Development of a Framework for Quality Assurance of Performance-based Fire Safety Designs

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ABSTRACT: In this paper, some fundamental problems concerning the verification of fire safety engineering designs based on performance-based building regulations are discussed. It can be questioned if the approach taken by many practitioners today is sufficient to fulfil the requirements laid out in the building code, i.e. society's demand for fire safety. Examples of this deficiency are that interdependencies between safety measures are not addressed and multiple purposes of safety measures are not recognized when trade-offs are evaluated. This poses a threat to the quality of the fire safety system. At the same time, there are few tools available to address these issues in a practical way. In this paper three tools are suggested as a means of addressing these issues. The tools have also been applied to a simple example to demonstrate their capability.

KEY WORDS: fire safety engineering, design, trade-off, performance-based, prescriptive, verification, quality, trial evaluation, hazard identification, interdependent system, building code.

INTRODUCTION

WHEN FIRE SAFETY engineering (FSE) is used in design applications, the choice of a verification method is very important. Verification is defined as "confirmation that a proposed design meets the established fire safety goals" [1], i.e. the exercise in which the designer explicitly demonstrates that the required level of fire safety is fulfilled in the design solution. However, in FSE design, safety measures and fire safety strategies are seldom designed with equations that correspond to an explicit safety level,

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as in many other engineering areas. The verification exercise is instead carried out by creating and evaluating a number of trial designs [1]. The overall criterion for such evaluation is that equivalent safety is required, i.e. the same safety as if the traditional prescriptive design method had been used and some form of risk assessment (RA) must be used to demonstrate this for each design solution. Acceptable absolute quantitative levels of fire risk for a building as a whole, suitable for design purposes, are not available in a general form. The level of safety afforded by the prescriptive solution is de facto the "acceptable safety". Therefore, a relative comparison of the safety, or some aspects of the safety, in a building can be made on the basis of specific hazards or identified scenarios [2]. The outcome of such an analysis is very sensitive to the selection of scenarios, and the scope and complexity of the analysis. In practice the magnitude of these issues varies from project to project and, likely, occurs because ad hoc methods rather than standard methods are used to make choices about which hazards and scenarios are worthy of consideration in the verification.

The use of the FSE method does not necessarily imply that the whole fire safety system (FSS) is new or has been re-engineered. Instead, the design solution resulting from the prescriptive method is used as a starting point and modifications are then made to varying degrees, i.e. deviations from the prescriptive solutions by making "trade-offs". There are several obvious reasons for this, for example, in parts of the FSS the prescriptive method has advantages since the method is simple, well known and not very time consuming. The concept of trade-offs is simple. One fire safety subsystem is increased or added and another is decreased or removed, while maintaining the same intended level of safety [3]. A design solution can therefore, very often be seen as a combination of the two design methods. Surprisingly, there is still relatively little guidance in design handbooks on how to deal with the boundary between these methods when they are combined [4,5].

In the fire risk assessment, questions regarding choice of analysis method, criteria, input data, model, etc. are often of great concern for all the involved parties. Little or no attention is paid during the design process to the first and most important phase in the RA process, i.e. hazard identification or, "What has to be analyzed in order to prove that the safety of the design is equivalent, i.e. sufficient?" [6]. This phase is the most important part of RA [7] as the scope of the analysis is determined, which indirectly influences the outcome of the verification analysis. If hazard identification is not done properly, verification will miss some of the relevant aspects of fire safety in the building, and several important scenarios that could cause the design to fail may be overlooked. Shortcomings in the choice of scenarios are one of the most serious threats to the quality of RA when used for safety evaluation purposes [8]. As a result, the "verified as equivalent" design may not meet the demands laid out in the building code and it is possible that the level of fire safety is inadequate, but remains unnoticed in the design solutions. If such mistakes occur, they should at least be identified in the design review, which must form an integral part of all design projects.

In this paper several of the underlying problems associated with the verification of fire safety designs are discussed. A framework that offers new input in the hazard identification phase of the RA is presented, which provides a systematic means of identifying verification needs. This approach will hopefully encourage continued discussion and development in this important area, but should not be seen as the final solution to the problem of evaluating trial designs.

THE QUALITY OF FIRE PROTECTION VERIFICATION AND REVIEW

Fire protection documentation from more than 40 Swedish projects was recently studied [6]. The purpose was to investigate how verification and review had been carried out in these projects where the FSE design method had been applied. Several serious errors and many cases of inadequate verification were revealed. Some major flaws that threatened the quality of the fire safety designs were identified in the project and are listed below.

- Safety measures were studied in isolation, only addressing non-compliances, and therefore little or no attention was devoted to the fire safety system as a whole.
- Parallel systems with built-in resiliency were replaced by more vulnerable single-chain safety components, without considering the consequences of failure.
- Some designers appear to be unaware that different demands apply for verification and review, depending on whether the prescriptive or the FSE design method is applied.
- Designers are eager to adopt the benefits of FSE, but are reluctant to take on the extra workload and engineering responsibilities.
- Inappropriate verification methods were used and no proper risk assessment was conducted.
- Identification of "what" requires verification is often performed in an ad hoc manner or totally forgotten. All emphasis is put on "how" to verify the design, i.e. the appropriate complexity of the model.
- The FSE solutions are sometimes unnecessarily inaccurate as a consequence of oversimplification and a lack of understanding.

