THE PERFORMANCE-BASED APPROACH
IN THE FIRE PROTECTION OF CULTURAL HERITAGE

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ABSTRACT

The necessity to preserve the authenticity of the buildings of cultural heritage makes in many cases the implementation of the conventional prescriptive codes of fire protection problematic. In such kind of buildings it is not only the human life that has to be protected, but the building itself as well, and sometimes its contents. The performance-based design is the rational way to find the right balance between preservation and fire safety, since the most of the regulations in practice have specific limitations and several drawbacks. In this paper are presented and briefly described the basic performance-based fire protection methodologies for the design of the fire safety systems of cultural heritage buildings in use. Moreover the general proposed frame of actions which is introduced based on the Analytic Hierarchy Process, could act supportive to the existing conventional fire safety prescriptive regulations, aiding in the fire risk assessment of the present situation of an existing building and estimating the influence of any of the proposing fire protection measures to the fire safety level of it. Through this procedure the extend of the required interventions could be minimized, without lowering the fire safety level.

INTRODUCTION

General scope

This paper refers mainly to existing buildings of cultural heritage which are in use, for example a neoclassical building which is used at present as a hotel, or a monastery in Mount Athos, etc. This fact does not exclude the possibility of using the presented methodologies during the design of a new building, no matter whether it belongs to cultural heritage or not. In fact the incorporation of the fire protection design in the overall building design is essential since fire protection is an integral part of the built environment. However, in the past fire protection was in most cases poorly considered during the design of a building, resulting in buildings with high fire risk. In these cases of existing buildings the performance-based design is the appropriate way to increase the fire safety level, without affecting extensively the authenticity of the building, when this is a concern.

Prescriptive codes

Despite the advent of performance-based design, much fire protection design is still prescriptive. Most of it is dictated through prescriptive codes. This kind of design has some advantages; it requires little analysis, and therefore little time or knowledge to apply. Moreover it can cover a broad range of conditions, being in many cases very flexible. And it is a “known”, which has worked for a long time in the past and its substitution could be difficult. On the other hand the prescriptive design may render the design unduly expensive. A second disadvantage is that in many cases it does not result in the most effective way of protecting a particular facility. The more
specialized the building, and the more its architecture departs from the assumed norms, the higher
the chance that performance-based design can better serve that building’s fire protection needs [1].

Decision making

The fire protection design is in fact the task to choose the best solution between a number of
alternatives. This choice is in most cases difficult, depending on a big number of factors most of
which are imponderable, and many of them interconnected, resulting to a chaotic system. In the
field of decision making, creating a structure is the first step in organizing, representing and
solving a problem. A structure is a model, an abstraction of a problem. It helps us visualize and
understand the relevant elements within it that we know from the real world and then use our
understanding to solve the problem represented in the structure with greater confidence [2]. This
kind of structures will be discussed later in the present paper.

Historical Preservation

The protection of historical structures is unlike that of almost any other type of building. In some
cases the objective is to preserve the structure itself, sometimes it is the contents that is of most
concern, and sometimes it is both. In some cases the aesthetics or the interior and exterior
architectural details are significant and sometimes the internal details of the structure itself are
unique and in need of preservation as part of the historical record. Thus, the art of historical
preservation must be free to find solutions that are consistent with the particular needs of the
building. Such freedom simply cannot be achieved with prescriptive approaches developed with
the typical building in mind.

Preserving the history of a building can involve some unique and sometimes contradictory issues.
The older the building the more likely that it had been at least partially destroyed and repaired.
These repairs then become an integral part of the history of the building. Larger structures that
provide examples of structural design that do not meet modern structural safety requirements are
especially difficult to retrofit to modern code while retaining their historical value. Fire has long
been an enemy of historical structures, with some older structures falling victim many times. In
prior reconstructions, materials and techniques reflected the norms of the time because historical
preservation is a modern concept. Today, we want to preserve the past but many of these old
buildings generally exhibit combustible construction and inadequate exits—long, single paths of
travel, narrow stairways and unprotected vertical openings that violate modern Codes and fire
protection practices [3]. Thus their fire protection becomes a difficult task that must be based on
modern effective techniques, both respecting history and culture and achieving a satisfactory
safety level.

