A Nordic approach to fire safety engineering

Will standardization of probabilistic methods to verify fire safety designs of novel buildings improve engineering practices?

Henrik Bjelland
Multiconsult
Oslo, Norway
Henrik.bjelland@multiconsult.no

Ove Njå
Center for Risk Management and Societal Safety
University of Stavanger
Stavanger, Norway
Ove.njaa@uis.no

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ABSTRACT

The last ten years standardisation enterprises (ISO and national units) have carried out extensive work to establish standards and codes for fire safety engineering. A Nordic initiative has now been launched for public comments, providing guidance on “Probabilistic Methods for Verifying Fire Safety Design in Buildings” [prINSTA/TS 951 - 1]. In this paper we analyse core concepts of the technical specification (TS 951) using the perspective of fire safety management. It is assumed that authorities, engineering resources and building developers must cooperate. Often, when a building is handed over from planning and development to the operation phase, new actors enter the field; the building owner, users and the rescue services. One can hope that novel building designs that will be subjected to probabilistic methods for verifying fire safety (the TS 951) will be based on trustworthy, traceable and sound designs. The essence is knowledge that must be open for review and discussion. We question the usefulness of the TS. Instead of enhancing flexibility in choice of solutions and fire safety awareness, we fear the TS will imply rigidity in fire risk analyses in an understanding of compliance with unclear statements of performance criteria.

BACKGROUND

Historical changes

A Nordic initiative has now been launched for public comments, providing guidance on “Probabilistic Methods for Verifying Fire Safety Design in Buildings” [prINSTA/TS 951 - 1]. Use of performance based fire safety designs was formally introduced in Norway in 1997, heavily influenced by the experiences in other high-risk industries, such as the oil and gas industry. This formed a new discipline; *fire safety engineering.* Practitioners of fire safety engineering cooperated with other professional engineering disciplines in the design of buildings and structures.

The experiences from 1980-ies in the oil and gas industry were the major accidents, such as Alexander Kjelland (1980) and Piper Alpha (1988) influenced the regulatory bodies to demand comprehensive risk assessment methodologies in the design processes [2]. In the 1990-ies the industry further discussed standardization of taxonomies, methodologies, models and data in order to enhance quality of assessments and reduce costs. Comprehensive quantitative risk analyses processes formed a consultancy branch providing “Total Risk Analyses (TRA)”. The usability of TRAs have been questioned and the industry is now looking for better solutions [3]. Safety management based on functional requirements was an important part of the design of the offshore facilities.

Safety management principles, based on functional requirements did not get foothold in the land-based construction industry after the introduction in 1997. Instead, methodologies based on comparative studies with reference buildings were developed. Risk assessments of novel buildings’ proneness to fires were rarely seen [4, 5], and when such analyses were presented, they were poorly founded in risk theory.

The historical development of the construction industry has been regulations based on detailed solutions incrementally improved by learning from events, such as fires. Designing novel buildings has become a mixture of pre-accepted solutions and major parts deviating from pre-accepted technical specifications. Performance-based fire safety engineering in Norway is usually assessing the deviations from pre-accepted solutions and developing support for that an acceptable fire safety level is achieved.

Restrictions related to the pre-accepted solutions motivates deviations. Such restrictions could be that the floor area of a fire section in a sprinklered building should in Norway not exceed 10 000 m^2. Another restriction is that the maximum travel distance to an emergency exit in a shopping mall should not in Norway exceed 30 m. Such restrictions are sometimes problematic to resolve in combination with other functional requirements, and are often deviated from. When deviations are introduced, consultants usually carry out an analysis of the possible consequences. Such analyses are usually qualitative, not in accordance with any overall procedure and usually restricted to the deviation only, i.e. it does not consider the holistic fire safety level of the building. This indicates that fire safety engineers in Norway have a poor general understanding of risk and methodologies for measuring fire safety levels [5].

Major issue and methodology

In this paper, we analyze core concepts of the technical specification (TS 951) in the perspective of fire safety management. It is assumed that authorities, engineering resources and building developers must cooperate to ensure fire safety. We present selected concepts from TS 951 and provide a critical review of these concepts based on theoretical controversies and related empirical evidence that represent underlying challenges for fire safety engineers. Our main issue is to investigate whether standardization of probabilistic methods to verify fire safety designs of novel buildings will improve engineering practices, or not.