Documentation in which flaws were discovered had passed both internal quality control at the engineering companies and the design review required by the local authorities. This indicates the need for better tools to determine the size or magnitude of trade-offs and the appropriate level of verification to assure the quality of the design solutions.

Is this only a problem in Sweden? Investigation by the author supports the idea that the problem is not unique. The development of the FSE concept is global and is characterized by international cooperation and exchange of ideas. Although no detailed analysis has been made of fire protection documentation from other countries, a number of case studies have been investigated [9–11]. The concerns raised here are relevant in several of these, and the similarities in the fire safety engineering design concept used in Sweden to those used in other countries are many, even if the codes and procedures are not identical. Many of the flaws presented have been recognized in other countries [3,12–14].

Several papers and reports have been published on how to verify the calculation tools used in engineering design [15–17], which is crucial to establish a sound technical basis for verification. But it is also necessary to address trial design evaluation on a more general and holistic level as well, since severe weaknesses in the hazard identification have been identified [6].

In the following sections, the underlying problems leading to insufficient hazard identification are analyzed and synthesized. The task of verification is discussed based on the following three postulates:

- Interdependencies between safety measures require a system approach to fire safety.
- The logical structure of the regulatory system is neither transparent nor fully understood, and
- Safety is defined by more attributes than just the function of a system.

which are supported by a systematic analysis of the fire protection documentation recently studied [6]. After the discussion, a number of tools are presented aimed at alleviating the underlying problems.

INTERDEPENDENCIES BETWEEN SAFETY MEASURES REQUIRE A SYSTEM APPROACH TO FIRE SAFETY

When analyzing the effects of trade-offs on the FSS, each safety measure removed or added cannot be studied in isolation because of interdependencies. It is necessary to adopt a system approach to identify the function and purpose of each safety measure, in order to redesign the system so that the total system performance is adequate. When trade-offs are evaluated the analysis cannot be limited to cover only non-compliance with the prescriptive solution, since the modification may affect the rest of the system.

Interdependencies in complex systems are not easily identified, but their consideration in fire safety design has proven to be crucial [18]. An interdependent fire safety system consists of subsystems that directly affect the course of events or conditions in the building, i.e., how the fire and smoke spread, but at the same time their effectiveness depends on how the conditions develop. For example, the limitation of fire size due to suppression systems might decrease the amount of smoke generated, but at the same time prolong the detection time at locations remote from the fire. It may not be evident whether the net outcome is positive or negative from a safety perspective in a complex building.

Gaining an overview of how the whole FSS fits together in the building is a major challenge to the designer. Attempts have been made to visualize the complex relationships between different subsystems, for example in the Global Information Bus [19], but these have so far been of little practical use.

One starting point is to consider the different types of safety measures required in the building code. These safety measures can be divided into three different types, according to their risk-reducing effects:

- those that reduce or eliminate the hazard or risk source, i.e. the probability of fire initiation
- those that reduce or eliminate exposure, i.e. fire development, and fire and smoke spread and
- those that prevent hazardous effects on the safety objectives, i.e. accumulation of heat, smoke and toxic products or products causing non-thermal damage.

The different types of safety measures can be seen as multiple barriers, which are combined to achieve the required performance of the FSS. A tool in which this is developed further is presented in: Tool 1 – The structure of the fire safety system.

THE LOGICAL STRUCTURE OF THE PRESCRIPTIVE REGULATORY SYSTEM IS NEITHER TRANSPARENT NOR FULLY UNDERSTOOD

The structure of a performance-based regulatory system is more or less the same in all countries. The common overall objective is to safeguard society's fire safety goals in buildings, even if the safety level is not necessarily the same. The model proposed by the Nordic Committee on

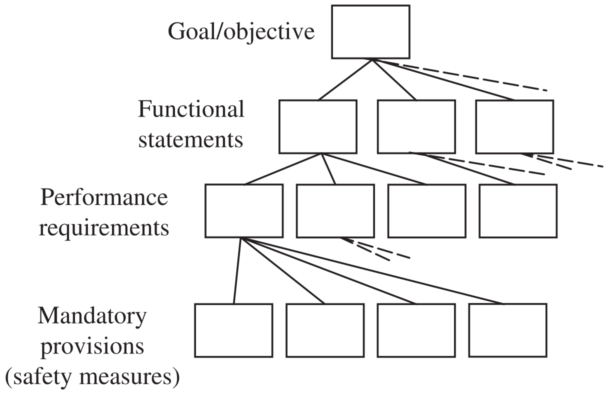

Figure 1. *The idealized structure of the performance-based regulatory system.*

Building Regulations (The NKB model) [20] is often used to illustrate the hierarchal structure of the regulatory system, where several levels correspond to different types of regulations. In Figure 1 the levels in the NKB model have been transformed into an idealized structure illustrating the organization of the regulatory system. In this structure the top level can be broken down into independent demands on the lower levels.