PERFORMANCE-BASED DESIGN (PBD) AND FIRE RISK

Performance-based design

Risk has two essential components; exposure and undesired consequences. Exposure is a potential
risk that becomes real with uncertainty, and so exposure refers to the likelihood or probability of
experiencing a destructive event, for example, fire. Undesirable consequences, ranging from
deaths or property damage, to significant intangible losses such as business interruption, mission
failure, environmental degradation, and destruction of cultural artifacts, are also potential risks.
They become real if exposure occurs. Thus when we speak of fire risk, we are referring to the
uncertainty of loss.

The main part in a performance-based fire protection design procedure is the definition of the performance objectives. A performance objective is defined as a given level of performance for a specific hazard level. Three performance levels that could be considered are: (i) Insignificant level: the overall damage is characterized as very light. (ii) Moderate level: the overall damage is characterized as moderate. (iii) Catastrophic level: the overall damage is characterized as severe.

Following the definition of performance levels and in order to establish the performance objectives, the corresponding fire hazard levels must be determined. The definition of the fire hazard refers to the probability of a fire to incident to happen, thus the likelihood of fire ignition, and involves many parameters such as the processes which are taking place in the building, the type of wiring, the presence of people, etc. The three levels of recommended fire hazard are defined as follows: (i) High Probability level, (ii) Medium Probability level, (iii) Small Probability level.

The combination of one performance level with a fire hazard level results in a performance objective. Figure 1 depicts the performance objectives for three classes of facilities. (i) For Standard Occupancy Facilities three performance objectives are defined. (ii) For Emergency Response Facilities two performance objectives are defined. (iii) For Safety Critical Facilities one performance objective is defined. The flowchart which is indicated of the PBD framework is shown in Figure 2.

Methods of Fire Risk Analysis

Fire risk analysis is basically a structured approach to decision making under uncertainty. More information and knowledge results to a diminished inherent risk during the design procedure (see Figure 3). Within this general structure, there are many techniques or approaches to both qualitative and quantitative fire risk analysis. Each application will want to individually consider the level of mathematical sophistication appropriate to meet objectives. A generalized concept of fire risk analysis has these components [4]:

1. Identify fire hazards.
2. Quantify consequence and probability of fire hazards.
3. Identify hazard control options.
4. Quantify impact of options on risks of hazards.
5. Select appropriate protection.

At each of the two stages of quantification, there is a wide range of possibilities of depth and detail, and the actual quantification can take place anywhere on a spectrum from a principal basis in hard data and established science to a principal basis in expert judgment. Fire risk analysis begins, and for some applications may end, with the identification of fire hazards. A preliminary assessment of areas of potential concern in facility design and operational concepts may be organized by location (e.g., area of a plant) or by activity (e.g., manufacturing vs. office functions, wherever they occur). This identification provides a structure for subsequent estimates of the probability of occurrence of the events in each possible accident sequence and thereby of each possible deleterious consequence.

Formal fire risk assessment evolved with the insurance industry in the nineteenth century. Methods of fire risk analysis may be classified into four categories: (1) checklists, (2) narratives, (3) indexing, and (4) probabilistic methods [7]. Checklists and narratives are non-quantitative
approaches that may address Steps 1, 3, and 5 above while bypassing Steps 2 and 4. Indexing is a thorough quantification method that is heuristic rather than fundamentally based. Probabilistic methods have grown in use over the last third of a century but remain rare even today.

![Figure 1](image1.png)

**Figure 1:** The design performances objectives for different importance classes. An example of a fire risk matrix diagram

![Figure 2](image2.png)

**Figure 2:** Overview of the performance-based design process [5]

Checklists are a common accessory of fire safety consisting of a listing of hazards, usually with recommended practices. A checklist is usually less generic than a model code or standard. It may even be so specific that it is intended to apply to a single class of buildings under management of a single owner, reflecting the special concerns of that owner.

A checklist is a practical tool to support analysis of a building relative to a code or standard that forms the basis for the checklist. It is very seldom that all criteria in a code or standard apply to a single building. The engineer must focus on only those requirements that are applicable to a specific project. A checklist can aid Fire Risk Analysis in this process. It also makes requirements easier to read, understand, and track to compliance.

