It is known that previous building regulations (35 years old or more) and (mainly undocumented) empiricism formed basis for the functional requirements [53] and that very little practical experience was obtainable at the time of their introduction [32].

Even without quantification, TEK17 display examples of well-formulated verifiable functional requirements:

Sect. 11-4 § 4	*Main load-bearing systems in construction works in fire classes 3 and 4 shall be designed to maintain adequate load-bearing capacity and stability for the complete duration of a fire, insofar as this can be modelled.*
Sect. 11-11 § 2	*The time available for escape shall be greater than the time required to escape from the construction works. An adequate safety margin shall be included.*

[12] "*Det er derfor et statlig ansvar å fastsette ambisjonsnivået hva gjelder sikker leveranse av kritiske varer og tjenester*"

The majority of functional requirements are however based on qualitative terms which without examples, benchmarks, or supplementing information are of low value to both regulators and practitioners, as seen in the following examples.

Sect. 11-9 § 1	*Construction works shall be designed and constructed to ensure that the probability of fires occurring, developing and spreading is minimal. The use of the construction work and the time necessary for escape and rescue shall be taken into account.*
Sect. 11-17 § 1	*Construction works shall be sited and designed to ensure rescue and firefighting personnel, and their required equipment, are able to gain useful access to and inside the construction works for rescue and firefighting efforts.*

Van Coile et al summarise [124]:

> *[…] defining acceptably safe designs involves uncertainty and subjectivity. This is unworkable, both from the perspective of the engineer developing the design, and from the perspective of stakeholders or governmental bodies wishing to assess the design, either proactively or reactively*

8.4.4. Statistically Based Acceptance Criteria

INSTA 951 and the proposed risk acceptance criteria in Australia are both justified by considering the fire risk as it is observed in the statistics [78, 168]. Although this offers an opportunity to monitor and tune the required level of safety obtained by the building regulations, there are some underlaying mechanisms which may obscure the picture.

Rationale

Statistics may be used to justify a certain risk, by arguing that the risk has been observed over time, without governmental interference. Thus, the risk may be seen as implicitly tolerated, due to lack of action. The justification may be strengthened by reducing the risk, as seen in INSTA 951, where the annual risk for loss of lives is reduced by a factor 10 compared to the statistics.

Occupancies

A vast majority of fire casualties in Norway are recorded in residential fires. Thus, if one criterion is given as a tolerable or acceptable risk across different occupancy types, a consent is given for a considerable increase in risk for the occupancies with a statistically lower fire risk.

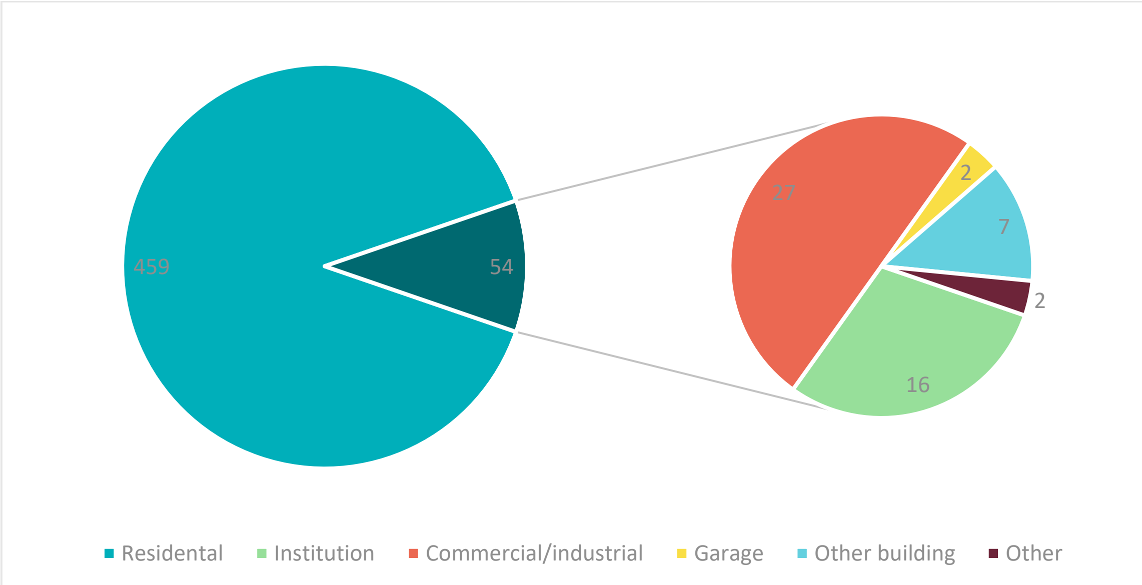


Figure 114 Number of fatal fires in the period 2005-2014, per type of building (n=513) (RISE Fatal fires 2005-2014) [169]

If no significant action is taken by building authorities over time, the above statistics may be used as a benchmark for design of residential buildings. But to what extent can this data indicate risk acceptance for less frequent fires?

Based on the above, different designers may take different approaches.

1. Observed fire risk may be deemed satisfactory for all occupancies.
2. A significant reduction to the observed fire risk may be deemed satisfactory for all occupancies.
3. There is insufficient basis for concluding on non-residential occupancies.

The first approach would also imply that non-residential occupancies are over-achieving, and that resources spent on non-residential occupancies would be better utilised elsewhere in society.

Society would most likely not accept 20 fire death in schools one year, even if no residential fires claimed lives. From a survey among 272 Swedish industry professionals in 2016, the following is summarised [170].

> *In regard to an introduction of a risk-based acceptance criteria within the Swedish building code, many of the participants have no opinion. However, among those who had an opinion, a majority was in favor of such an introduction and that such a criteria should be adjusted in regard to building occupancy.*

Where is performance-based design applied?

There are no publicly available statistics on what type of buildings most often are solved by performance-based design, and where pre-accepted performance levels most often are applied. An European survey has however mapped the types of construction were fire safety engineering is applied [58].

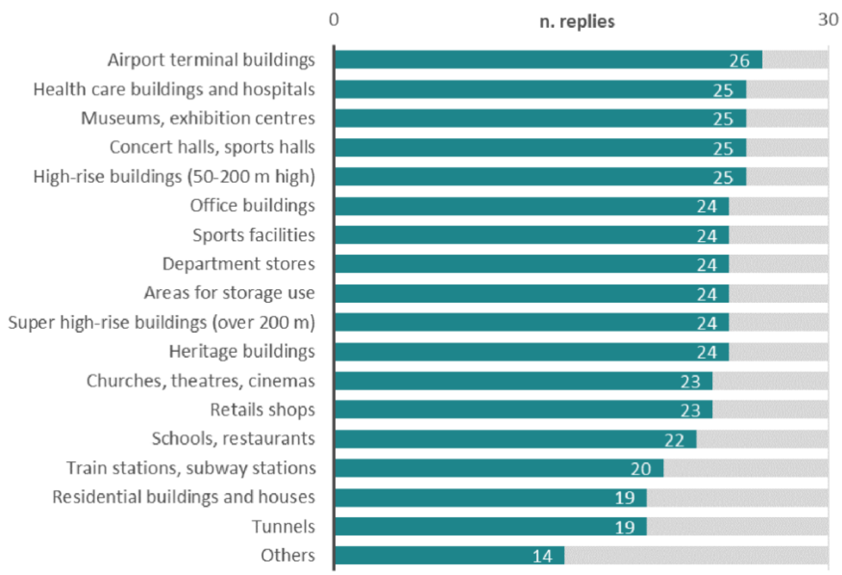


Figure 115 Survey results, showing for which construction type performance-based design is most frequently used [58]

Not all objectives or sub-systems of fire safety are readily compatible with statistically based acceptance criteria. It is therefore useful to also consider the objectives of the analyses.

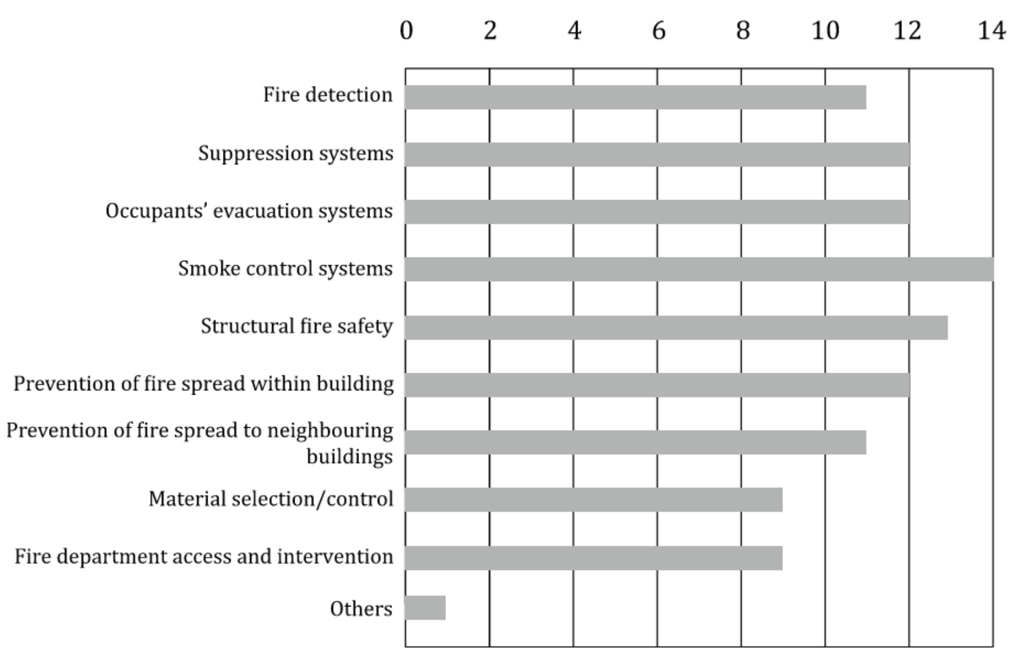


Figure 116 ISO survey results to the question "Which fire safety systems or features are included in P-B FSD analyses?" [3]

High Consequence – Low Frequency

Novel risks or events not yet recorded may be found unacceptable to society, and one of the benefits of performance-based design is being able to assess novel designs and risks, to identify suitable risk mitigating measures, and implement these in the design.

Other factors affecting risk tolerability

Society's and individual's risk aversion should also be assessed when considering criteria for risk.

Risk factors and their scales	RCF values
Voluntary–involuntary	100
Ordinary–catastrophic	30
Immediate–delayed	30
Common (old)–dread (new)	10
Controllable–uncontrollable	5–10
Clear benefit–unclear benefit	Risk is roughly proportional to the third power of its benefit.
Necessary–luxury	1
Continuous–occasional	1
Natural–man-made	20

Figure 117 Risk factors and their scales [78]

By applying risk factors, one can calibrate or modify criteria found elsewhere in society, e.g. Beta value from Eurocodes or landslide/ avalanche safety class TEK17 § 7-3, as exemplified by INSTA 951 [78].

Equivalency

As long as there are pre-accepted performance levels, equivalence can be a viable option. Thus, a distinction is made between three different approaches to fire safety design;

1. Pre-accepted performance levels are applied
2. Pre-accepted performance levels form basis for equivalence assessments
3. The design is assessed against the functional requirements

8.4.5. Construction Works Where Fire May Affect Societal Interests – Fire Class 4

Introduced in 1997, fire class 4 is defined as construction works where the consequences of fire are deemed very serious. In the first version of the guide to the building regulations, this is exemplified by chemical industry, production of environmentally hazardous goods, storage of hazardous goods and construction works where fire can pose a threat to a great number of people [33].

The functional requirements have included language considering societal consequences of fire since 1997, but the topic has gradually gained more attention over the years. Since 2010, the exemplification of fire class 4 also has included infrastructure like transport terminals, telecom.

No pre-accepted performance levels or solutions are given for fire class 4. The first version of the guide stated that it would be impossible to create general minimum solutions for such buildings, given their distinctive character. Hence, a comprehensive and exhaustive analysis was to be done for fire class 4. Since 2010, the guide has acknowledged that some fire class 4 buildings will not differ drastically from more conventional buildings, and states that pre-accepted performance levels found in the guide only can be applied to fire class 4 if the responsible designer demonstrates that they are relevant and adequate.