In an actual regulatory system, the safety goals, performance requirements and mandatory provisions leading to acceptable solutions are not arranged in a strict hierarchy. Many safety measures are part of an integrated safety solution which can have multiple purposes and contribute to fulfil several functional statements. An example is escape routes, which serve both as a way out for occupants, and as an entrance for the rescue service. This makes the true structure of the cause–effect relation between the safety measures, the performance requirements and the functional statements not fully transparent, i.e. the rationale behind the safety measures is not always fully known. This result is understandable considering the evolution of and influences on the regulatory system. Traditionally, the acceptable level of safety has been defined by detailed demands in terms of acceptable solutions and "deemed-to-satisfy" provisions. These demands reflect building tradition and have been developed over many years, driven by public perception of accidents that have happened, and can be seen as an historical patchwork [3].

The discrepancy between the formal regulatory system, depicted in Figure 1, and the "actual" safety achieved by the FSS, shown schematically in Figure 2, makes it difficult to understand how a trade-off affects the safety. If the formal regulatory system is used to determine what should be verified, it may be difficult to identify which functional statements and performance requirements are actually affected.

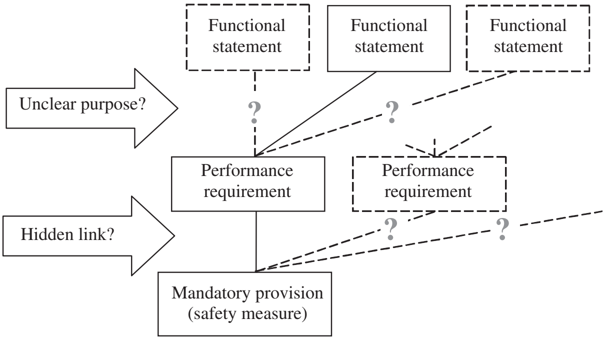

Figure 2. *Unclear purposes and hidden links can cause problems for the designer when trying to structure verification needs.*

In the Scandinavian countries the performance requirements in the building codes cover a number of functional statements originating from the interpretive document Safety in Case of Fire [21], issued by the European Union. These were introduced "on top" of the prescriptive code before the performance-based code was introduced. In some other countries, the USA for example, the regulatory system is arranged in a more transparent way. The same structure as in the NKB levels is used, but each functional statement is covered by a single code, for example there are separate codes for life safety and the safety of the fire fighters. Since both codes have to be covered explicitly in the design, the risk of overlooking multiple purposes of modified measures is smaller.

SAFETY IS DEFINED BY MORE ATTRIBUTES THAN JUST THE FUNCTION OF THE SYSTEM

Verification is often limited to comparing the "functions" of different safety measures. This may be inadequate, since several attributes or properties of the safety system can be affected. For example, it is not self-evident that two separate escape routes in a high-rise building can be replaced by one wider staircase and a sophisticated ventilation system to pressurize the single staircase. Even if a quantitative risk analysis shows that the high reliability of the ventilation system will result in a lower risk than in the prescriptive solution, there may be other concerns indicating that the safety level is not deemed to be equivalent to that obtained with the original solution. The possibility of a fire blocking the only exit can be perceived as a very high risk, even if the probability is low and thus also the risk measure.

Fire safety is a multidimensional or multi-attribute characteristic. Obviously, when searching for a system of attributes suitable for ranking or grading fire safety, a number of such systems can be proposed. In this paper the methodology chosen is based on a system analysis model proposed by Meister [22]. He suggests that a system as a whole can be described by a number of attributes characterizing the system and its performance. He uses a very general definition of the term "system", but these thoughts can be applied to the whole FSS of a building. A rough translation to the area of fire safety engineering leads to the following suggested attributes:

- Function
- Human action/performance
- Complexity of the fire safety strategy
- Complexity of the fire safety system
- Flexibility
- Sensitivity
- Reliability
- Vulnerability

Function

When the safety strategy is changed, many things must be considered to assure that the safety system works according to the demands. Have new risk sources been introduced? Have the conditions that affect the need for protection of any safety objective changed? Have the safety objectives changed, for example are there more occupants in the building? If so, are additional safety systems, in terms of number of exits needed to achieve the same level of safety as available before?

Human Action/Performance

Human actions and organizational measures are often an important part of the fire safety strategy, for example, in complex environments like high-rise buildings, large shopping malls or subway stations where phased evacuation or routing is necessary. At the same time, there are many catastrophic fires clearly related to erroneous human actions or lack of action. Traditionally, technical and organizational safety measures have been handled separately. Today, the effectiveness of a safety system is often dependent on both technical systems and human action in an integrated way. Responsibilities, routines and training are other aspects that must not be forgotten, and are important in assuring that the safety system works as planned. Adopting a fire safety management system that deals with organizational and administrative aspects of the fire protection in a building is one way to address this attribute.