Checklists face a trade-off between practicality and ease of interpretation. A long checklist might
list 50 fire safety factors, with each item described in a manner that is readily visible or measurable, but those 50 items are not all likely to be comparably important. A short checklist, on the other hand, is usually comprised of conceptual features of fire safety, which may all be very important but may all require interpretation to be made measurable.

Moreover, checklists do not capture the interaction of fire risk factors, including the manner in which the importance of one fire risk factor will change as a function of performance on another factor. For example, the relative value of hydrants, sprinklers, and extinguishers is not constant but a function of other features of a structure’s form and utility.

Narratives consist of a series of recommendations - things to do and not do - related to fire risk and safety. They are probably the earliest approach to fire risk assessment, stemming from the observation that fire is capable of destroying certain materials, such as wood, fur, and flesh. This realization would have led to a communication from parent to child on the avoidance of these fire dangers. In this earliest form, narratives were much simpler and less finished than checklists. They were not comprehensive with regard to hazards, and so they did not support a thorough review.

Like checklists, narratives do not attempt to evaluate the fire risk quantitatively. A risk is judged acceptable if it is addressed in accordance with published recommendations. The criterion is one of pass or fail, and the residual risk remaining if you pass is never quantified or evaluated. Also like checklists, narratives cannot hope to cover the myriad conditions of human activity. While there is much common ground among different fire hazard situations, there is considerable variation in detail.

Indexing is representative of the quantitative fire risk assessment that originated with the insurance rating schedule. The approach has broadened to include a wide variety of applications. In general, fire risk indexing assigns values to selected variables based on professional judgment and past experience. The selected variables represent both positive and negative fire safety features and the assigned values are then operated on by some combination of arithmetic functions to arrive at a single value. This single value can be compared to other similar assessments or to a standard to rank the fire risk.

Some measures used in fire risk analysis, such as probable maximum loss (PML), sound more fundamentally grounded than fire risk indexes but may actually be less so. There is no established consensus on how improbable a loss must be to be ineligible as the probable maximum loss, and the designation is sometimes given without benefit of any explicit or formal analysis. The resulting subjectivity of such a determination suggests that this value is more of an ordinal label than a quantitative measure of risk (which is not to say that it does not have usefulness).

Probabilistic methods are the most informative approaches to fire risk assessment in that they produce quantitative values, typically produced by methods that can be traced back through explicit assumptions, data, and mathematical relationships to the underlying risk distribution that all methods are presumably seeking to address. Some common, generic methods of fire risk analysis follow.

Event tree: An event tree is a graphical logic model that identifies and quantifies possible outcomes following an initiating event [8]. The tree structure is organized by temporal sequence. Probabilities can be calculated from the tree, and consequences are typically assigned to the end states but may cumulate along the tree.
Fault tree: A fault tree is a method for representing the logical combinations of various system states that leads to a particular outcome [8]. The tree structure is organized by logical dependency. Probabilities can be calculated from the tree. Consequences are typically defined in an either/or form (success or failure) so that the probabilities suffice to calculate the risk, as defined.

Decision tree: A decision tree is a method for representing the possible outcomes following a succession of events, combining points where the ensuing path is subject to choice and points where it is not. The analysis operates similarly to an event or fault tree, and the simplest decision trees consist of a set of initial choices and an event or fault tree associated with each.

Influence diagram: An influence diagram is a graphical representation of the relationship of the decisions and uncertainties in a decision problem [9, 10]. The diagram is more flexible and less unidirectional than any type of tree diagram. It is designed to focus more on the elements of decision making and less on relevant underlying physical phenomena.

THE PROPOSED FRAME OF ACTIONS

Introduction - The Analytic Hierarchy Process (AHP)

The method which is presented here is the analytic hierarchy process which belongs to the indexing methods. Development of a hierarchical approach to fire risk ranking was initially undertaken at the University of Edinburgh, sponsored by the U.K. Department of Health and Social Services [11, 12, 13]. The objective of this study was to improve the evaluation of fire safety in U.K. hospitals through a systematic method of appraisal. This approach was further developed at the University of Ulster for application to dwelling occupancies [14, 15]. It has been refined and implemented for the assessment of fire risk in telecommunications facilities [16, 17].