PR/INSTA/TS 951 – PROBABILISTICS METHODS FOR VERIFYING FIRE SAFETY DESIGNS

The Nordic initiative *"Probabilistic Methods for Verifying Fire Safety Design in Buildings"* (prINSTA/TS 951) exist as a hearing document. In the introduction to the TS, it is stated that fire safety engineering methods can be used to demonstrate fire safety, either *1) to compare a design to pre-accepted solutions, or; 2) for the evaluation of a design against absolute criteria.* This statement provides a good understanding of why the TS has been developed. While the first approach is common in the Nordic countries and specified in an earlier guide (INSTA/TS 950), the second approach is not. A major goal of the TS is to change current approach, and provide guidance on how to conduct a probabilistic analysis for evaluation against absolute criteria. From the statement, we draw two key assumptions:

1. FSE is limited to either comparative analyses or probabilistic risk analyses compared with absolute criteria.
2. The major purpose of FSE is verification of designs against national regulations.

In the description of the new approach, there is still a major focus on deviations from pre-accepted solutions (see sections 4.2 - 4.7). This is odd, because the major idea of the TS is cases where no valid pre-accepted solutions exist.

The TS is organised in a traditional way. This means mechanical evaluation of risk results against risk acceptance criteria. Methods, models, data and assumptions are based on common knowledge. According to the developers, the TS does not represent anything new, but is rather a collection of "known tools" made more accessible to Nordic fire safety engineers. Based on a critical review of the TS we will discuss the following claims/hypotheses:

- *Risk acceptance criteria as the reference safety level reduces fire safety management to an issue of compliance without knowledge of analysis contents.*
- *Validation of predictive fire risk models and verification of designs is not possible.*
- *Design processes require decision support that deviates from the knowledge gained from PRA.*
- *Uncertainty is understood as a mixture of variability, lack of knowledge and imprecision. It is a troublesome but important concept that needs clarifications before use in fire safety designs.*

PERFORMANCE CRITERIA (ACCEPTANCE CRITERIA)

Traditional safety design based on prescriptions makes a clear distinction between acceptable and unacceptable safety. Either there is compliance, or there is not. In the former case, the design is safe and in the latter, it is unsafe. However, this follows from the assumption that everything else, besides technical safety measures, is equal. For instance, an office building is just an office building no matter where it is located; who works there; what maintenance procedures are implemented, and so on.

Risk acceptance criteria establishment is said in TS 951 [6] to be the most important achievement for the success of the technical specification. National risk acceptance criteria have never been proposed, neither as an individual nor as a societal criterion. The TS advocates the use of absolute criteria, relating to a risk number. The societal risk criteria are developed from a "recommended" individual risk criterion of 10^{-6} per year. This means: "an individual may be subject to fatal conditions due to fire every 1 000 000 years, which is said to be a tenth of recorded loss of lives (all occupancies) in the Nordic countries."

How shall actors in fire safety engineering understand these statements of risk criteria? It seems crucial that the regulators must decide whether the TS 951 should be a normative reference as a guide to the building regulations and the requirements presented there. Are the risk acceptance criteria in TS 951 consistent with pre-accepted solutions? Is it fair to say that technical designs contributes approx. 10 % to the number of fatalities from fires? Furthermore, what are the authors' intentions and interpretations of these criteria? How shall we relate uncertainty to them? The questions are numerous and they are currently unresolved.

Recently, we have seen that the field of risk research and risk assessment is rejecting the positivist worldview and adopting more of a constructivist approach. For instance, it is acknowledged that uncertainty is more than probabilities. In practice, this calls for a clear distinction between the analysts and decision makers, acknowledging that the application of mechanistic risk acceptance criteria is excessively simplistic.

We think that the most important question is how to separate good designs from bad designs. The quality of a system design may be determined and measured by its fitness for the intended purposes. Hence, quality comes down to values about what purposes are relevant and how these values are prioritized, e.g., based on the importance viewed by the stakeholder.

VALIDATION AND VERIFICATION

Validating fire risk models and verifying fire safety of novel designs put huge challenges to the fire safety engineer. The user of the technical specification is given the following instructions: "The user of this Technical Specification must verify that applied models are valid for the relevant design situation and that national requirements are met". Some challenges are as follows:

Firstly, the user shall verify that applied models are valid. What does it mean? When is a model fully verified? How can we validate a risk model or a probabilistic model of a novel design? We have found no solution to this in the academic literature [7]. ISO 16730 – Fire Safety Engineering – Assessment, verification and validation of calculation methods notes: *Verification* is the "process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method". *Validation* is the "process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method".