Complexity of the Fire Safety Strategy

A number of small changes to a fire safety strategy often have a marginal impact on the safety, as long as the changes are independent. If a trade-off is characterized by the reduction or elimination of several independent safety measures and replaced by a single measure, or a measure that is linked to several other subsystems, a single failure can occur which will render the entire fire safety system useless. This failure can be seen as a ‘‘common cause failure’’. Such a failure threatens the function of several other subsystems. As the fire safety strategy becomes more complex when the FSS is integrated with other building functions, safety measures generally have multiple purposes and are dependent on the functioning of other measures. The consequence of errors in the design will be more serious and, therefore, the need for verification will increase with increased complexity.

Complexity of the Fire Safety System

A complex FSS increases the probability of error since there are more sources of error and more possible combinations of errors. A safety measure may be dependent on several subsystems functioning correctly, for example smoke control in atria. Detectors, control systems, opening devices for ventilators and inlet air, are all subsystems that have to work in order for a fire safety system to operate properly. Complex systems may also require additional coordination to achieve their purpose, for example ventilation to assist escaping people or sprinklers in combination with smoke control systems. Additional requirements of inspection and control might be appropriate for a complex FSS. Due to complexity and the importance of the system for the overall safety strategy, functional testing may be an option in the verification process. The hot smoke test [23] is one example of such a test used in practice.

Flexibility

The attribute of flexibility indicates whether a safety measure is directed towards a single hazard, or covers the whole or a large part of the building, such as sprinklers. A flexible system covers a range of scenarios and has the potential to deal with new, or unforeseen scenarios. The rescue service can also be seen as a flexible safety measure, since they are mobile and can act on the basis of the events occurring at the fire scene. As a flexible system has the ability to deal with unforeseen events the performance of the safety system is more robust. The fire protection demands of a society normally include some degree of flexibility. Fire spread between buildings, for example, is prevented with both passive measures, such as separation distances, and by the rescue service. Arson is another threat that is linked to this attribute. A large proportion of fires in public buildings are caused by arson, but there are no specific design requirements intended to deal with this threat. Is it acceptable for the flexibility of the FSS to be decreased such that the risk due to arson is drastically increased?

Sensitivity

To what extent is the solution sensitive to the assumptions made in the design process? Will different use of the premises result in an unacceptable level of safety? How dependent is the occupant safety on the interior layout, which might be rearranged without consulting a fire protection engineer? For example, sports arenas are rarely used only for sporting activities. Exhibitions and concerts are likely to take place, and the premises may be used to provide sleeping accommodation for competing teams. Can temporary protection be arranged for such occasions or is a permanent installation necessary? The issue of responsibility is also of great concern. Is it the tenant's or the owner's responsibility to assure fire safety for special occasions? How will information concerning these arrangements be communicated to the various stakeholders? By considering sensitivity, the designer is able to assure that important safety aspects will be safeguarded, by taking into account potential events that may make design assumptions invalid. Assumptions found to be crucial for safety must be analyzed in detail. This type of sensitivity analysis should not be confused with a sensitivity analysis of the calculations, which provides the basis for a more detailed uncertainty analysis.

Reliability

Reliability can be defined as the probability that the system will fulfil its purpose. If an error occurs in the system, or if the system is exposed to higher stress than it is designed for, failure can be expected. It is necessary to investigate the effects of any kind of failure. If the impact is predicted to be high, measures to ascertain whether the system is working or not may be needed, and increased service and maintenance necessary. Which conditions must be met to assure that the safety systems will work during the lifetime of the building? What is the lifetime of the FSS? How will the function of the safety system be affected by time? To what extent are service and maintenance necessary? Does the reliability differ between the measures exchanged in a trade-off? The consequence of failure must be considered when safety is evaluated; otherwise the scope of the risk analysis will be insufficient. This can be done with a quantitative risk analysis, event-tree analysis, for example. Reliability can often be easily increased, for example by activating an evacuation alarm both with smoke detectors and by manual intervention. In the Life Safety Code [24] this problem is recognized and explicit demands for multiple safeguards are made.

Vulnerability

This attribute describes the conditions for the survival of the system itself, when exposed to internal and external stress, i.e. the stress in terms of threat to the conditions necessary for the system to operate [25]. What will happen if the power is cut off as a result of the fire, or if the rescue service or police cut off the power during an emergency operation? How will the FSS respond if a fire occurs at the same time as a software failure or if the communication equipment (PA system) malfunctions? How will the system operate if a water pipe is broken or if it is windy or cold? Sprinklers outside a building can freeze, and wind can cause pressure conditions that prevent a smoke control system from operating. What can threaten a safety system or the design solution itself? Is the system vulnerable, and what measures should be taken to reduce its vulnerability? It is not possible to eliminate all threats to the system. There are no fault-proof systems, although it is possible to reduce the vulnerability of the FSS in the design process. For example, the inlet and outlet openings of a smoke control system need not be located on the same side of the building. When analyzing vulnerability, experience from previous fires is very important. Only through experience can we learn which measures look good only in theory, and which actually work in practice. All FSSs must be evaluated and judged not only on their expected performance but also on the basis of history.