Defining fire safety is difficult and often results in a listing of factors that together comprise the intent. These factors tend to be of different sorts. For example, fire safety may be defined in terms of goals and aims, such as fire prevention, fire control, occupant protection, and so forth. These broad concepts are usually found in the introductory section of building codes and other fire safety legislation. Or, fire safety may be defined in terms of more specific hardware items, such as combustibility of materials, heat sources, detectors, sprinklers, and so forth. These topics are more akin to items listed in the table of contents of building codes. A meaningful exercise is to construct a matrix of fire safety goals versus more specific fire safety features. This matrix helps to identify the roles of these two concepts, in theory and in practice.

Decision-Making Levels

As a logical extension of a single fire safety matrix, consider that there are more than two categories of fire safety factors. This idea suggests a hierarchy of decision making levels, or lists denoting things that comprise fire safety. A hierarchy of fire safety decision-making levels is presented in Table 1 and in Figure 4. These represent common levels of fire safety decision making, but there may be more or fewer in a particular application. For example, an even lower level dealing with individual physical items could be added or intermediate levels could be used to better define certain relationships.
This hierarchy of levels of detail of fire safety suggests that a series of matrices is appropriate to model the relationships among various fire safety factors; that is, a matrix of policy versus objectives would define a fire safety policy by identifying the specific objectives that are held most desirable. In turn, a matrix of objectives versus strategies would identify the relationship of these factors, and a matrix of strategies versus attributes would suggest where to use what. Thus, a matrix may be constructed to examine the association of any two adjacent levels in a hierarchy of fire safety factors. An even more appealing aspect of this approach is that two or more matrices may be combined (multiplied) to produce information on the importance of specific detail of building elements to an overall fire safety policy - information not previously available. This approach is the only such grading of fire safety with an explicitly defined relationship to fire safety goals and objectives.

<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Policy</td>
<td>Course or general plan of action adopted by an organization to achieve security against fire and its effects</td>
</tr>
<tr>
<td>2</td>
<td>Objectives</td>
<td>Specific fire safety goals to be achieved</td>
</tr>
<tr>
<td>3</td>
<td>Strategies</td>
<td>Independent fire safety alternatives, each of which contributes wholly or partly to the fulfillment of fire safety objectives</td>
</tr>
<tr>
<td>4</td>
<td>Attributes</td>
<td>Components of fire risk that are determinable by direct or indirect measure or estimate</td>
</tr>
<tr>
<td>5</td>
<td>Survey items</td>
<td>Measurable feature that serves as a constituent part of a fire safety attribute</td>
</tr>
</tbody>
</table>

Table 1: Hierarchy of fire safety decision-making levels [18]

![Figure 4: Typical fire safety evaluation hierarchy [6]](image)

**Generalized Procedure**

A generalized procedure for ranking fire safety attributes to determine their relative importance is summarized in the following five steps:

1. Identify hierarchical levels of fire safety specification.
2. Specify items comprising each level.
3. Construct and assign values to matrices of each sequential pair of levels.
4. Combine (multiply) matrices to yield importance ranking of items.
5. Verify the results.

Table 1 represents an example of Step 1. Step 2 requires that lists of objectives, strategies, attributes, and survey items be developed. A list of fire safety objectives might include statements about life safety, property protection, continuity of operations, environmental protection, and heritage preservation.

The objectives of fire safety consist a very subjective list since the priorities could differ from project to project (i.e., allocation of resources for fire safety is not generally directly associated with a specific corporate objective). One benefit of the hierarchical approach is facilitating the incorporation of fire safety into more global organizational objectives. In most applications a Delphi process [22] is used to define fire safety policy in terms of the specified list of objectives. That is, a group of experts is asked to rank fire safety objectives with respect to their importance to policy. Each member of the Delphi group receives feedback in the form of response averages, and the process repeats until an acceptable level of consensus is reached. The Delphi exercise yields a vector representing the relative importance of each objective to organizational policy. In some work the more formal Analytic Hierarchy Process (AHP) is used [19, 20].

The next decision-making level involves fire safety strategies. Example fire safety strategies are ignition prevention, limitation of combustibles, compartmentation, fire detection and alarm, fire suppression, and protection of exposed people or things [21]. Now, a matrix of objectives versus strategies can be constructed. Values of the cells are again supplied by Delphi or some other subjective decision-making process. In this case the question to be answered is how important is each strategy to the achievement of each objective?