The number of calculation tools has increased in sophistication as well as complexity. The complexity of these tools places requirements on the fire safety analysts' competence. It is important to remember that the arbitrariness related to assumptions and required information might not be proportional with the degree of accuracy of the software models [8]. Regrettably, personnel with insufficient competence in their field sometimes perform analysis with tools they do not understand. For instance, the Sleipner A GBS accident [9] was partly caused by erroneous use of a FEM-analysis (Finite Element Methods) program. Analogies can be made to complex CFD analyses.

Secondly, the rhetoric of the concepts "verify" and "validate" can be misleading as it implies a mechanistic link between analysis and decisions. I.e. the decisions simply follows the analyses. This can make the formal decision makers passive bystanders, rather than encouraging them from discussing safety assessments. This is a threat to the quality of risk management. The basic assumption in the TS is that there exist true fire safety levels and the verification and validation procedures manifest these levels. Thus, stakeholders may approach the safety assessments similar to how they would approach recognized procedures for calculating structural integrities. Dealing with probabilistic fire safety designs, this is unusual, involving significantly more uncertainties. Authorities that supervise the activity must follow up practices on performance based fire safety engineering. How can authorities accept that a Standardization organization puts themselves into the regulator's driving seat?

The focus on verification of safety levels indicates that a building is either safe or unsafe, independent of context. This may lead users to assume that the building may be appropriate for "every type of use". We argue that safety is highly context dependent, which may be illustrated by the concept of car safety: A Volvo has a good reputation for being a safe car, but if the car is driven by an inexperienced, drunken driver on a narrow, icy road during the night, safety will be compromised. Consequently, safety is an emergent property of the *car-driver-environment system.*

Verification may be, and often is, used about compliance with safety objectives in the regulation. Thus, rather than verifying a safety level, per se, one verifies whether the objectives of the regulations are fulfilled. This may be possible if the safety regulations are prescriptive, when there is universal agreement about categorization of both the IF and the THEN side. However, for novel building designs there are no prescriptive regulations, and even if there were, there would be disagreement about interpretations. Nevertheless, at best one would be able to verify that the design complied with the regulation at a specific point in time of the design phase. During later design phases, the construction and operation phases, it is likely that something is changed, rendering the verification work useless [10].

Thirdly, assessing what is the relevant design situations compared with national requirements needs clarifications. It must be seen in relation to the dilemmas in engineering.

DILLEMAS IN ENGINEERING

Designing is an act of balancing different values and goals. Hence, to assume that goals (safety, aesthetics, operations, etc.) or can be predetermined in an objective way, at least in a precise quantitative way, is another simplification [4]. According to Krippendorff [11] designers need to understand how others (the stakeholders) understand the design. Hence, designing is not mainly about calculations and evaluations against objective criteria but about making sense of the designs to the stakeholders in a language they can understand.

Designing is also inherently a creative task. It is about finding innovative solutions to new needs and problems. Consider the activity of designing a new building. The building owner may have a rather clear specification of what he/she wants before the project is initiated. However, as the designers bring the ideas to life through models and drawings in accordance with the specification, new needs may emerge from the new contexts, leading to the original specification being adjusted or clarified. Similar processes may be present within the design team.

The TS does not correspond to design processes' characteristics on this matter. Instead of reinforcing processes that faces inherent complexity, the TS relies on simplifications and structuring of problems. Some examples of simplifications:

- Use of floor area as an indicator for determining the probability of fire, which is an indicator distant from system knowledge. Recommendations from the Norwegian Oil and Gas Association emphasizes more appropriate and enhanced risk analyses, in which knowledge is decisive [3]. The contrast is noticeable.
- Predetermination of reliability of different fire safety measures, e.g. fire alarms, detectors, partitioning walls, sprinkler systems. Reliability numbers are indirectly included through reference to PD 7974 that do not mention from which kind of walls, systems etc and what circumstances the data has been gathered.
- Predetermination of models and parameter values (e.g. fire growth model, peak heat release and corresponding parameter values). The authors have gathered a set of data (including referenced documents) for the purpose

of feeding the probabilistic models. If the models and data is standardized, no one will ask questions about their validity/relevance.

Although a design proposal solves the client's original specified needs, there may be tacitly understood qualities that are not acknowledged or appreciated before the design is brought to life at some level of abstraction. For instance, when the floor plan is drawn, it is possible to picture the activities to be carried out in the building and assess how it will function in specific operational scenarios. Schön [12] provides an example of what he calls a reflective conversation with the situation. The process he is describing is circular, involving framing and reframing the problem based on the challenges posed by new design proposals.