A FRAMEWORK TO IDENTIFY THE VERIFICATION REQUIREMENTS

It has been concluded by Kaplan et al. [18] that it is impractical to represent all aspects of a large-scale system by a single model when performing RA. This is probably also true when evaluating fire safety designs with RA as well. A single model rarely covers multiple objectives, the different phases of the fire development or can be used to analyze all relevant fire and/or smoke spread routes in a building (see ISO 13387 – Fire

Safety Engineering – Part 6: Structural response and fire spread beyond the enclosure of origin [26] for major examples). Furthermore, it is imperative to consider multifaceted aspects of the safety system when evaluating equivalent safety. At the same time, it may be difficult to avoid overlap between different models when analyzing the safety aspects of a system. However, a modest amount of overlap can be tolerated [18], in order to reduce the likelihood of important aspects being overlooked. Therefore a framework consisting of three supplementary matrix tools are suggested in this paper, which highlight different aspects of the effects of trade-offs on fire safety.

The tools are not verification methods by themselves. By using the tools the designer can obtain input to determine the magnitude of the trade-off and "what" the verification analysis must cover, by obtaining knowledge on how the FSS will be affected. The tools are not claimed to be complete and cannot be used to get a "go" or "no-go" decision in trial evaluation, which may limit their practical use. These tools should be seen as support in systematic hazard identification to define the relevant scope of the verification analysis and to detect the potential flaws in solutions. This will indicate where further risk analysis is needed in order to verify that the level of safety is acceptable. The tools provide an overview of the verification problem, and it might be necessary to develop more complex tools for each specific purpose. The tools are listed below and described in the following sections.

- **Tool 1** – The structure of the fire safety system in a building: This is a tool to identify which part of the fire safety strategy is affected by a trade-off. This is done by analyzing the structure of the total FSS in the building and the impact when the system is changed.
- **Tool 2** – The purpose of the performance requirements: In building legislation and building codes the purpose must be well understood to assure that the demands of the society in terms of fire safety are fulfilled. If several functional statements are affected by the trade-off, several analyses may be needed and different design scenarios and acceptance criteria may be required. This tool is used to establish the various cause–effect relations between each safety measure and the objectives in the building code.
- **Tool 3** – The attributes (properties) of the fire safety system: Many attributes are relevant for the level of safety in the building. Safety is not just a function of the performance or the functioning of the FSS. Tool 3 indicates whether the trade-off has serious effects on the overall safety strategy.

By using these matrix tools, the designer gets a better understanding of the need for verification and how the safety system in the building is affected by the trade-off. This facilitates the selection of scenarios in the trail evaluation so that the effect of the changes can be evaluated.

These matrix tools will be applied to an example in which a simple trade-off is made for illustrative purposes. In the analysis of the FSE approach, the prescriptive design is used as a reference or base case to define the acceptable level of risk. A brief description of the example is given here.

The Example: Trade-off between an Evacuation Alarm and Reduction of Load-bearing Capacity

A contractor has been engaged to remodel an industrial building with few occupants and low fire load into a three-storey office building. The original load-bearing system was made of unprotected steel, which was not controversial since the structural requirement for the original building was low and the probability of a fully developed fire was also low. The owner of the building intends to make extensive changes to the layout, by adding two floors. The architect wants to retain the unprotected steel beams in the roof (Figure 3). According to the requirements of the Swedish building code [27], the demand for fire resistance in three-storey office buildings is 60 min according to the ISO curve [28] or complete burnout. The unprotected steel does not meet these requirements but, as mentioned earlier, was sufficient for the original premises.

A fire protection engineer is hired as a subdesigner to prove that a sufficient safety level can be achieved without protecting the load-bearing system if an evacuation alarm with smoke detectors is installed. The designer's verification is carried out with enclosure fire dynamics calculations and simulation of the evacuation time. The preflashover conditions in the fire room are analyzed. The time to reach critical conditions is compared with the evacuation time and it can be shown that the employees can leave the building before critical conditions occur. The smoke temperature is

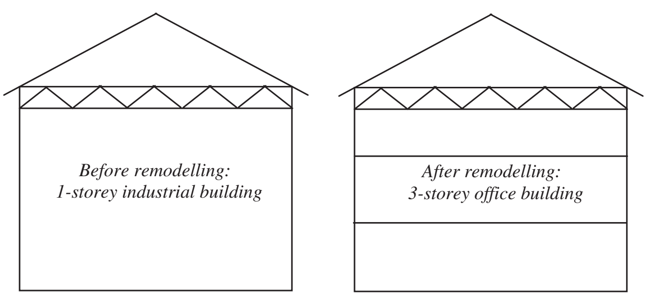

Figure 3. *Layout before and after the remodelling of the industrial building.*

calculated to show that the load-bearing capacity of the steel beams is sufficient, at least for the period of time required for evacuation. According to the fire protection documentation this is sufficient to prove that the level of fire safety has not been reduced. Equivalent safety has been established, or has it?