In order to facilitate mathematical manipulation, the values of the matrices can be normalized. Then, multiplying the objectives/strategies matrix by the policy vector yields a new vector that shows the relative contribution of each strategy to overall fire safety policy. While this vector is not essential to the fire safety evaluation, it illustrates the matrix manipulation process that is the essence of the hierarchical approach. Continuing this procedure, the next level of fire safety attributes is considered. The following is a typical list of these attributes: construction, equipment, fixed suppression, height, special hazards, fire department, compartmentation, detection, egress, system building services, alarm, personnel, furnishings, smoke control management.

A matrix of strategies versus fire safety attributes is then constructed and evaluated. Multiplying this matrix by the previously derived vector yields a new vector that weighs each fire safety attribute according to its relative contribution to organizational fire safety policy. The significance of this vector is that it is the only such weighing of fire safety factors that has an explicit link to fire safety goals and objectives. The matrix manipulation process is summarized in Figure 5.

**Evaluating Attributes**

In order to use the resulting vector of attribute weights to develop a fire risk ranking of a building or facility space, the extent to which each attribute is present must be evaluated. That is, a level of functional value of each fire safety attribute must be assessed. These attribute grades may be directly observable or, more often, they are derived from various functions of a lower level of features that includes specific hardware components, for example, fire safety survey items.
Attributes are defined as components of fire risk that are quantitatively determinable by direct or indirect measurement or estimation. They are intended to represent actors that account for an acceptably large portion of the total fire risk. In most cases they are not directly measurable.

![Figure 5: Schematic summary of hierarchical approach [18]](image)

This case is especially true for existing buildings for which only limited information is readily available. Each attribute has a specific relative importance that is universal for all facilities within the scope of the assessment method. Individual buildings will vary in the degree to which attributes exist or occur in a space. Attribute grades are a measure of the intensity level or degree of danger or security afforded by the attribute. Partitioning them into measurable constituent parts facilitates grading of attributes. Usually these parts are directly assessable survey items, the next lower level in the decision hierarchy. The determination of attribute grades is dependent on those features of a space identified as survey items.

A survey item is a measurable feature of a space that serves as a constituent part of one or more attributes. In developing means to grade attributes in a given building, each attribute is associated with one or more survey items. These specific features evolve from analysis of the attributes. Items are chosen for contributing significantly to the effectiveness of the irrespective attributes and for being directly measurable. It is, therefore, necessary that survey items be defined in sufficient detail to support these traits. Detailed descriptions of the survey items are required to frame questions that provide input into the decision logic that produces the attribute grades.

In one application, grades were established for each fire risk attribute by associating readily measurable survey items, using logic described by decision tables [23]. Input to these tables included fire test results, fire hazard modeling, field experience from previous fire events, logic diagrams, and professional judgment. The scalar product of the resulting attribute weights and grades yields a relative measure of fire risk. The result may be used to rank facilities, or it can be compared to a standard value.
Areas of Application

As indicated in the beginning of this section, the hierarchical approach has evolved from applications in the areas of health care facilities, dwellings, and telecommunications central office facilities. Recent applications of this approach to fire risk indexing have developed in many forms and for many uses. In the United States, a Historic Fire Risk Index has been developed that includes an assessment of the cultural significance as a parameter of fire risk [24, 25]. While most fire risk indexing methods focus on life safety issues, FireSEPC (fire safety evaluation procedure for the property of parish churches) is insurance motivated and deals with building worth [27].

CONCLUSIONS

Performance-based design is being implemented in many countries, replacing the traditional prescriptive systems. This kind of design is especially attractive for addressing in a rational way the special needs of unique buildings, that can’t be easily categorized such as historic or cultural significant buildings. Thus, performance approaches are well suited to finding the balance between the need to protect often irreplaceable buildings and their contents and the desire to preserve the significant historical or cultural aspects of the building.

The application of the proposed hierarchical approach to the cultural heritage buildings is particularly appropriate, since it allows the designer to determine the priorities and the possible ways to fulfill the objectives [28]. The methodology creates a frame that allows architects and engineers to act more efficiently with respect to the authenticity of the buildings but as well give the guidelines to achieve an acceptable fire safety level. Through this procedure the extend of the required interventions could be minimized, without affecting the fire safety level or the fire safety level could be upgraded without affecting negatively the architectural form of buildings of historic or cultural interest.

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