TEK17 sect. 11-1 § 4 reads:

> *Construction works where fire may pose a serious environmental hazard or affect other material societal interests shall be designed and constructed to ensure that the probability of harm to the environment or other material societal interests is minimal.*

The official Norwegian version of the regulation uses the term "liten sannsynlighet", which directly translates to small or low probability, rather than "minimal" as used in the translation made available by DiBK. Minimising the probability would resonate with principles of ALARP (see subsect. 7.4.2) and MAD (see subsect. 6.8.5), hence being seen as more ambitious or stringent.

The guide to the building regulations state [73]:

> *De preaksepterte ytelsene som er angitt til § 11-7 vil ikke nødvendigvis ivareta behovet for beskyttelse av byggverk som representerer særlig store samfunnsøkonomiske verdier eller vesentlige samfunnsinteresser. For slike byggverk vil det være nødvendig, i samråd med tiltakshaver, å gjøre en særskilt vurdering av behovet for seksjonering eller andre tiltak for å beskytte byggverket mot konsekvenser av en brann.*

> *The pre-accepted performance levels specified in Section 11-7 are not necessarily sufficient to meet the need for the protection of buildings that represent particularly large socio-economic values or significant societal interests. For such buildings, it will be necessary, in consultation with the project owner, to make a special assessment of the need for sectioning or other measures to protect the building from the consequences of a fire.*

In the Official Norwegian Report (NOU) 2006:6 it is discussed how an increasing share of the critical infrastructure is privatised, and the report discusses the implications for roles and responsibilities [166]. It is concluded that government regardless is not free from liability since the public expects the government to adequately ensure a safe and resilient society. Furthermore, privatisation of critical infrastructure inevitably includes trusting private actors to operate and maintain the infrastructure responsibly. Thus, involvement of the project owner is reasonable, although this practice means government is not determining "*the level of safety for critical supplies and services*" [166].

A discussion within the fire safety engineering community followed in the aftermath of the carpark fire at Stavanger airport Sola, as the evaluation report stated the following [106].

> *In our opinion, the multi-storey car park should have been placed in Fire class 4 ("brannklasse 4"), since it was adjacent to important infrastructure for society.*

Although the national building authority hosted a webinar where the differences in interpretation and opinion were apparent, no clarification was given neither in the webinar nor in subsequent revisions of the guide to the building regulations [171].

One webinar participant directed attention to the above quoted text from the guide, stating that the project owner is to be involved, setting the minimum safety level for the infrastructure. The participant asked how this process would be if the project owner of the carpark was not the owner of the infrastructure. DiBK responded "*The responsible designer shall design construction works in compliance with the building regulations, TEK, regardless of who the developer/ owner is.*"[13] [171]

The certainty of compliance is in this case highly volatile from both a regulator's and a practitioner's perspective. Here, the "opinion" of the evaluator is left uncontradicted by the authorities, and no precedence was set.

8.4.6. People in the Construction Works Cannot get to Safety Unassisted

As per TEK17 Section 11-2, hazard classes are determined by 4 characteristics, one of which is:

> *People in the construction work are familiar with the opportunities for escape, including escape routes, and can get to safety unassisted*

If the above statement is false for a given building, or section thereof, the hazard class shall be 5 or 6. Construction works designed for overnight stays shall be classified as hazard class 6, while construction works designed for awake occupants can be hazard class 5. No distinction is made between occupancies where people are unfamiliar and where people are detained or otherwise unable to escape unassisted.

The guide, VTEK mentions hotels, prisons, detention premises and healthcare institutions as examples of hazard class 6. This implies that pre-accepted performance levels are valid for correctional and psychiatric institutions. The general requirements of TEK17 section 11-1 does not exclude these occupancies:

> *Construction works shall be designed and constructed to ensure the attainment of an adequate level of safety in case of fire for people present in or on the construction works, for material assets, and for environmental and societal factors.*

An adequate level of safety in case of fire for people can be obtained by a variety of measures, one of which could include rescue. VTEK elaborates that the overarching requirements for safety in case of fire, can be achieved by

a. The use of materials and products not giving unacceptable contributions to the fire development,
b. Limiting fire spread,
c. Designing the building for speedy and safe escape, and
d. Facilitating for speedy and safe fire brigade intervention.

Section 11-11 gives general requirements relating to escape and rescue, e.g.:

[13] "*Ansvarlig prosjekterende skal prosjektere et byggverk som oppfyller TEK uavhengig av hvem som er tiltakshaver/eier.*"

(1) Construction works shall be designed and constructed to allow speedy and safe escape and rescue. Account shall be taken of people with disabilities.

(2) The time available for escape shall be greater than the time required to escape from the construction works. An adequate safety margin shall be included.

The first paragraph sets requirements for escape and rescue, whilst the second paragraph only mentions escape. With the case of detained occupants and occupants not able to escape unassisted, it is unclear how these functional requirements can be met.

Section 11-13 and 11-14 go further into detail, mandating doors to be openable, and generally set forth requirements only fit for buildings designed for evacuation (self-rescue).

It seems evident that for buildings where occupants are detained or unable to escape unassisted, the building itself cannot provide the occupants with sufficient safety in case of fire. Even with detection and fire suppression systems, untenable and lethal conditions may occur in the room of fire origin, and the occupant needs assistance from staff. Rather than acknowledge this fact and give guidance, the building regulation and the guide neglect these occupancy types and their associated distinctive features and risks.

One of the goals of the introduction of performance-based building regulations, was to drastically reduce the need for dispensations (Benefit 14 on page 41). This has largely been achieved, but it has also led to a situation where many municipal building authorities are under the impression that dispensation from the fire safety section of the building regulation is impossible or unsafe. Thus, the conflict between the functional requirements (biased towards traditional buildings where occupants can self-evacuate) and the special needs of occupancy types where occupants are not able to evacuate unassisted remains unsolved.

As will be discussed further in section 8.6, the resulting fire safety of construction works, and particularly occupancy types where occupants are unable to evacuate unassisted, cannot be adequately addressed within the constrains of the Planning and Building Act. A more holistic approach, including fire safety management and rescue procedures is imperative.

8.5. On the Available Predictive Modelling Tools

From centuries past, we have regulated fire safety in buildings as a reaction to fire events where the results were deemed unacceptable.

As mentioned in subsection 8.3.4, the pre-accepted performance levels and solutions are based on empiricism, which may be rational for traditional buildings if the rate of change is low. The downside is of course, that many fires in comparable buildings are required to gain insight into the performance of the concepts used. Considering the relative low frequency of fires, a significant lag will be embedded in this approach.

The aim for performance-based building regulations is however to also regulate novel buildings and risks. The same perspective can be seen regarding climate adaptation in the Ministry's instructions to the national building authority 2022 [172]:

Vi står overfor store klimaendringer, og byggteknisk forskrift må tilpasses dette. Forskriften lener seg hovedsakelig på historiske værdata, i motsetning til plan- og bygningsloven, som i større grad legger forventede klimaendringer og levetidsbetraktninger til grunn	*We are facing significant climate changes, and building regulations must be adapted accordingly. The regulations primarily rely on historical weather data, in contrast to the Planning and Building Act, which takes expected climate changes and life cycle considerations into greater account.*

In this context, engineering methods are essential to inform decisions for regulators and designers. For fire safety, climate change is used as an analogy, but environmental considerations affect the built environment in many ways, some of which also challenge the building tradition as found in the pre-accepted performance levels and solutions.

Thus, section 8.5 discusses the need for analytical tools for fire safety engineering, rather than applying traditional approaches to new challenges, resulting in an unknown level of safety. A level of safety which may be considered inadequate after the occurrence of many fires, and an even greater number of existing construction works designed by the same principles.

8.5.1. Fire Safety Performance in Novel Buildings

The Norwegian building regulations have a defined category, fire class 4, for buildings where the consequences of fire are very serious. For these buildings pre-accepted performance levels cannot be applied unless they are found appropriate and adequate by the responsible designer. Some buildings may have other features or properties making the pre-accepted performance levels and solutions inapt, even if the consequences are deemed to correspond to fire classes 1-3.

In both situations, adequate fire safety must be demonstrated, but comparisons against pre-accepted performance levels may be impossible or counterproductive.

An example can be the use of mass timber in tall buildings. The pre-accepted performance level for fire class 3 is R 90 A2-s1,d0, meaning the main load-bearing system shall be non-combustible and maintain its load-bearing capacity when subjected to the standardised fire exposure for 90 minutes. The functional requirement calls for a load-bearing system to withstand a complete burn-out. Here, the analyst must address the fact that the load-bearing system potentially contributes with fire load to the fire for the full duration of the fire – i.e., a complete burnout could imply that the load-bearing system also is consumed by the fire.

The Norwegian Building Authority has been challenged to include tall timber buildings in the guide to the technical regulations, and have given the following response [173]:

I høye og komplekse byggverk er funksjonsbaserte byggeregler og en risikobasert tilnærming derfor mer egnet enn "preskriptive sjekklister" som innebærer at aktørene slipper å tenke selv. En viktig forutsetning for at denne tilnærmingen skal fungere er selvsagt at de ansvarlige aktørene har høy kompetanse.	*In tall and complex structures, performance-based building codes and a risk-based approach are therefore more suitable than "prescriptive checklists" that imply that the actors do not have to think for themselves. An important prerequisite for this approach to work is, of course, that the responsible actors have high competence.*

This is well-aligned with the intentions of performance-based design, where “prescriptive checklists” are based on conservative simplifications of well-known phenomena, and adequately conservative solutions or performance levels where authorities have reason to assume compliance with the functional requirement. Within the international fire science community, the understanding is still incomplete on how mass timber behaves in fires, and how exposed mass timber influences the enclosure fire.

Thus, in leu of sufficient empirical data, the application of analytical tools, accompanied with the most updated knowledge available is the only viable approach for implementing new technology and novel designs safely.

8.5.2. Hand-Me-Downs

There are great benefits of reusing concepts, methodologies, and techniques across disciplines and industries. Ideally, universal equations and methods were established throughout, and regulators were given the task of setting the required level of safety by metrics.

1. When verification and design tools recreate the real world, statistics, experience, and new knowledge can more easily be fed back to the regulation.

2. Holistic assessments of cost-benefit can be done at a societal level, where the regulators can make informed decisions and prioritise.
3. Advances in one field, may benefit others, thus reducing the cost and time required for development.
4. Common principles across different safety related disciplines can ease aggregation of risks (e.g. risks to occupants posed by a fire suppression agent can be weighed against fire risk reduction by the suppression system).

On the other hand, some concepts may not translate easily, or … Put in another way; Hand-me-downs come free of charge, but do not always fit perfectly.

Processing, nuclear and offshore industry has paved the ground for much of the risk concepts. Although many of the same principles apply to the general built environment, there are a number of significant differences. The perceived risks are generally lower, and there has been a tradition for authorities setting requirements, assuring a certain minimum level of safety in case of fire. Thus, an owner of an industrial site with large quantities of combustible gas will to a greater extent understand the need for mitigating fire risks, than a developer of real-estate. The real-estate developer is most likely content with meeting the minimal requirements, potentially seeking to optimise by minimising the negative impact of the fire safety measures (in terms of cost, rentable area, construction time, uncertainty, loss of flexibility, maintenance, aesthetics etc). This example indicates the differences in interaction between the designer and client in fire risk assessments for two sectors. For industrial fire safety, also insurers may take a more active role, setting the premium based on risk assessment or insurer policies. For the general Norwegian building industry, insurers will not take part in the design stages of a project and will most usually simply require a code compliant building. The risk to the insurers is generally assumed to be lower (or at less uncertain) when pre-accepted performance levels and solutions are applied. Deviations from pre-accepted performance levels and bespoke fire safety design is furthermore a complicating factor for reinsuring companies.

The concept of available and required safe egress time (ASET-RSET) is widely applied in fire safety engineering, where the time to untenable conditions is quantified and compared to the time needed to evacuate (see subsection 6.8.2). The concept is taken from structural engineering, where probabilistic models for load and resistance (capacity) are developed. Experimental data are obtainable for the structural capacity of different materials, and data for dead and live loads can be measured.