The verification procedure described has several weak points. The designer's analysis is limited to preflashover conditions, but in the performance requirement it is clear that the structure must withstand a post-flashover fire. No arguments are given that a fully developed fire would not occur in this type of building, which could be used to question the relevance of designing for a fully developed fire. One important purpose of the requirement on the load-bearing capacity is to assure the safety of the members of the rescue service, since they assist in evacuation and must be able to extinguish or control the fire. No effort was made to verify that this feature of the FSS was not reduced when the trade-off was made. In this case, the trade-off affected several safety goals but only the impact on the one related to occupants was analyzed. The result of this was serious since the safety of the members of the rescue service was clearly reduced.

TOOL 1 – THE STRUCTURE OF THE FIRE SAFETY SYSTEM

In order to analyze the impact of a trade-off on the safety system a number of important questions must be asked. Examples are: "What type of risk did the measure aim to reduce or eliminate and how? What was the aim of the measure and was this achieved in combination with other measures?".

Tool 1 applied to this example is presented in Table 1. The purpose of this matrix tool is to visualize which type of risk-reducing measures have been removed or added as a result of the trade-off. The designer starts by defining which safety measures are required according to the prescriptive method. This solution is then compared with the solution suggested by the designer to identify non-compliances and trade-offs. The matrix consists of a number of columns for measures added and for measures removed. Each column has an index number. The number of columns is defined by the number of measures added and removed. The type of protection provided by the measure is indicated in the appropriate row in the column corresponding to the measures index.

The information in the matrix does not give an automatic pass or fail answer, but several conclusions can be drawn. By regarding the vertical spread in the position of the '+' and '−' signs it is easy to determine whether the trade-off affects one or several types of safety measures. If the spread is

Table 1. A tool to identify the effects of trade-offs on the structure of the FSS.

Type of safety measure	Purpose of the fire safety measure (linked to performance requirements)	Trade-off							
		Added measure				Removed measure			
	Index no.	A_1	A_2	A_3	A_4	R_1	R_2	R_3	R_4
Hazard mitigation	Protection against the outbreak of fire								
Exposure reduction	Protection against the spread of fire inside a fire compartment								
	Protection against the spread of fire and fire gases between fire compartments								
	Protection against the spread of fire between buildings								
	Fire-fighting facilities								
Effect reduction	Escape in the event of fire (escape-supporting systems)	+[1]							
	Load-bearing capacity in the event of fire					-[2]			

Added: A_1 = smoke detectors and evacuation alarm; Removed: R_1 = load-bearing capacity.
[1] An evacuation alarm with smoke detectors (A_1) will result in earlier detection by the occupants and presumably a shorter time for them to leave the building.
[2] The unprotected steel will result in reduced fire resistance of the load-bearing system (R_1) compared with the legal requirements. The trade-off will have no other obvious effect on any other type of risk-reducing measure.

significant, the original safety measure is likely to be replaced by another type of risk-reducing measure; hazard mitigation, exposure reduction or effect reduction. This calls for an extensive analysis, since the structure of the safety system has been modified. It is necessary to check that the new safety measure provides protection for all the safety objectives covered by that removed. For example, if compartmentation, which prevents fire and smoke from spreading, is replaced by an evacuation alarm, several safety objectives which were protected may be unprotected, for example the load-bearing system or the safety of the rescue service personnel. If the measure replaced formed an integral part of the safety system and contributed to the protection of several safety objectives, extensive verification is necessary to assure that the new measure can provide the same performance from a system point of view.

If there is an imbalance between the total number of '+' and '−' signs in the vertical direction the number of independent barriers, i.e. the defence in-depth, is likely to be reduced. The fire protection required by the prescriptive method is generally designed with defence in-depth in mind, which results in a combination of measures aimed at hazard mitigation, exposure- and effect-reduction. A vertical spread in the signs also indicates that it is important to check if measures with multiple purposes have been removed without adequate compensation.

If there is an imbalance between the total number of pluses and minuses in the horizontal direction or in the horizontal and vertical directions, great care must be taken. This is an indication that the protection relies on only a small number of safety measures, and that the risk of common cause failure has increased. Each single reduction may appear negligible, but together, they can have serious implications on the safety. For example, installing a sprinkler system is sometimes used to reduce the protection of a number of independent safety measures, for example the ventilation system, lower rated surface material, reduced compartmentation, allowing longer travel distances to escape routes, etc. Each of the replacements may be considered appropriate when studied in isolation, but the total effect must be evaluated. What would happen if the sprinkler did not work? Is this acceptable or not?

TOOL 2 – THE PURPOSE OF THE PERFORMANCE REQUIREMENTS

Another important aspect in identifying the verification requirements is that the purpose of the performance requirement affected by the trade-off is well understood; otherwise it is difficult to choose models and criteria that measure the effect on the level of safety appropriately.

The second tool is presented as a matrix in Table 2. The tool can be used to assist the designer in identifying the impact of the trade-off on the safety goals, represented by the functional statements. The aim of this tool is to elucidate whether the added and removed measures have effects on several functional statements, which is an indication of multiple purposes of a performance requirement.

The tool has been applied to the example described in the previous section. This tool is used in a similar way to the first, but no trade-offs between the different statements are allowed. If a '–' sign appears without any '+' sign for a functional statement this must be interpreted as a warning. Then it is possible that the safety effect of the measure removed has not been adequately compensated for. If the '+' and '–' signs imply that both reduction and compensation have taken place, verification should be focused on showing that the replacement measures are sufficient to assure the same safety level as before.