We doubt that a fire safety engineering process based on PRAs according to the TS would effectively support this kind of thinking. Instead, the TS promotes a stringent process where fire safety engineers are more concerned with whether a design proposal is acceptable (yes/no), instead of how, or under what circumstances, a design proposal is acceptable. It is our view, that providing such reflections would be more valuable to the architect and building owner in terms of delivering a safer building.

UNCERTAINTY – A TROUBLESOME CONCEPT

The technical specification is oriented towards compliance with fire safety objectives that need to be addressed in the design. These objectives or performance criteria will according to the TS; "in most cases be a quantification of a qualitative functional requirement". This task will constitute a major challenge for the users of the technical specification, especially in terms of uncertainties.

Uncertainty is defined as "quantification of the systematic and random error in data, variables, parameters or mathematical relationships, or of a failure to include a relevant element". Furthermore, the authors of the TS states: "Uncertainties may be related to the reliability and validity of a model, accuracy in estimating the effect of exposure, randomness in the attributes of a population or randomness in the possible events that may occur".

Uncertainty management is assumed to be strategies to manage uncertainties in methods, input data, criteria, models and other relevant variables. The authors of the technical specification emphasise that the users "must verify that applied models are valid for the relevant design situation". Section 7 in the TS introduces uncertainty in many different dimensions; It is variability and represented by distributions; It is the analysts lack of knowledge; It is scientifically unresolved knowledge; It is imprecisions in models and data; It is erroneous models; and It is sensitivities related to parameters and variables used in analyses. This requires a consistent knowledge base and a clear message to the users of the PRA of how to interpret uncertainty. The unclear description of uncertainty introduces ambiguity in the design process.

Some claim that uncertainty can be handled, and consequently reduced, in risk analyses and risk management. The thought is that if we have more knowledge, uncertainty could be further reduced, as the uncertainty analyses will be more reliable and accurate (correspond more to the future). If we had all knowledge there would be no uncertainty and thus we would know the future, which of course is impossible (see Laplace Demon[1]). So what is the limit of our knowledge? Can we have a little knowledge and thus reduce uncertainty with a small amount, or can we have a lot of knowledge and thus reduce the uncertainty a lot? No, the uncertainty of the future cannot be handled. What can be handled, is uncertainty in methods and measuring (epistemological). But that only contributes to narrowing the quantification; it has nothing to do with the possible future state of the world per se [13].

The TS 951 is very conclusive about the uncertainty quantification and claims that uncertainty and risk represents the same. This is misleading and odd, and should be altered in the edition intended for public use.

DISCUSSION – IT IS ALL ABOUT KNOWLEDGE

Current fire safety engineering practice shows that the risk concept is not commonly adopted by fire safety engineers. Still, fire safety science perceives the risk concept as fundamental to solving future fire safety engineering problems. The previous couple of decades show a vast number of articles that focus on developing methods for calculating risk and making decisions from risk results. However, the search for objective risk and decision criteria seems futile [10].

Section 5.3.1 of the TS introduces a relationship between FED and probability of incapacitation and fatalities. What is the strength of knowledge behind this relationship? Section 5.3.1.1 introduces an individual risk criterion of 10^{-6} per year. It is stated that this represents approximately a tenth of the recorded loss of lives in the Nordic countries. In a study part of the creation of the NOU *"Trygg Hjemme"*, we found that "vulnerable groups" must have a considerable higher individual risk than the average. However, statistics were not available to document the actual numbers, as "vulnerable groups" is a poorly defined concept in the construction industry.

Furthermore, social variables (mental & physical health, income, drug abuse history, criminal record, etc) are not included in national fire statistics, but pointed out as important drivers in some in-depth studies [14]. Consequently, if the fire safety community really decided to look into this subject matter, we would find that some "vulnerable groups" have a statistical record maybe 30-40, if not 100, times higher than the average, and that "the average" statistical record would be below the 10^{-6} per year criterion by default in any kind of occupancy. This would make it nearly impossible to design houses for "the vulnerable groups", and render fire safety engineering meaningless for "the average" population, as the criterion is always met. We find that there is lack of knowledge with regard to statistics related to fires and related explanations and impacts. In addition fire frequency and individual risks are

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[1] Laplace Demon: according to Laplace; a machine that has the capacity to know every detail about the existing world and its intrinsic cause-effect relations, and in addition holding the capabilities to calculate the future based on the preconditions.

more associated with social characteristics than building design. Hence, it is generally problematic to describe the fire frequency as a function of building characteristics (see TS page 43-44).