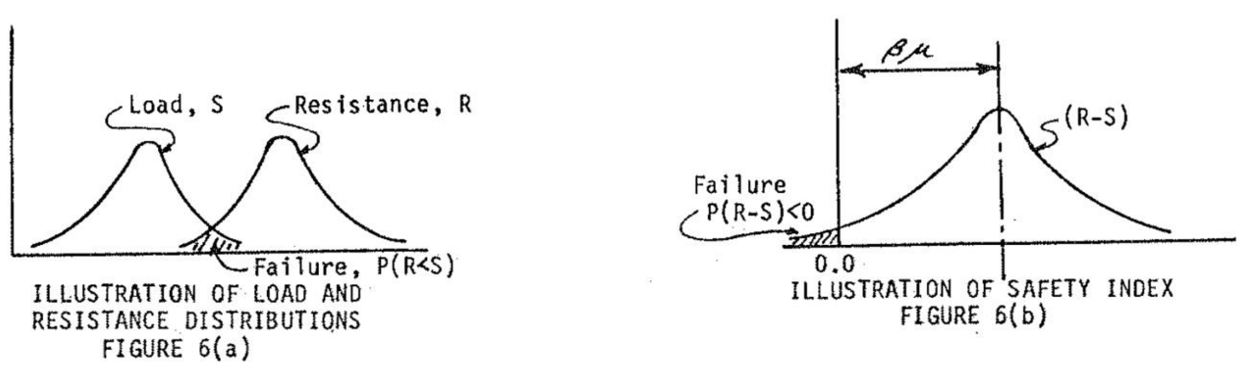


Figure 118 Probabilistic representation of load and resistance [116]

The uncertainty embedded in a priori quantification of fire development, evacuation and human behaviour in fires is immense, resulting in wide probability distributions with extreme values, where loss of lives is expected. Traditionally, a worst-credible-case approach (see subsection 6.1.2) has been taken to address this uncertainty. Even if probability distributions are produced, like Figure 118, the available and required safe egress time are interconnected, in ways not relevant for structural engineering.

Considering the full distribution of ASET and RSET, the longest required egress times are not necessarily relevant for the shortest available egress times and vice versa. The longest RSET values may be found for smouldering fires, where detection is delayed due to low smoke production and weak buoyant forces in the plume. For these fire scenarios, available safe egress times are expected to be on the higher end of the spectrum. Another example could be that occupant movement (RSET) affects the air supply to the fire (ASET).

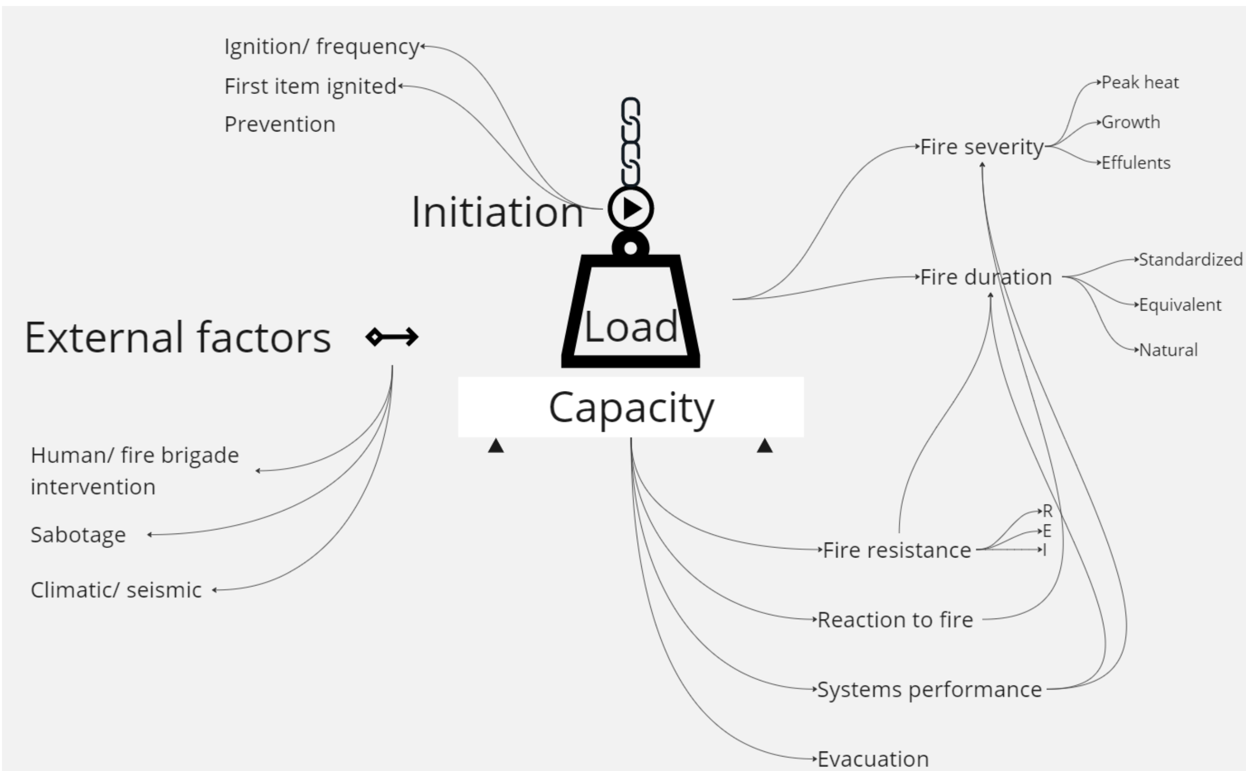


Figure 119 Complicating factors in fire safety engineering added to the analogy of structural load and capacity

Another significant difference is the frequency. A load-bearing system will be subjected to loads – although the magnitude may be uncertain. Many buildings will through their operation not experience a fire, and statistics show that small fires are more frequent than large fires.

8.5.3. Standardisation and Repeatability vs. Flexibility and Accountability

There are some inherent dilemmas to performance-based fire safety design, given the tremendous complexity and uncertainty involved in predicting fire development, and its interaction with occupants, systems, fire service and the building elements. Thus, conservative assumptions and simplifications are needed.

Regardless, the analysis is sensitive to cognitive biases, as discussed by Kinsey et al [174]. Taking the example of ASET RSET (available and required safe egress time), the resulting level of safety is solely at the designer's discretion, unless requirements are set on how the analysis is conducted. Primarily, the required safety margin will represent a considerable variation.

Figure 120 Illustration of interrelation between uncertainty and necessary safety margin

If the analysis could determine ASET and RSET with 100 % certainty, a safety margin of zero could be acceptable. This is not the case, and the safety margin should reflect the uncertainty of the analysis, based on the assumptions made, the models applied, the degree of conservatism, etc. Consequently, the safety margin cannot generally be prescribed.

Variability caused by different users, has been widely reported, most noticeably by the Dalmarnock fire tests [63], unveiling immense scatter amongst the participants of the round robin study, even if the participants were given detailed descriptions of the enclosure, its contents and ventilation conditions. In a design setting, the analyst will not aim for a realistic representation of one given fire, but rather study the scenario(s) that adequately encompass the worst credible case for the building [123].

NFPA 101 require 8 fire scenarios to be considered [8]. Similarly, NS 3901 require 4 fire scenarios to be considered [42]. The scenarios are qualitatively described, indicating a certain level of conservatism. Both sources also require consideration of scenarios where certain barriers fail. Neither dictate details regarding heat release rates, growth rate, species yields or other input of vital importance to the outcome of the analysis.

Not even criteria for untenable conditions are given in these two standards, but these criteria can be found in SN-INSTA 950 [1] and elsewhere in literature [112, 20]. As pointed out by Babrauskas [148], also interpretation of modelling results may cause variation.

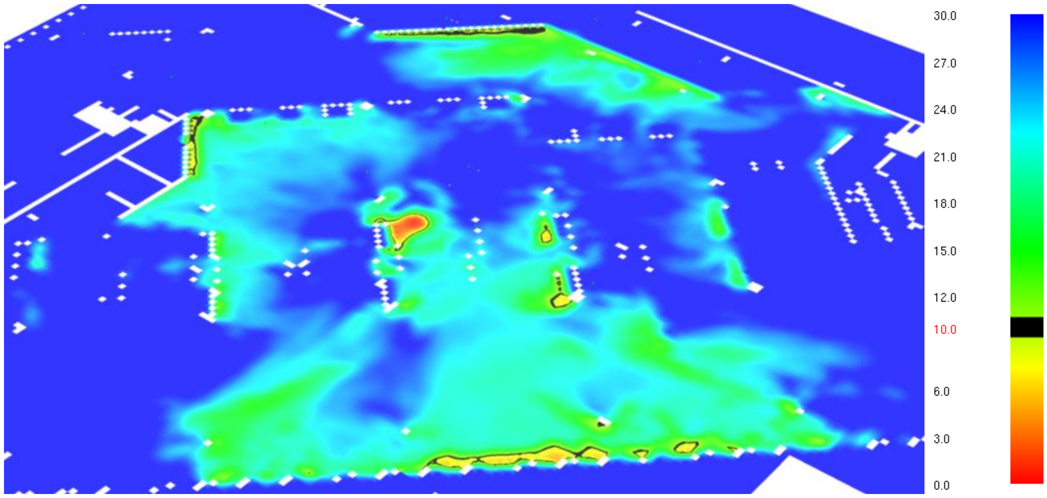


Figure 121 Exemplar results of fire simulations, showing visibility [m] as basis for determining available safe egress time (ASET)

As seen in Figure 121, the onset of untenable conditions is a matter of interpretation, even if there is consensus on tenability criteria.

To limit the variability, some jurisdictions prescribe the verification process and the most sensitive input data. Westlund-Storm presented the examples of prescribed verifications from Australia, New Zealand and Sweden [175], and as of January 2020 also Denmark [128] have a detailed prescription of acceptable input parameters for demonstrating compliance by analysis.

As with pre-accepted performance levels, the incentives for risk reduction are removed or reduced when compliance can be demonstrated. The designer is not tasked to identify project specific risks and then propose measures to mitigate them. The process is purely a mechanistic and mathematical exercise of producing calculation results in accordance with the specification, referred to as “cosmetic system safety” or “compliance only exercises” – superficial, isolated, or misdirected safety engineering activities [66].

Quantification and Implications for Pre-Accepted Performance Levels

It is expected that quantification of building regulations should be calibrated to the pre-accepted performance levels, so that designs according to the prescriptive design route also would be found acceptable when assessed by the analytical design route. This is a notion that has been verbalised when proposing quantified risk criteria, but not to the same extent problematised for other verification metrics. By applying conservative sources for pre-movement time, many pre-accepted designs would render a negative safety margin when analysed with an ASET RSET approach.

Rather than enforcing the idea that one absolute level of safety exists, the industry should acknowledge that the tolerable uncertainty is greater for pre-accepted performance levels than for fire safety engineering. Whether or not this is sensible is beyond the scope of this thesis. As discussed in subsection

8.3, to some, the implicit safety attained by pre-accepted performance levels will be more attractive than explicit safety level demonstrated by fire safety engineering.

Transferability – Cherry-Picking

Prescribed verification methods must be seen in their own context, as an extension of the pre-accepted performance levels of the jurisdiction where the guidance is given. As discussed, by Pauls [118], the prescribed flow rates in traditional codes are highly optimistic and do at best represent a nominal minimum egress time. However, when used with the accompanying conservative occupant load factors, the resulting design can be assumed to yield a reasonable egress time.

If a designer of an assembly building in Norway looks up internationally available building codes, an argument can be made, advocating for an increase in occupant load. While the guide to the Norwegian building regulations, VTEK call for 1 cm egress width per person, NFPA 101 allows for 0.76 cm per person in stairways, and 0.5 cm per person in level components and ramps [8, p. 84]. For one, the designer must be aware that egress capacity is only a component performance requirement, and not a measure of the fire safety performance of the building (with reference to chapter 6). Hypothetically, the occupant load factors of the two compared guides may be drastically different, yielding the same egress width for two comparable assembly occupancies. Furthermore, other aspects of the guide must be understood before one can transfer guidance across jurisdictions: Are the premises for detection and reaction time comparable? Do the requirements to furnishing and reaction to fire correspond, so that the fire growth is comparable? Are there other requirements or cultural differences resulting in different likelihood for early occupant intervention?