There is an obvious need to verify that the positive effect on the egress safety due to the evacuation alarm compensates for the reduced safety due

Table 2. A tool to investigate the effect of removed and added safety measures on the functional statements.

Functional statements	Trade-off							
	Added measure				Removed measure			
Index no.	A_1	A_2	A_3	A_4	R_1	R_2	R_3	R_4
The load-bearing capacity in the case of fire is endured for a certain period of time					-[2]			
The outbreak and spread of fire and fire gases within the building is limited								
Fire spread to adjoining buildings is limited								
People in the building can escape from the building or be rescued in some other way	+[1]				-[3]			
Consideration is given to the safety of the personnel of the rescue service					-[4]			

Added A_1 = smoke detectors and evacuation alarm; Removed: R_1 = load-bearing capacity.
[1] Since the smoke detectors and evacuation alarm (A_1) will shorten the time required for the occupants to leave the building, these will have a positive effect on the safety of the occupants.
[2] The load-bearing capacity will be reduced (R_1) since the beams are made of unprotected steel.
[3] Due to the reduced load-bearing capacity (R_1), falling construction elements can threaten the occupants during evacuation.
[4] The safety of rescue service personnel is reduced (R_1).

to the reduced load-bearing capacity. A quantitative analysis of the egress time and time to collapse is suitable for such a comparison. The tool shows that the reduced load-bearing capacity will lead to reduced safety of the rescue service personnel without any compensation from the added safety measure. The need for safety of the rescue service is not reduced by the trade-off. Verification of the overall safety must include an extensive analysis of the consequences of this aspect of the trade-off. It is likely that other safety measures may be required to safeguard the rescue service personnel.

TOOL 3 – THE ATTRIBUTES OR PROPERTIES OF THE SAFETY SYSTEM

It is difficult to give general guidance on how to deal with the attributes discussed earlier in practical design situations. There may be an overlap between the attributes depending on how they are defined. For some attributes there are well-established quantitative analysis methods on a detailed level, for example reliability and sensitivity analysis, while for others qualitative methods seem more suitable. For many of the attributes there are no explicit acceptance criteria in the building code or in other literature. However, it is obvious that when significant trade-offs are made from prescriptive solutions these attributes cannot be neglected.

As a starting point a third tool is presented in an attempt to assist the designer in making a systematic qualitative analysis of how the attributes of the system are affected. This tool forces the designer to examine each trade-off and consider how the overall safety of the building is affected. If an attribute changes such that the safety is affected in a negative way this must be investigated further. If an attribute of the overall safety system is affected this is indicated by an asterisk (*). If the attribute is not affected the box is left empty. When an attribute is affected the designer considers the impact on the level of safety and enters a minus sign (−) if further analysis is necessary or a zero (0) if no additional analysis is necessary. The tool has also been applied to the example, as is shown in Table 3. The questions that were exemplified for each attribute have been used as a simple checklist in the qualitative assessment.

The tool in Table 3 indicates that two attributes are affected negatively by the trade-off. This is a highly subjective judgement. It is necessary to verify that functional statements are fulfilled and that the reliability of the FSS is sufficient. This tool is mainly used to identify the impact of sizable trade-offs, which makes it necessary to consider whether the attributes are affected. These are aspects that are difficult to deal with in the traditional fire RA.

SUMMARY OF THE ANALYSIS OF THE EXAMPLE

The result of the remodelling of the building can be seen as a trade-off; an evacuation alarm is added and the requirement of fire resistance of the load-bearing structure is reduced. As a consequence of this, according to the analysis presented, several functional statements have been affected. In the analysis it has been identified that the following issues need to be addressed in the verification in order to prove equivalent safety:

– Since the smoke detectors and evacuation alarm will shorten the time required for the occupants to leave the building, these will have a positive effect on the safety of the occupants. Will this compensate for the risk for structural collapse or falling structural elements, which will increase since the load-bearing capacity will be reduced when the beams are made of unprotected steel?

Table 3. A tool used to evaluate the effect of trade-offs on the attributes of the safety system.

Attributes of the overall fire safety system	Trade-off							
	Is the overall safety system's attribute affected by the trade-off?				What is the impact on the fire safety?			
Index no.	1	2	3	4	1	2	3	4
Function	*[1]				-			
Human action/performance								
Complexity of the fire safety strategy								
Fire safety system complexity	*[2]				0			
Flexibility								
Sensitivity								
Reliability	*[3]				-			
Vulnerability	*[4]				0			

∗ attribute status is affected
− safety negatively impacted
0 safety not significantly impacted.
[1] Based on the observations from Tables 1 and 2 it can be concluded that the function of the FSS is affected by the trade-off. The impact may be significant since several functional statements are affected and the reduction in safety is not compensated for.
[2] An additional technical system will lead to a more complex FSS, which requires maintenance in order to assure reliable operation. This is not likely to have a serious effect on the safety, but the designer must include this in the maintenance instructions.
[3] A technical system is always associated with a certain degree of reliability. Protection of the load-bearing system is likely to have a higher degree of reliability than the evacuation alarm. The consequence of operational failure of the alarm must be investigated and included in the assessment.
[4] The evacuation alarm will affect the vulnerability of the FSS, since routines and instructions must be established, and malfunction, loss of electrical power or sabotage will cause problems, etc. The evacuation alarm is nevertheless a well-known system and it is easy to establish maintenance routines and backup power.