We also note that concerning data the TS 951 makes many references to PD 7974-7 (see e.g. page 45). Published in 2003, the PD 7974-7 contains references to literature mainly from the period 1960-1980, with data from Great Britain and heavily influenced by the research of a single person (Ramachandran). A previous study [5] has shown that PD 7974-7 [15] is a popular reference for Norwegian fire safety engineers. This may indicate some kind of institutionalization of the numbers therein, especially the reliability data for fire safety systems (see PD 7974-7 table A.17), by the Norwegian FSE-community. The quality of numbers gathered from this document is usually taken for granted. This is odd, given the lack of references and the generality of system descriptions. Instead of fire safety engineers having discussions about how to design a reliable sprinkler system for a specific building, the discussion is more concerned with what is the correct reliability number for a sprinkler system in general. The first type of discussion could actually lead to improvements in design, while the second type of discussion has no meaningful answer.

Bjelland et al. [10] argue that engineers may be more comfortable speaking the language of safety rather than risk. Discussing safety performance of systems and the behaviour of important phenomena is simply closer to the engineering epistemology than probabilities and uncertainty. This promotes comparative analyses or the equivalence approach, leading to design processes going into the *intelligence trap*, which entails providing logically sound answers to the wrong problems. Consequently, one may end up selecting poor designs even though the analyses conclude the opposite. In order to meet the challenges represented by novel design proposals, a strengthening of the performance-based option is necessary. This is why we support the intentions of the work with TS 951.

The traditional approach to PRA has an *impersonal* assumption of knowledge. The idea is a *formalization of knowledge* into structural models, standard data, quantitative laws, and predetermined decision criteria. Consequently, it should not matter who is designing a building as long as the designer is in possession of the standard and relevant knowledge within the engineering discipline. This view stands in sharp contrast with how competent designers think and work in practice. Quantitative models may lead to rigorous results, but they are only useful to some extent and do not tackle the most important and fundamental problems of design. Technical rationality cannot bring clarity in cases of ill-structured and multi-faceted problems the way skilled, experienced practitioners can [12].

Transferring knowledge from planning and design phases to the operation phase of the novel building is challenging. The building owner, users and the rescue services often lack background assumptions and assessments of the fire risks. We think that a shift into a real performance-based fire safety engineering practice requires changes to the structures forming the cooperation between the actors in the building sector. Assumptions from the design phase need to be transferred to operational conditions. Recommendations on how the local fire authorities shall approach supervision of these buildings must be provided. The sector must prioritise how to express fire safety and furthermore how to interpret fire safety analyses.

CONCLUSIONS

In this paper we address numerous pitfalls with the technical specification that need consideration in order to ensure more robust design practices related to fire safety.

Firstly, we miss references to decision-making processes in construction projects in the TS. This includes how the probabilistic methods to fire safety designs interact with critical decisions, and how to achieve the expected increase in the quality of decision-making.

Secondly, the implementation of the technical specification in fire safety engineering can contribute to increase, rather than reduce, the distance between actors that need to cooperate in fire safety management. We argue that *complex modelling*, rigor use of *unclear terms* and *too strong messages from analysis results* will inhibit discussions. We claim that the authors behind TS 951 lack scientific justifications. They should also advocate conditions for its use in future design processes.

Thirdly, novel buildings are complex socio-technical systems constantly adapting to changes within themselves and the environment. Designing for safety, then, is not about verification but, rather, about creating a management structure that enables the system to change safely. In order to achieve this, mathematical rigor may have to give way to more qualitative and discursive processes, but this may not be such a bad thing. After all, what do we gain from rigorous solutions to problems that are simply not relevant?

A different approach would be to recognize that designing is not just about developing technical solutions. It is also about developing the goals and values by which the technical solutions are to be judged. This implies a new way of thinking about the goal of fire safety design. Instead of assuming that there exists a universal and objective acceptable safety level, the goal could be to identify critical safety constraints associated with the selected design [10, 16]. For instance, a design proposal introduces constraints on usability/operation. Risk assessments in the preliminary stages could look into such specific issues. Risk assessments may clarify knowledge associated with the decisions by identifying, for instance, appropriate safety measures or boundaries of safe operation. Analyses are needed during the whole design process, but their level of detail needs to reflect the decision that is to be made given the available information.

Too detailed probabilistic fire risk analyses in the early stage of the project may be useless due to changes in later design stages, or they may impose unwanted constraints on creativity and innovation in the design process.

Based on our discussion we support the initiative to standardize parts of probabilistic fire safety assessments, but the draft needs major improvements. In its present form, the tools and design principles are too rigid and the TS lacks ability to penetrate into the design and systems of novel buildings.

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