Although the above considerations relate to pre-accepted performance levels, the same applies to guidance documents for performance-based design.

8.5.4. Too Loose or Too Tight Regulation

The terms loose and tight used in this subsection refers to the taxonomy discussed in subsection 3.4.1, where tight regulation imposes strict restrictions on the designer and specifies on a detailed level. Loose regulation, on the other hand, is generic, non-specific, and more quantitative.

Examples of tight regulation of fire safety engineering analyses are found internationally [127, 128, 129].It is worth mentioning that small nuances in how the guidance or specification is presented may have profound effects on how they are applied. The use of examples in an otherwise loosely regulated regulatory framework may be effective in reducing variability, whilst still allowing the analyst to make project specific decisions.

Tight regulation

As with pre-accepted performance levels, prescribed input parameters for analytical design removes incentives for the analyst to diligently identify risks and hazards, study their magnitude, and propose mitigation. With prescribed verification, the analysis is reduced to a mechanistic exercise in demonstrating compliance.

Efforts have been made to collate performance criteria, tenability criteria, and other input values of importance to the analysis. An example of such is shown in Figure 122.

Stage	Suggested deterministic criteria	Lower limit	Upper limit
Pre-flashover (ignition and fire growth)	Radiant heat flux for ignition (kW/m^2)		
	● pilot	12	27
	● spontaneous	–	28
	Surface temperature for ignition (°C)		
	● pilot	270	350
	● spontaneous	–	600
	Heat flux for ignitability (kW/m^2)	10	40
	Maximum heat release rate (kW/m^2)	250	500
Flashover	Time to reach flashover		
	● Temperature (°C)	–	600
	● Radiation (kW/m^2)	–	20
Post-flashover	Thermal insulation of a separating structure (°C)		
	● average	140	200
	● maximum	180	240
	Structural steel temperature (°C)	–	538
	Critical received radiation (kW/m^2)	10	50
	Glass breakage temperature (°C)		
	● ordinary glass	100	175
	● tempered glass	270	350
Pre-flashover (life safety)	Convection heat (°C)	65	190
	Radiation heat (kW/m^2)	2.5	2.5
	Oxygen (%)	10	15
	Carbon monoxide (ppm)	1400	1700
	Carbon dioxide (%)	5	6
	Hydrogen cyanide (ppm)	–	80
	Upper gas layer temperature (°C)	183	200
	Visibility (m)		
	● primary fire compartments	2	3
	● other rooms	10	–
	Critical time to reach untenable limits (min)		
	● unprotected zones	2	6
	● partially protected zones	5	10
	● protected zones	30	60

Figure 122 Example of deterministic performance criteria from literature [117]

Although international benchmarking may be of great value, it is imperative to remain critical to "magic numbers". Generally, one can assume that tenability in the general public is comparable across jurisdictions. As seen exemplified in subsection 5.4.6, certain buildings are expected to be occupied by persons more vulnerable to smoke than the general public.

Furthermore, tight regulation and specification may pose a barrier to the implementation of new knowledge. One example could be the term "ordinary glass" in Figure 122. If new knowledge revealed that the "ordinary" glass types of 1999 would give too onerous results, the analyst would have incentives to apply new, documented knowledge. If, however, the "ordinary" glass types of 1999 gave the analyst improved safety margins and greater design freedoms, the analyst would most likely use the prescribed input data. To avoid this type of cherry-picking, regulators may want to prohibit the use of alternative data sources, making the specification even less flexible.

Ultimately, too tight regulations may give a passive and non-diligent fire safety engineering community. The lack of accountability can result in a "compliance culture", where the overarching visions, goals, objectives, and functional requirements are irrelevant.

According to Meacham, the increased use of prescribed verification methods in the 2010s defines the low point of the profession [67].

The use of a full scope verification method for fire safety engineering in Norway is thoroughly discussed by Westlund-Storm [175].

Loose regulations

The consequences of too generic guidance are discussed by Alvarez et al [57], concluding that the document fails to provide the analyst for specific projects with sufficient support. This may lead to a considerable scatter and variation among the practitioners under the same regulations, consequently allowing for a variation in safety level.

When practitioners lack guidance, there is a risk of misuse of data from other jurisdictions, or otherwise out of their field of application. Guidance on the use of statistical data and assessing data quality is given in INSTA 951, but the same document reproduces reliability data extracted decades ago for other jurisdictions [78].

Balance

Obviously, a balance will have to be achieved, where the designer and analyst is accountable for the adequacy of the design and analysis. Provided this accountability and trust, the guidance can be non-mandatory, specific, and thus, reduce variability, whilst retaining the diligence of the analyst.

And finally, quoting Alvarez [57]:

> *it is more important to tell a FPE [fire protection engineer] what problem he/she needs to solve than how he/she needs to solve the problem*

8.6. Better Return on Society's Investment in Fire Safety

Prescriptive regulations and stringent enforcement of pre-accepted performance levels inevitably directs the designer's focus away from fire safety and towards compliance. Although compliance is necessary, this creates the risk of sub-optimisation and renders the building regulation sensitive to loopholes, where lack of detail, ambiguous language, or other deficiencies in the pre-accepted performance levels most likely will be exploited in a market where the lowest bidder and the actor providing the most cost-efficient fire concept prevails.

Furthermore, this section will discuss the implications of legislative segregation between design and use.

8.6.1. Calls for a Holistic Approach

With reference to the Independent Review of Building Regulations and Fire Safety by Dame Judith Hackitt [151], the Norwegian Building Authority gave the following message through their website [176]:

Kulturen må endres fra å "følge minimum", til at aktørene tar eierskap og ansvar for å prosjektere og bygge trygge byggverk. Aktørene må tenke helhetlig.	*The culture must change from "following minimum" to the actors taking ownership and responsibility for designing and building safe structures. The actors must think holistically.*

Similarly, evaluations of fires (e.g. [106, 155]) and research (e.g. [162, 151]) calls for a more holistic approach to fire safety design, where all relevant parameters affecting fire safety are considered. The bowtie diagram below was presented to illustrate the different barriers worth exploring in an effort to improve safety against residential fires [87].

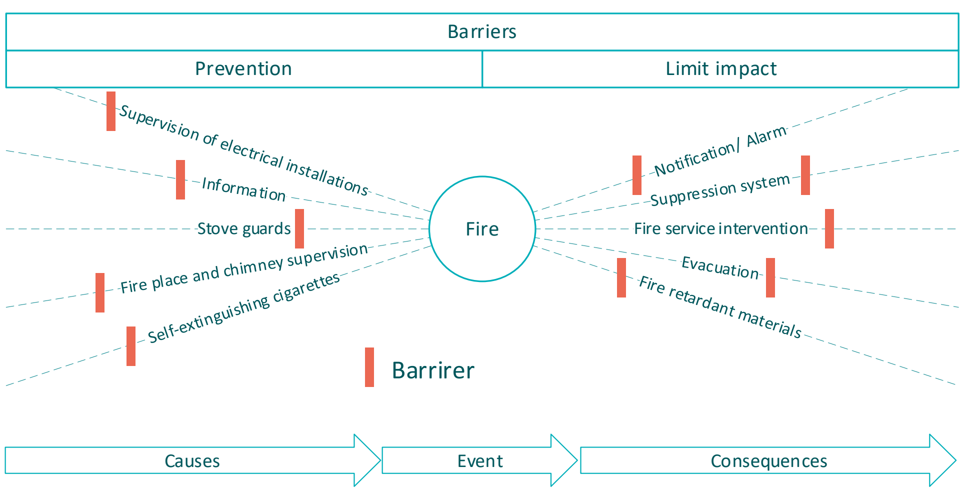


Figure 123 Bowtie diagram illustrating barriers in residential fires [87]

8.6.1. An Ounce of Prevention is Worth a Pound of Cure

TEK [4] and CPR [69] both use the term safety in case of fire, leading the reader to assume that a fire can occur, and that the following regulations have no intention to reduce the probability of a fire occurring. Thus, there are no incentives for the designer to explore strategies to prevent fire ignition (accidental or arson), consequently excluding half of the strategies outlined in Figure 124.

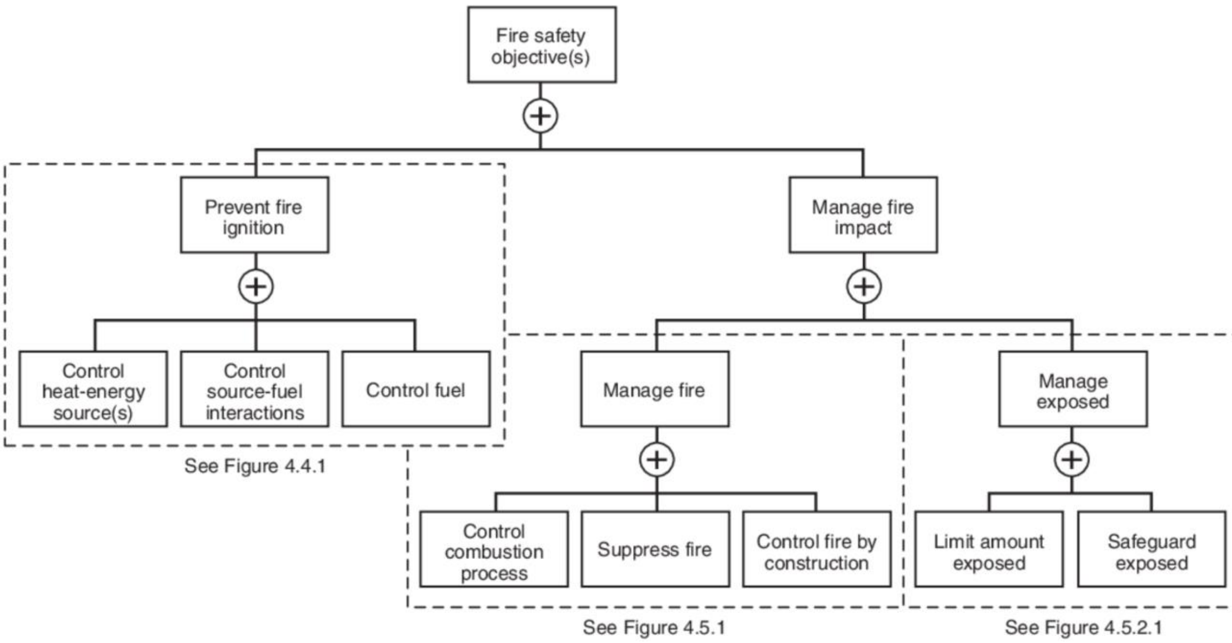


Figure 124 Fire Safety Concept Tree, as presented in NFPA 550 [177]

8.6.2. Barriers to Holistic Fire Safety Design

As seen in section 3.10, fire safety during operation is regulated under one jurisdiction, while design and construction is regulated under another. The illustration below has been used repeatedly by the national building authority to clarify the scope of fire safety design of construction works.

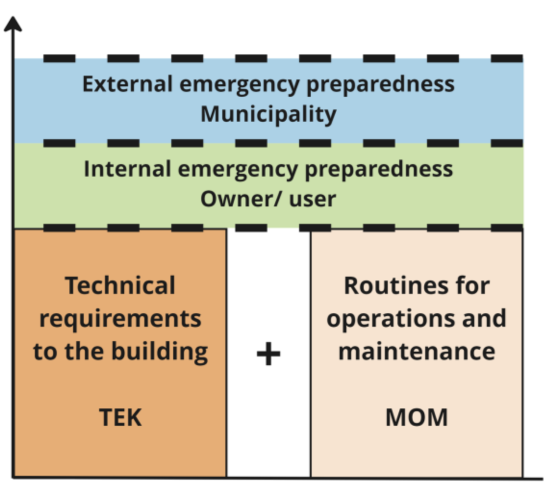


Figure 125 Illustration of how technical requirements to the building are independent of fire safety management and emergency preparedness. Translated from [59]

The message being, TEK regulates the technical properties of the construction works, forming a foundation of fire safety performance, independent of fire safety management and emergency preparedness. Thus, the designer should generally not account for fire service intervention or intervention by the occupants or staff. The reasons for this are presented as two-fold; 1) Municipal emergency preparedness is not governed by the Planning and Building Act, and 2) There is no guarantee for future presence or capacity/ capability of the external emergency preparedness.