– The safety of rescue service personnel is reduced without compensation. Does the solution meet the minimum requirements or can it be shown that the level of safety is sufficient?
– The load-bearing capacity will be reduced since the beams are made of unprotected steel without compensation. Will the underlying objective with this functional requirement be fulfilled?

– A technical system is always associated with a certain degree of reliability. Protection of the load-bearing system is likely to have a higher degree of reliability than the evacuation alarm. The consequence of operational failure of the alarm must be investigated and included in the verification.

These issues answer the question "What has to be verified?" in the example. The next step is to determine "how to verify", i.e. which methods and criteria to select in order to evaluate whether the identified impact on the fire safety in the building is acceptable or not.

DISCUSSION

When using the three tools to identify the need for verification, subjective judgement is inevitably introduced and the potential bias associated with the person performing the identification must be addressed. The designer's judgement can be affected by demands other than thorough verification, for example limited time or budget, or demands for cost-cutting, etc. A designer-induced bias can affect the scope of the verification, i.e. the completeness, and thereby threaten the quality of evaluation of trial designs. This is one reason why review of the verification is necessary. In Sweden, quality control is an issue both for the contractor, in terms of internal quality control, and for the authorities having jurisdiction (AHJ), in order to safeguard the quality from a societal perspective. In contrast to many other countries the AHJ performs no independent review of the design solution in Sweden. Instead they determine the appropriate level of design review for the specific project and can require that the contractor hires an independent third-party controller. The different levels are as follows:

1. Self check – The designers are responsible for their own quality control.
2. Internal review – Another designer with at least the same level of competence performs the quality control. This person may work for the same company as the original designer.
3. Third-party control – The person performing the peer review should work for another company so as to be considered independent. This person should not have been previously involved in the design project.

The AHJ's decision regarding the level of review may not be based on the verification analysis carried out by the designer. Critical assumptions and simplifications made by the designer may contain errors, leading to a poor decision on the part of the reviewer. At the same time, it is inappropriate to perform an extensive analysis in order to determine the need for review for each project, since the available resources spent on review are limited. This indicates the need for the development of additional tools in the design process, i.e. simple tools to determine the appropriate level of review, to assure the quality of fire safety design.

Even if there may still be problems associated with the subjectivity in applying the tools, one should not forget that the whole FSE design process is characterized by a high degree of subjective influence today. As long as we use RA in the evaluation of trial designs for specific buildings subjective judgement will be present [2,29]. It is impossible to standardize design scenarios with a sufficient level of completeness to capture all the potential design flaws.

One obvious area of development is the tool concerning the attributes of the fire safety system. At the moment simple checklists are used, but having the ability to define different levels of impact for each attribute is appealing. The attributes can be expressed as key performance indicators for a solution. Measurable parameters can be used to direct the designer to a specific level, which would decrease the problem with subjectivity and make ranking of the design alternatives possible. A number of well-known semi-quantitative methods [30–33] would fit this purpose, for example index methods.

A simple example has been chosen to demonstrate the tools for reasons of space. More rigorous examples have been tested with promising results while developing the tools and their potential usefulness has already been recognized by several interest groups in Scandinavia. There are several examples of the application of the tools.

- Handbooks for designers [34,35].
- Handbooks for AHJ when determining the need for review [36].
- Several projects carried out in the Scandinavian countries, influenced by the above handbooks.

Despite the fact that the terminology used to present the tools in this report is based on the Swedish conditions many of the issues addressed are so fundamental to the design process that differences in national codes and standards are of less importance. Minor adjustments may be necessary, but can easily be done on a national basis.

CONCLUSIONS

The quality of the verification of equivalent safety in FSE designs can be questioned and examples of potential flaws have been illustrated in this paper. Present guidance is inadequate on ''what'' should be verified in order to demonstrate equivalent safety for many practical design applications. To address the underlying problems a qualitative framework with the purpose of structuring the verification process and identifying verification needs is presented.

The framework consists of three supplementary tools that should be regarded as the first approach to addressing several problems in quality control of designs with a broader scope than before. The tools are coarse, but offer the potential to structure hazard identification when determining ''what'' should be verified. They aim to increase the level of completeness of the hazard identification phase in RA, which must be the base for trial evaluation in performance-based fire safety design. They have limitations in terms of bias and incompleteness due to subjective judgement. However, these tools should not be regarded as the final solution to the quality control problem of fire safety designs, but rather a possibility of systematically moving one step forward.

The tools are based on an evaluation of Swedish design documentation and the Swedish regulatory structure, but the similarities with those of many countries are so great that they can easily be adopted in other countries.

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