Routines for operations and maintenance are required for all buildings, and is to some extent pursuant to the Planning and Building Act, by section 21-10:

For a certificate of completion, there shall be sufficient documentation from the developer or the responsible enterprises of the properties of the structure, including the properties of the building products, as a basis for the management, operation and maintenance of the building.

The objective and scope of the requirements is to maintain the required performance levels throughout the life of the building. Optimisations, fluctuations, and changes in risk is not within the scope of the Planning and Building Act, unless the changes trigger requirement for approval pursuant of Planning and Building Act section 20-1. A project on an existing building will have to comply with all relevant requirements of the current Planning and Building Act and the technical regulations - relevant meaning the requirements being affected by the project.

Internal emergency preparedness is described as preparedness to mitigate risks specific to the use and occupancy of the building. Hospitals, elderly homes, hotels, assembly/ retail occupancies and industrial facilities are given as examples.

The implications of this for performance-based fire safety design are given in NS 3901 [42].

Oppfyllelse av byggteknisk forskrift innebærer at byggverk skal ha en innebygget basissikkerhet, uavhengig av beredskapsmessige eller organisatoriske tiltak i bruksfasen. Det er derfor ikke mulig å forutsette slike tiltak som kompensasjon for svakheter i den branntekniske utformingen av et byggverk som skal oppfylle forskriftens krav.

Compliance with the Building Regulations entails that a building should have inherent basic safety, independent of emergency or managerial procedures during its operational phase. Therefore, it is not possible to assume such measures as compensation for weaknesses in the fire safety design of a building that is required to meet the regulations' requirements.

Consequently, the analyst is to disregard fire safety management, thus potentially neglecting highly effective, easily obtainable measures to reduce the likelihood of fires occurring. Similarly, risk mitigating measures not governed by the Planning and Building Act are out of bounds for the analysis. Thus the holistic approach visualised in the bowtie in Figure 123 (see page 200) is segregated by jurisdictions, as indicated in Figure 126.

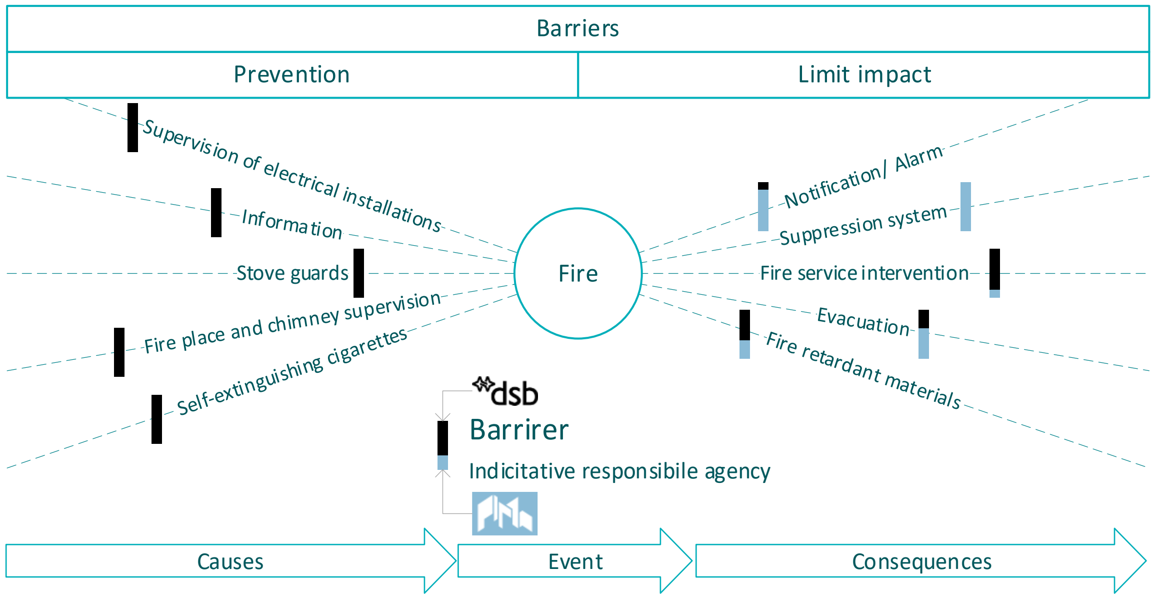


Figure 126 Reproduction of a bowtie diagram presented in NOU 2012:4 [87]. A sliding scale for each barrier is added by the author to indicate which regulator is the main responsible – DSB, or DiBK.

The barriers shown in colour black in Figure 126 are governed by the Fire and Explosion Prevention Act, and out of scope for an analysis performed in the context of fire safety design under the Planning and Building Act. The blue colour indicates barriers under the Planning and Building Act, although many barriers also are governed by the Ministry of justice (e.g. fire retardant materials are relevant for the reaction to fire of construction products, whilst furniture, inventory, and other sources of fire load in the building are not).

Example

RISE Fire Research carried out a project on behalf of DiBK and DSB on the fire safety in buildings used for play and recreational activity.

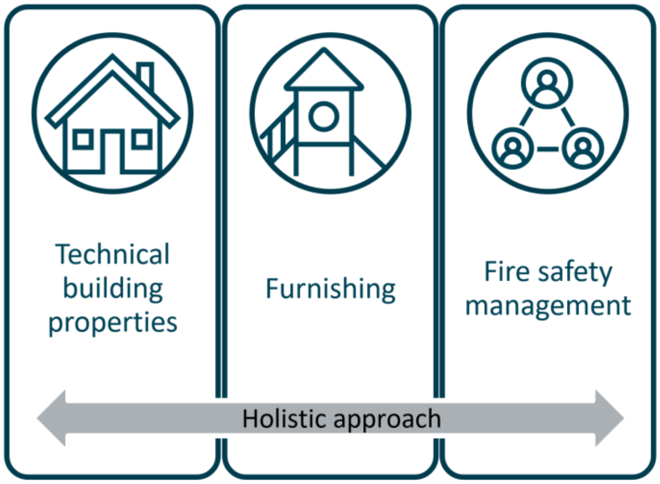


Figure 127 Holistic approach to fire safety in buildings used for play and recreational activity [162]

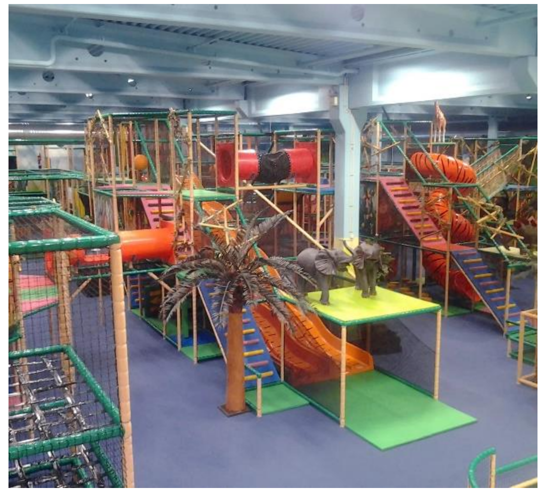


Figure 128 Image for exemplifying buildings for play and recreational activity

The main findings were [162] (numbering added for ease of reference):

1 *Lacking overall fire safety evaluation regarding the building and the safety plans of the responsible business owner with respect to*

1.1 *The significance of the furnishing and use of material for personal safety.*

1.2 *Distribution of responsibility to evaluate the furnishing in a risk perspective.*

2 *Ignition and early fire development:*

2.1 *There is not enough focus on ignition sources in the design and planning phase.*

2.2 *The fire performance of materials is not sufficiently taken into account during the design and planning phase and the requirements for documentation are insufficient and not relevant enough.*

3 *Escape:*

3.1 *Children's behaviour during escape is not taken into account when planning.*

3.2 *The activity in activity centres is not taken into account during the planning phase.*

3.3 *The effect of the interior (both material properties, physical position in the room and geometry) on the escape routes and escape time is not taken into account when planning.*

3.4 *Deviations from the requirement for low-placed way guidance systems are made on an uncertain basis.*

4 *Organizational measures:*

4.1 *Organizational measures are hardly mentioned in the fire concepts*

4.2 *Deviations regarding organizational measures during the operational phase is the responsibility of business owners. This indicates uncertainty or lack of competence of regulations and of implementation and follow-up of organizational measures.*

Excluding elements not governed by the Planning and Building Act, buildings used for play and recreational activity are simple, open space with a generous ceiling height. Although the designer must plan for increased travel distances due to furnishing, a building complying with pre-accepted performance levels and solutions is feasible – potentially straight forward.

So, how should a responsible fire safety professional act upon the findings referenced above. It is worth keeping in mind that the designer's client may be the contractor – not owner of the building or the tenant/ end-user of the building.

Furnishing is regulated by different legislation. The regulation of furnishing and apparatus for play are safety driven, designed to mitigate the risk involved in the intended use. Thus, imposing more onerous fire safety performance levels may inadvertently lead to a reduced personal safety.

Escape from the furnishings and apparatuses for play is also regulated through different legislation, and can be replaced, relocated, and altered without interference from the building authorities. Pre-accepted performance levels are fully applicable for the general portions of the buildings, whilst the four concerns for escape are related to escape from the furnishings and apparatuses.

Organizational measures are assumed to supplementary to the technical performance of the building and its fire safety systems. Thus, the managerial procedures of a third party (not necessarily known to the designer) is outside the scope of a responsible designer as stipulated under the Planning and Building Act.

8.6.3. Government Views

In the early 1990s, the Norwegian government directed focus towards fire safety, in an effort to reduce the fire losses which had increased during the 1980s. The whitepaper, St meld 15 1991 set quantified goals for reduction in material fire losses and a reduction of fire casualties by 30 % [29]. Furthermore, a plan involving the following four principles was laid:

- Strengthened efforts in fire prevention and information.
- Better coordination and cooperation (organising).
- Improvement of competencies.
- More efficient use of available resources.

An official Norwegian report (NOU 1999:1) clearly stated that ideally, the fire and building legislation should have been merged into one, governed centrally by one agency [178]. The committee did not propose this change, as it was considered outside the scope, and due to the legal and administrative extent of such a proposal.

In a whitepaper in 2000, the following was stated [179];

Departementet vil også utrede en samordning av brannvernkravene i bygningslovgivningen med kravene i brann- og

The Ministry will also investigate the coordination of fire safety requirements in building legislation with the requirements in the fire and *eksplosjonsvernregelverket med tanke på å samle disse i ett regelsett, fortrinnsvis bygningsregelverket. Brannvesenet skal fortsatt være tilsynsmyndighet, men det vil være naturlig også å utrede mulighetene for en nærmere samordning og bedre ressursutnyttelse av bygningsmyndighetenes og brannvernmyndighetenes ressurser på lokalt nivå.*

explosion prevention legislation, with the aim of consolidating them into a single set of regulations, preferably the building regulations. The fire department will still be the supervisory authority, but it would be natural to explore the possibilities for closer coordination and better resource utilization between local building authorities and fire authorities.

And further in a whitepaper in 2009 [180]:

Forholdet mellom de to regelverkene og samspillet mellom disse er svært viktig for en helhetlig og samordnet regulering av brannsikkerheten i bygninger.

The relationship between the two legislations and the interaction between them is very important for a holistic and coordinated regulation of fire safety in buildings.

A project conducted a mapping of legal interfaces and special provisions with relevance to the Planning and Building Act in 2011 [181]. The greatest challenges were identified for the Pollution Control Act and the Fire and Explosion Prevention Act, before elaborating:

Brann og eksplosjonsloven fordi bestemmelser i denne særloven må utfylles/ tolkes/ harmoniseres med konkrete bestemmelser i TEK - før valgte løsninger må dokumenteres jfr. TEK kap 2 - gjerne ved verifikasjon av ytelser ved analyse. Dette er komplisert - og fagområdet er viktig og sentralt dersom plan- og bygningslovens formål skal ivaretas på en god måte.

The Fire and Explosion Prevention Act, because provisions in this special law need to be supplemented/ interpreted/ harmonized with specific provisions in the TEK - before chosen solutions need to be documented according to TEK Chapter 2 - preferably through performance verification by analysis. This is complex, and the field of expertise is important and central for effectively fulfilling the mission of the Planning and Building Act.

Finally, the mandate and participation in the recently formed committee on "comprehensive review of the fire and rescue domain" (*arbeidsgruppe for helhetlig gjennomgang av brann- og redningsområdet*) [182] reveals how the work within fire safety is confined by the legal structures.

The segregation between the Planning and Building Act and the Fire Prevention Act still constitutes a barrier to a holistic approach to fire safety.

8.6.4. Curing the Right Disease?

As seen in section 7.6, performance-based is primarily applied in larger, complex buildings. Thus, the design competences and analytical efforts are focused on limiting consequences of unlikely events in airports, hospitals, museums, concert halls, etc (see 8.4.4).

In terms of life safety, the statistical data unambiguously points towards residential fires as the main challenge, representing close to 90 % of all fatal fires (see Figure 114 on page 185). Commercial/ industrial and institutions represent 5 % and 3 % respectively.

The continuing demographic changes are widely acknowledged, and there is an increased research focus on at-risk (vulnerable) groups. The relevance to technical requirements for construction works is however weak, as seen in the following subsection.

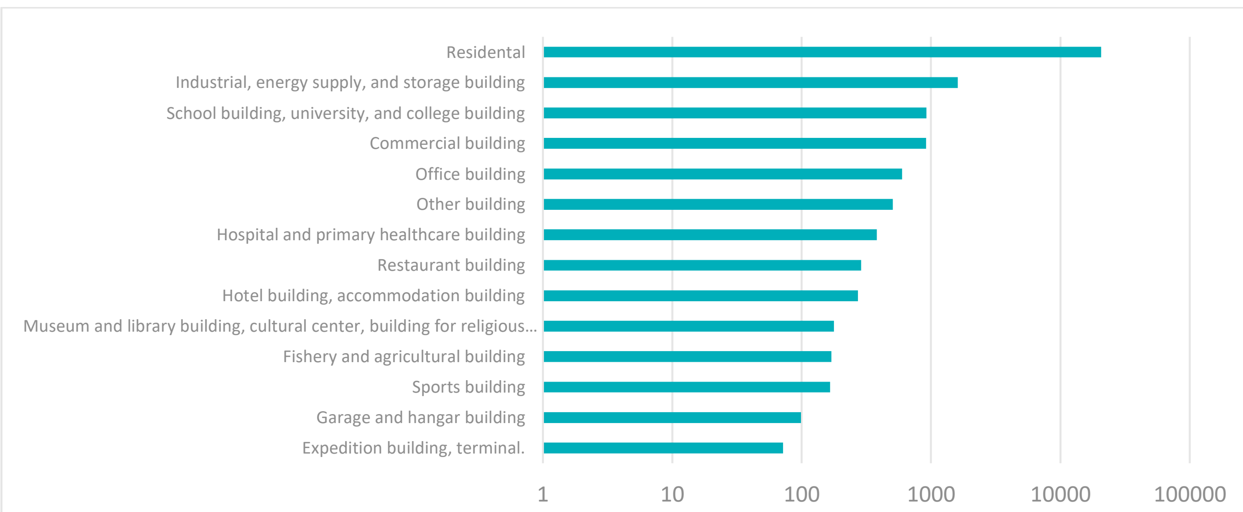


Figure 129 Number of fires from 1 Jan. 2018 through 31 Dec. 2022, grouped by building type (main occupancy). [183]

Comparing the number of fires to the types of building in which performance-based fire safety design is applied in Europe (Figure 115 on 186) there is no correlation between where analytical tools are applied, and the building types in which fires occur frequently. This aligns well with the survey results on reasons for applying performance-based design approach: Allowing for new fire safety technology, or designing attractive/ innovative buildings, or addressing features not explicitly covered by the deemed-to-satisfy (see Figure 22 on page 40).

8.6.5. Using the Right Medicine?

As seen in subsection 8.6.2, Norwegian fire safety engineers use only a fraction of the tools available for fire safety design. The following chart shows which system or measure has been reported to contributing to limiting further escalation in 35 000 fires in Norway since 2016.

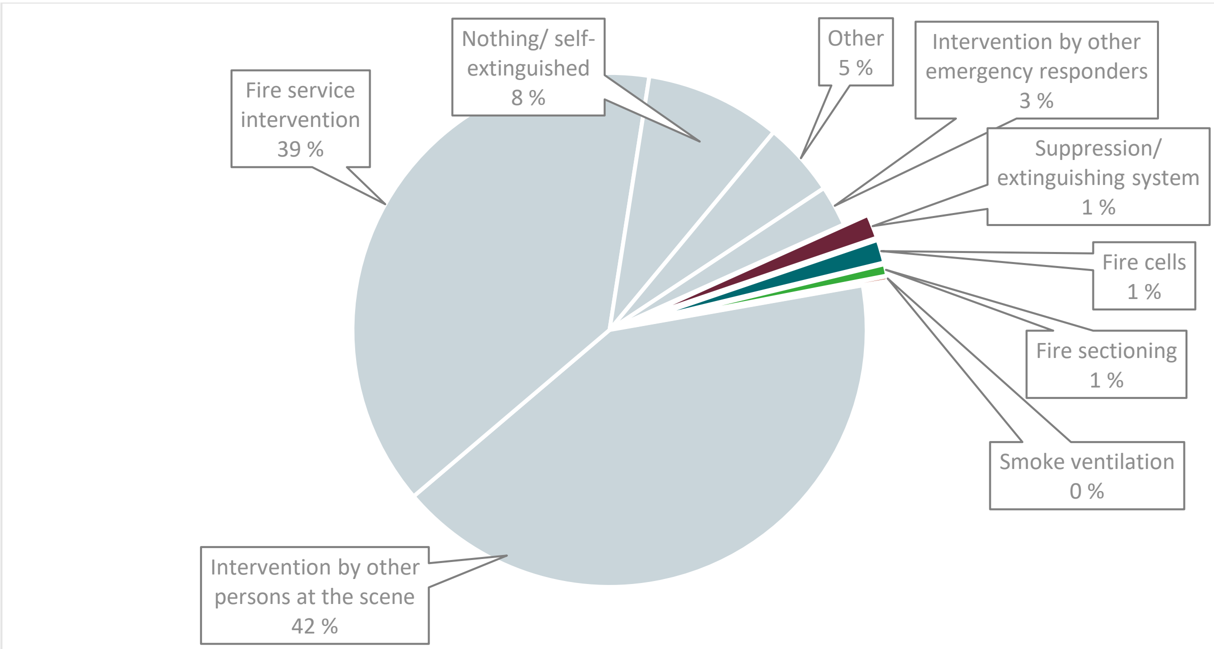


Figure 130 What contributed to preventing fire escalation in building fires[14]? N=35 516 [183] Grey sectors represent measures regulated under the Fire and Explosion Prevention Act.

They grey sectors represent systems and measures regulated by the fire and explosion prevention act, whilst the coloured sectors represent the toolbox available to fire safety design, which collectively amount to almost 4 % of the fires.

8.6.6. Other Undesirable Effects of Segregated Regulation

Authority surveillance

Among municipal building authorities, it reported to be a problem for authority surveillance that the regulations for design and construction are not the same as the regulations for operations [156].

Difficulty of Coordination

It is observed that clarification on principles in the interface between the two legislations require much time and resources. One example, being the overlapping requirements for access to fire water in TEK17 sect. 11-17 and the waver in the fire prevention regulations sect. 21 § 2 for situations where the fire department are in possession of a truck with sufficient water capacity.

Similarly, TEK17 sect. 11-13 § 2 states:

[14] "Hva bidro til å stoppe brannspredningen?"

Fire compartments in construction works in hazard class 4 with up to 8 storeys can have an exit to a stairwell designed as an escape route. This requires that each dwelling unit has at least one window or balcony that is accessible for rescue and fire extinguishing efforts, cf. section 11-17.

Seeing that the fire service is not governed by the Planning and Building Act, TEK cannot impose duties on the fire service. Thus, the requirement is limited to accessibility – not for actual rescue operations. As seen in the example below, the time required to reach a high building complying with the above quoted requirement can grossly exceeds the pre-accepted performance levels for fire cells.

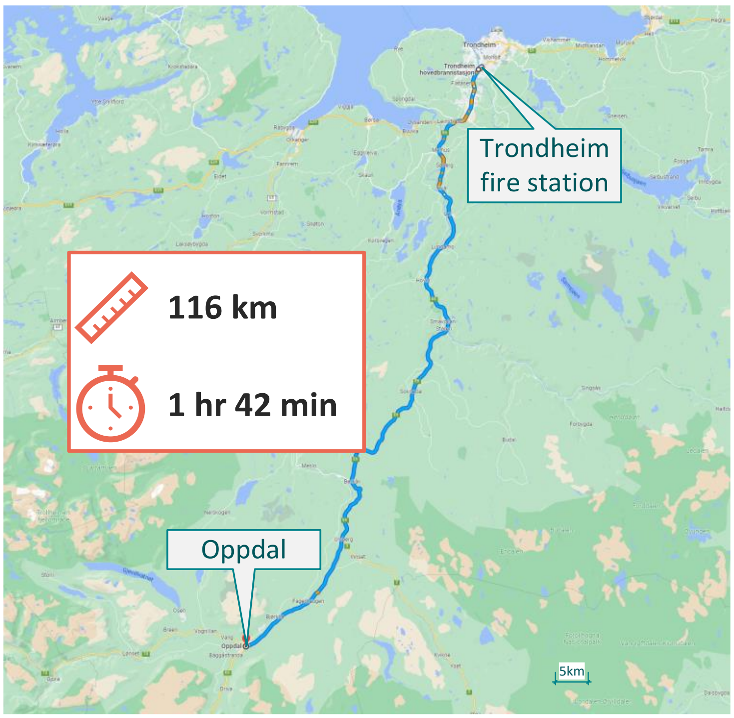


Figure 131 Driving distance and time from Trondheim to Oppdal station. Graphics added to Google maps

Fire service involvement in design

As described in 4.3.6, flow of information between designers and the fire service is below par. Improvements in this dialogue would give the designers better understanding of the needs of the fire service, increasing confidence in the design, which ultimately would give the fire services better conditions for intervention. The fire service would furthermore benefit from a brief from the designer on the fire strategy for the building – especially for novel design and bespoke fire strategies.

8.6.7. Proposal to Change

Although a substantial legal and administrative processes most likely are required to fully rectify the challenges highlighted in section 8.6.7, significant improvement can be obtained by nudging, working on culture and non-mandatory guidance.

The less restrictive language describing risk analysis in the 2003 version of the guide to the regulations could be reintroduced, inviting designers to consider a wider array of fire safety measures [53].

Another “low-hanging fruit” would be the requirement for evacuation plans found in TEK17 sect. 11-12 § 4 and documentation for management, operation, and maintenance in TEK17 chapter 4. By providing more guidance (if necessary, with warrant in and PBL sect. 21-10 § 2 and TEK chapter 4), the designer’s attention would be drawn towards important considerations for the operational phase of the building.

As seen in subsection 7.4.1, there are examples of different agencies regulating different aspects of one system (e.g. road safety). If the responsibility cannot be placed with one agency, it is important to place the overarching responsibility to one. For building fire safety, the Planning and Building Act could be seen as a segment of the domain primarily governed by the fire and explosion prevention. The effect of the two agencies (DSB and DiBK) collectively communicating that the overarching responsibility lies with either could go a long way.

Finally, the fact that a change in this field is will be time-consuming should be seen as an argument for immediate initiation.

9. Conclusion

9.1. Status of Performance-Based Building Regulations

In leu of defined performance criteria, pre-accepted performance levels and solutions remain instrumental to performance-based fire safety design and regulation.

Functional requirements were introduced knowing that objective proof of compliance would not be possible. No significant improvement is seen in this respect over the last 25 years, whilst the expectations to verification have increased, resulting in a lack of confidence in the functional requirements' ability to adequately regulate fire safety.

In Norway support structures were established to compensate for the shortcomings of the functional requirements, by regulating practitioner qualifications, accountability, and review/ oversight. Over time, some of these mechanisms are weakened, thus increasing the need for certainty of compliance.

The discipline seems to be at a crossroads, where one road involves further quantification, where performance criteria can be set by regulators, and verification methods are provided to mechanistically prove compliance with the criteria. The other road represents abandoning verification in favour of a more holistic approach to fire safety, where the interaction between humans and organisations are considered.

9.2. Methods and Criteria for Performance-Based Regulations

All the considered metrics may have a place in the domain of performance-based design, but the lack of standardised predictive modelling results in low precision. Thus, the intended benefits of quantification (increased control, whilst retaining flexibility) are lost due to the variability in verification. A remedy to this could be to apply prescribed verification methods, where the flexibility is reduced or removed. This approach may however result in less diligent professionals without incentives for mitigating new risks, and potentially hinder the implementation of new technology – counterproductive to the fundamental ideas of performance-based design.

The domain of quantification of fire safety performance is considered not mature enough to implement a strictly quantitative regulation. Regulators are left with the dilemma of either allowing for case specific engineering judgement (and accepting the variability) or introducing simplifications and prescribed verification (thus reducing flexibility).

9.3. Recommendations

9.3.1. Norwegian Building Regulations

There are three distinct ways of applying the fire safety chapter of TEK;

1. Applying pre-accepted performance levels without deviations.
2. Mainly basing the fire strategy on pre-accepted performance levels, but to have some deviations, which are analysed, primarily comparatively.
3. Applying the functional requirements directly to verify compliance for a novel design.

The first approach calls for clearly described unambiguous pre-accepted performance levels. Efforts should be made to clarify the applicability. This is the application suited for digitalisation.

The second approach will also benefit from less ambiguous pre-accepted performance levels, but here the greatest benefits will come from intent statements, giving the user a better understanding of what the goals and objectives, and to some extent, the history of the different pre-accepted performance levels is.

The third approach has little to no guidance in the current guide. Even though the aim of the building regulation is to allow for flexibility and innovation, it is necessary to elaborate on the building authority's attitude towards the functional requirements. Guidance is also needed to better describe the required level of documentation when it comes to analytical fire safety engineering. A process of revising the functional requirements is advised, where the 25 years of experience with the current regulatory framework and science form basis, rather than the (obsolete) building tradition of past building regulations. The empiricism the building regulation is limited to few building types and is more relevant to pre-accepted performance levels than the functional requirements.

9.3.2. Remove Barriers Between Fire and Building Regulations

Absolute risk matrices require a regulatory framework where fire prevention (not only safety in case of fire), fire brigade intervention and other aspects currently governed by the Fire and Explosion Prevention Act to be within the scope of a fire risk assessment.

Regardless of the verification method chosen by the designer, the current strict limitations of the fire safety concept to technical requirements to construction works is a hinder to a more holistic perspective on fire safety, and for a more efficient use of society's resources.

9.3.3. Status of Pre-accepted Performance Levels

If the principle of legality is to be respected, restrictions to citizens' rights and freedoms shall have warrant in in the legislation (act or regulation). Furthermore, the process of creating, amending, or revising the requirements shall follow the principles set out in Public Administration Act. Thus, a continued practice with functional requirements in regulations (without real means of objectively demonstrating compliance), and pre-accepted performance levels in guidance documents (not legally binding) is not a desirable option.

Over the past 25 years, advancements have been made within verification methods and functional requirements, but this thesis compiles evidence that these methods and requirements are still inadequate. The future development of building fire safety legislation in Norway will have to choose one of the following approaches, if the principles of a performance-based building regulation is to be preserved;

1. Establish means of measuring fire safety for all relevant objectives, in order to regulate the actual level of safety in legally binding documents.
2. Place pre-accepted solutions and performance levels in legally binding documents, and establish procedures and forums for revision and amendments, abiding to the Public Administration Act. A certain level of design flexibility can be maintained by allowing for equivalency assessments (e.g. medium- and high-rise buildings shall be separated by a distance not less than 8.0 m, unless equivalent safety against fire spread is obtained by other means).

3. Acknowledging the pre-accepted solutions and performance levels as not legally binding minimum requirements, but as examples resulting in an acceptable level of risk. Direct efforts toward regulating the practitioners, to a point where confidence in the adequacy of fire safety can be achieved without mechanistic verification.

9.3.4. Rebuild Trust

The creep towards more prescriptive legislation is counterproductive if the goal is for fire safety design to be more holistic and to aim beyond compliance. While increased prescription will increase the risk of a “compliance culture”, the result of increasing trust between practitioners, regulators, and society, will be a more robust and endurant building legislation fit to handle the considerable inflow of new technology and risks.

9.3.5. Verification vs. Holistic Fire Safety Design

Under the current regulatory framework, documenting compliance is mandatory, and the benefits of a holistic approach to fire safety design cannot be obtained. Conversely, a shift towards holistic fire safety regulation may result in less regulatory detailed control, but society is expected to get a better return on its investment in fire safety.

The fire safety engineering community and society would benefit greatly from abandoning verification, in favour of a more holistic approach to fire safety design. Efforts will have to made to further develop a framework where this can be done safely with adequate certainty of outcome.

10. Further work

During the research for this thesis, the adolescent state of the profession has become apparent. Although some concepts are established and widely adopted, the majority of the fire safety engineering domain remains unstructured with substantial gaps in analytical tools, data, and performance criteria. Thus, research on many scales is still required to further advance the field [11, 12, 58]. With relevance to this thesis, some topics are highlighted in the following.

Fire safety engineering in the context of socio-technical systems

In view of the lack of progress in establishing verification methods for fire safety engineering over the past 30 years, it is sensible to consider alternatives to verification. Systemic thinking is a promising alternative framework to the established verification based on worst credible case assumptions. The approach must still be considered immature in the context of fire safety design, so a collaborative research effort is proposed based on the 8 steps for advancing performance-based design for fire safety by incorporating STS concepts, as suggested by Meacham [67].

International collaboration and coordination

It is inspiring to see how the work of the Nordic collaboration in NKB has created a lasting impact on the realm of performance-based building regulations and design. Although it is rational and reasonable to aim for wider cooperation through CEN, ISO, or SFPE, with increasing differences, the research results become more generic to fit all interested parties, with the risk of less useful results. Thus, part of the explanation for NKB's success may be the relatively small differences in terms of culture, regulatory framework, history, climate, etc. between the participants. Alternatively, the international cooperation must have a scope encompassing all relevant aspects (e.g., system description as provided by Bjelland et al [44], as seen in Figure 24), allowing the cooperating jurisdictions to be explicit on their roles, responsibilities, competencies, and whether/ how these factors interact with the more technical questions of fire safety science and engineering.

Predictive models and quantification of fire safety performance

Even if the concepts of verification are abandoned, there is a substantial need for predictive models and analytical methods for assessing fire safety performance of buildings. Science-based expressions representing fire safety related phenomena are instrumental in coping with the increasing complexity in society and allowing for the safe implementation of new technology – without undue fire risk, and in the case of fire safety technology, with a reasonable confidence on the performance and reliability of the technology.

Transparency, user involvement, and long-term perspective from regulators

It recommended to improve dialogue between regulators, practitioners, and the research community. A roadmap, informed by the 25 years of experience with performance-based regulations would increase predictability, and improve transparency. The roadmap should point out the desired long-term strategic development of the building regulations, and identify the need for research and standardisation.

11. Commentary on Building Legislation for the Future

According to the annual report of the national building authority, the work with a new strategy for long-term development of the building regulations was initiated in 2022, *BFF – Byggeregler for framtiden* [86]. The annual report was published in the spring of 2023 and brought to the authors attention days prior to the deadline, meaning there has been very limited time to fully study the possible implications. Furthermore, the available information is currently limited to the following excerpt from the annual report:

Målet med strategien innebærer blant annet å tydeliggjøre forholdet mellom overordnede funksjonskrav, ytelseskrav og de preaksepterte ytelsene i veiledningen. Det skal bli enklere å forstå når et krav gjelder, hva kravet innebærer helt konkret, og ikke minst når kravet er oppfylt. Som en del av arbeidet skal dagens preaksepterte ytelser flyttes over i forskrift*.*

The goal of the strategy includes, among other things, clarifying the relationship between overarching functional requirements, performance requirements, and the pre-accepted performance criteria in the guidance. It should become easier to understand when a requirement applies, what the requirement entails specifically, and most importantly, when the requirement is fulfilled. As part of the effort, the current pre-accepted performance levels will be transferred into the regulation*.*

Considering the tremendous impact on performance-based design in Norway, a commentary is included in the following sections, based on the following assumptions:

1. The Planning and Building Act will remain unchanged. The regulations shall still be considered performance-based, governed by functional requirements, structured as seen in Figure 132.
2. The level of safety (and cost) is assumed to be consistent with the TEK17.
3. The primary objective is to clear up legal issues as described in section 3.12.
4. The secondary objective is to increase regulatory control of the safety level.
5. The change is motivated by facilitating for digitalisation.
6. It is assumed that the necessary flexibility can be retained by equivalency wavers.
7. User involvement will be limited to circulating draft for comments.
8. No changes are proposed to reduce the barriers to holistic fire safety design.

11.1. Structure

The structure is expected to be like the current, as adopted from NKB, with one vital difference: The pre-accepted performance levels are made mandatory and legally binding. Some other adjustments may be made, potentially taking shape of the example of Australia in Figure 11 on page 21.

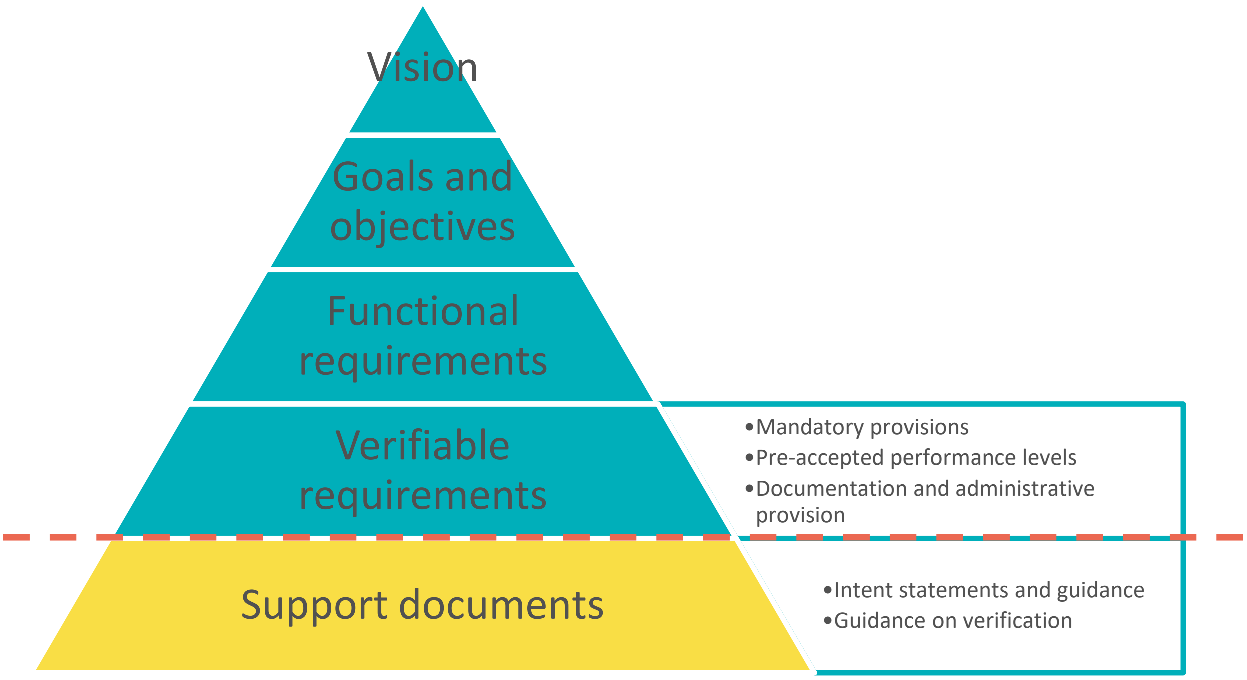


Figure 132 Anticipated structure of the proposed strategy for future building regulations. Blue components, above the dotted line, are mandatory.

Vision, Goals, and Objectives

A clearly stated long-term vision for fire safety within the jurisdiction can set the ambition and over-arching aims for the following levels of regulation.

The vision could be that no lives are lost due to fire, or quantified reduction in fire losses as seen in STM 15 of 1992 [29]. Other topics for the vision could include no loss of irreplaceable heritage sites, communities, artefacts, etc. or resiliency of critical infrastructure.

Vision should be something to work towards, even though it seems unattainable. The existence of an ambitious vision may reduce controversy around metrics representing tolerability of fire risk > 0, as it can be seen in a greater context, where society is making steps towards the vision.

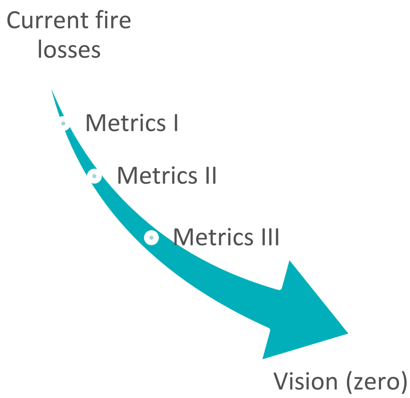


Figure 133 Idealisation of a systematic reduction of risk towards a vision (zero) by metrics

Reference to vision zero was made in STM 41 of 2001 [179], and expanded in STM 35 of 2009 [180].

The author is not aware any proposed changes of relevance to the Planning and Building Act. Thus, the goals and objectives of the current act is assumed to be retained.

One of the strengths of performance-based building regulations is to allow political decisions to be made into acts and regulations, whilst technical decisions are made on a lower level, where industry actors and specialists can take a more active role.

Functional requirements

Ideally, functional requirements should be agnostic with regards to;

- Means of obtaining the required level of safety (passive or active, increasing ASET or reducing RSET, etc)
- Means of demonstrating compliance (pre-accepted, qualitative, quantitative, risk, deterministic)

By making pre-accepted performance levels legally binding, the functional requirements lose much of their meaning. Rather than being at a higher legal level, the functional requirements will in the proposed strategy form an informative backdrop to the pre-accepted performance levels.

The improved clarity on relationship between functional requirements and pre-accepted performance levels will increase the understanding of the pre-accepted performance levels, which is useful when analysing alternative designs.

In the strategy applied since 1997, functional requirements have been instrumental for novel/ extraordinary designs, and buildings in fire class 4, seeing that pre-accepted performance levels cannot be applied for these buildings.

Pre-accepted Performance Levels

It is expected that the pre-accepted performance levels are assumed to be largely adequate in the guide to TEK17, and that minor adjustments are required when transferring them to regulations. Most likely, TEK section 2-2 will remain unchanged, allowing for demonstrating compliance either by analysis, or by the use of pre-accepted performance levels.

Alternatively, new general equivalency wavers are given for the fire safety chapter of the regulations, effectively regulating all pre-accepted performance levels like the fire spread between buildings, as discussed in section 5.2.

The shortcomings and challenges of pre-accepted performance levels are thoroughly discussed throughout this thesis, and in particular sections 8.2 and 8.3. These shortcomings are however discussed in a context where the pre-accepted performance levels are not legally binding. Stricter specification and a more prescriptive approach will increase the risk of a “compliance culture”, incentives to reduce risk are lost, ultimately rendering the pre-accepted performance levels vulnerable to misuse and misinterpretation.

11.2. Consistent Level of Safety

Based on the historical development described in chapter 0, it is reasonable to believe that the transition of pre-accepted performance levels into regulations is intended to take place without substantial change to the level of safety. The new regulations will however be an opportunity to implement previously proposed changes, as discussed in section 8.2.5, like more stringent requirements for external cladding. The 2010 revision of the regulations does however serve as an example of significant increase in required safety level, contrary to the expressed intention (see [68, pp. 5-8]).

11.3. Legal issues

The legal issues discussed in section 3.12 have effectively reduced the authorities’ ability to maintain the guide to the building regulations. Despite clear and justified proposals for change (see section 8.2.5), the guide remain unchanged.

It is however worth noticing that although suggestions for change were given, Hjort DA found the current practice to respect the principle of legality [49].

11.4. Increased Regulatory Control of the Safety Level

The need for increased regulatory control is assumed to have two main sources. For one, the continuing lack of confidence in functional requirements, gives reason for raising the status of pre-accepted performance level even further – the natural next step, extrapolating from Table 12 in subsection 8.3.3.

The other factor is the reduced control over practitioner qualifications, as central approval for accepting responsibility has been reduced to a voluntary system, and not adequately replaced by other mechanisms to ensure sufficiently qualified designers [30].

Attention is drawn to section 8.3, where the adequacy of pre-accepted performance levels is discussed. Furthermore, it must be understood and acknowledged that most traditional pre-accepted performance levels, inherited from previous building regulations result in unknown fire safety performance, where the empirical evidence is scarce, scattered, or missing altogether.

11.5. Digitalisation

A goal of more machine-readable pre-accepted performance levels has been expressed for many years. The below figures show how qualitative pre-accepted performance levels were proposed to be translated into verifiable quantitative requirements.

Figure 134 Composition of types of requirements per 2016 [41]

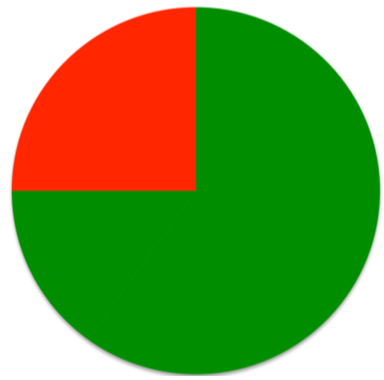


Figure 135 Proposed types of requirements for the future [41]

Green sector*: Pre-accepted performance levels (measurable) which directly can be translated into a digital rule.*
Blue sector*: Pre-accepted performance levels (qualitative) which can be deduced into measurable terms, and then translated to digital rules.*
Red sector*: Qualitative functional requirements, which must be interpreted and assessed by a professional.*

As seen in Figure 135, the functional requirements are retained, and the increased number of verifiable requirements have only been on the expense of qualitatively stated pre-accepted performance levels.

The need for facilitating digitalisation and the status of pre-accepted performance levels are unrelated. If confidence was regained in the legal questions discussed in 3.12, machine-readable pre-accepted performance levels could have been placed on a non-legally binding level.

11.6. Necessary Flexibility Retained by Equivalency Wavers

The risks involved in relying heavily on specification in discussed in section 5.2, and further expanded in sections 8.2 through 8.4.

For traditional buildings, comparative analysis is adequate, and provides the flexibility to justify minor deviations. There are, however, situations, where the comparative approach significant limitations.

Fire Class 4

Fire class 4 has no pre-accepted performance levels, and will most likely not be given pre-accepted performance levels under the new strategy. Here, the responsible designer must demonstrate compliance with the functional requirements. Paradoxically, the buildings characterised by having the most severe impact in case of fire are under the least regulatory control.

Novel or Extraordinary Designs

Some buildings differ significantly from pre-accepted performance levels, while still classified as fire classes 1 through 3. Their geometry, use, or other properties may make pre-accepted performance levels incompatible.

Hazard class 4 and 6

Acknowledged in the discussion document to TEK17, mandating fire suppression systems and fire detection and alarm systems in addition to all the performance levels deemed adequate prior to 2010, the level of fire safety in hazard classes 4 (where lifts are required) and 6 is very high. The pre-accepted performance levels and solutions include almost all known passive and active fire safety measures, rendering comparative analysis useless. Although 25 m travel distances were allowed in non-sprinklered hospitals in 2007 [54], 25 m is kept as the maximum travel distance in VTEK10 and VTEK17, after the introduction of sprinklers [55, 73]. Prior to the mandating of sprinklers, fire safety engineers could introduce sprinklers to allow for slightly increased travel distances – justified by a significant improvement to the available safe egress time. The same argument cannot be made when the reference building is sprinklered.

Sustainability

The call for more sustainable building materials and increased energy efficiency challenge many of the pre-accepted performance levels – typically pre-accepted performance level of A2-s1,d0 for insulation materials and/ or load-bearing structures. In a comparative analysis, any alternative to A2-s1,d0 fail to meet the same performance, regardless of the protection.

Dispensations

As an intended effect of the reform of 1997, the need for dispensations has reduced drastically. Furthermore, the municipal building authorities have reduced the workforce with technical expertise, seeing how they no longer were to assess the technical contents of the design. Even with broadly formulated equivalency wavers, the need for dispensations will increase significantly if the proposed strategy is implemented.

Projects on existing buildings are expected to suffer even more from this. Even under the current regime, municipal authorities fail to acknowledge any alternatives to pre-accepted performance levels as viable for existing buildings [184].

11.7. Holistic fire safety design

The national building authority has called for a more holistic approach to fire safety design, advocating risk reduction beyond compliance [176]. The increasing risk of a "compliance culture" should be recognised and addressed before the proposed strategy is implemented. As seen in chapter 5.2, the focus is expected to shift (even more) towards semantics and definitions. Where the national building authority previously have had a chance to rely on competent and responsible designer to interpret ambiguously formulated pre-accepted performance levels (seeing that they were not mandatory), the ability of DiBK to handle questions from the industry must improve significantly compared to what is seen in subsection 4.4.6.

Despite repeatedly acknowledging challenges in the regulatory separation of the fire legislation and the building legislation (see section 8.6), no information is found indicating progress being made to mitigate. The segregation seems to be as strong as ever, considering the mandate and participation in a recently formed committee on "comprehensive review of the fire and rescue domain" (*arbeidsgruppe for helhetlig gjennomgang av brann- og redningsområdet*) [182]. The scope is clearly confined by the existing fire legislation, not including fire safety design.

11.8. User Involvement and Transparency

No other official mention of the proposed new strategy is found by the author publicly, than the short text in the DiBK annual report. The committee revising NS 3901 (SN/K-015) has asked for feedback of relevance to the verification of functional requirements, and whether alternatives to comparative analysis will be allowed in future building regulations, but no response is received.

The need for change has become apparent through the research for this thesis, and the fact that national building authorities are actively working for improvement is positive. It is however surprising to see how regulators work in total isolation on these substantial changes in legislation. When publishing the annual report, DiBK decided that the knowledge of the strategy could be shared, but to the knowledge of the author, the annual report is the only publicly available information, no call for dialogue is made through DiBK's website/ newsletter, Twitter, or LinkedIn. A Google search for "*byggeregler for framtiden*" (in quotes) gives no results.

The ongoing process of quantification in Australia [113] is a good example of how practitioners can be used in the preparatory, which serves more than one purpose:

- The practitioner perspective is being considered.
- Practical experience is fed back into the new regulations.
- The practitioners are given an opportunity to better prepare for the new regime.
- More supporting information for the new regulations is available.
- Regulators and regulated may gain better insight into the other's perspective.

The Norwegian Association for Consulting Engineers (RIF) has recently published a list of questions and answers, with the intention reducing uncertainty regarding pre-accepted performance levels [185]. It is not currently known whether this service can continue with legally binding pre-accepted performance levels. The initiative is however a clear indication of insufficient clarity in the guide to the building regulations.

Other relevant stakeholders could include academia, research institutes, municipal building officials, fire services, insurers, legal firms, and organisations, such as RIF.

11.9. Concluding remarks

A shift towards a more prescriptive building regulation is one of the alternatives identified in this thesis as remedy to the challenges of the current regulatory framework. It is, however, not the proposed long-term solution for performance-based building regulations. This thesis has shown that society's resources would be better spent by making legal and administrative amendments required to allow for a holistic approach to fire safety, in line with the principles of systemic thinking.

The proposed strategy further weakens the trust and confidence in functional requirements and the professionals working on them. Considering the lack of maturity in systemic thinking, the proposed BFF strategy could serve as temporary remedy to the legal issues, but in parallel, an open and inclusive process should explore the next big step away from prescriptive building regulations.

I would like to cite Margaret Law, who in leu of progress, remains immensely relevant, 30 years after publishing this text [123]:

> *The magic numbers embodied in regulations are accepted without question whilst any engineering solution is subject to a disproportionately high standard of proof. To move forward, rules need to have an engineering basis and to be goal related: the purpose of the rules needs to be understood by both researchers and regulators.*
>
> *…*
>
> *Lastly, we appeal for a rational approach to the regulation of fire safety design, which is goal related rather than disaster driven, which encourages flexibility and imagination, and which uncovers opportunities which can be fed back into research programmes.*

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