

Key Distinctions in and Essential Elements of Fire Risk Analysis

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ABSTRACT

The growing volume of research on fire risk has yet to produce convergence on the meaning of the term "fire risk" or on closely related concepts like "scenario" and "fire hazard". These differences in terminology are not simply semantic but often reflect either disagreements or confusion over the essential elements of fire risk analysis. This paper presents a number of basic concepts and a very general format for fire risk measures and models. Then the elements of these concepts are discussed to underline key distinctions between appropriate and inappropriate designs for fire risk analysis. The principal theme is the need to define a model to capture all the variations in fire conditions and other conditions that can affect the fire involvement of the subject of interest, whatever it may be.

KEYWORDS Risk analysis

INTRODUCTION

In the past decade, the term "fire risk analysis" has been used to refer to an ever-increasing variety of forms of analysis. Some of this variation occurs because different decisions and problems require different kinds of information. However, much of the variation reflects the use of the term "fire risk" to refer to a range of fundamentally different types of analysis. Fire risk analysis can encompass every branch of fire science. Since no one person is likely to have that breadth of knowledge, there is sometimes a tendency for models to be built and labeled as fire risk analysis models without sufficient strength in all the requisite areas.

In a recent issue of *Fire Technology*, the author and Dr. Ai Sekizawa of Japan's Fire Research Institute proposed a general framework that could identify the key elements of any fire risk analysis method [1]. After briefly recapitulating this framework and its key concepts, this paper will focus on key distinctions that tend to be crucial in deciding what models are appropriate for different kinds of problems and decisions. Inappropriate or deficient modeling approaches will be cited in places to further illustrate the key elements of fire risk analysis and why they are necessary.

BASIC CONCEPTS AND DEFINITIONS

1. Let U be the universe of all possible fire situations, where each element e of U is defined by a complete physical description of a fire; the environment in which it began, developed, and ended; and the consequences of its occurrence. The terminology used to describe elements of U is not standardized among researchers, which accounts for the use here of the term "fire situation".

2. Probability Density Function of the Universe of Fire situations. Let $p(e)$ be the probability density function for the universe (U) of all possible fire situations (e). Therefore,

$$\int_U p(e) \, de = 1 \quad (1)$$

3. Measure of Severity. Let s be a measure of severity, defined so that (a) the measure can be calculated for every element e of U and (b) the measure is a monotonic indicator of better and worse outcomes. That is, in comparing two elements of U , if a higher value of s means a worse outcome (a more severe fire) for one pairwise comparison, then in any other pairwise comparison of elements of U , a higher value of s also will mean a worse outcome. This definition does not exclude the use of multiple measures of severity in a single analysis.

4. Probability Distribution for a Measure of Severity. The severity function, s , and the probability density function of the universe of fire situations, $p(e)$, jointly define a probability density function $P(s)$ for the severity measure, s . Here, $P(s=s')$ is given by:

$$P(s=s') = \int_U p(e|s(e) = s') \, de \quad (2)$$

5. Fire Hazard. For the purposes of this paper, "fire hazard" is a measure of fire severity for a specified fire situation. This definition differs from the usage of "hazard" in conversational English, where "hazard" refers to an object, activity, building, or other item that is a source of danger. (This usage is also common in the technical literature on risk analysis [2].) Here, the term "hazard" is used to refer to the degree of danger and not to the item that poses that degree of danger.

6. Fire Hazard Analysis. A method for analysis of fire hazard is a method for calculating one or more severity measures, given a specified fire situation, e , from the universe of fire situations.

7. Fire Risk. "Fire risk" is a summary statistic, which may also be called the "outcome measure of fire risk", from a probability density function on a well-defined fire severity measure (i.e., fire hazard measure).

$$\text{Risk} = \int_{-\infty}^{+\infty} g(s') \, P(s=s') \, ds' \quad (3)$$

The function g transforms the severity measure s into the measure of interest for the fire risk analysis. (In fact, $g(s)$ constitutes a severity-measure function itself, but it may be useful to keep this distinction so that a more natural and simple definition of severity can be used for s .)

For example, let s be defined as the number of deaths. Then if the measure of interest is simply deaths, $g(s) = s$. Suppose instead that one is interested only in catastrophic fatal fires, that is, fires that kill five or more people. Then $g(s) = 1$ if s is five or more and zero otherwise. Or, suppose that one is interested in the size of the death toll in catastrophic fatal

fires only. Then $g(s) = s$ if s is five or more and zero otherwise. These three examples from one simple severity measure should illustrate the point.

8. **Fire Risk Analysis**. Analysis of fire risk involves the specification of one or more outcome measures, each of which is a well-defined statistic based on the probability density function of a specified severity measure. A method for analysis of fire risk must specify methods for calculating the outcome measure(s).

DEFINING THE SUBJECT OF ANALYSIS

The purpose of a fire risk analysis is to calculate and assess the fire risk values obtained when part of the specification of relevant situations includes the specification of some fixed subject of analysis. If the subject of the fire risk analysis is a particular building or type of building, this will imply a series of specifications. The fixed characteristics of that building or the common characteristics of that type of building will be treated as fixed in defining all fire situations to be analyzed. If the subject is a particular product, material, assembly, process, building feature, or fire protection system, than that also will imply a series of specifications. Fires that are not affected by the product, for example, may be excluded from the analysis.

In fire risk analysis, it is important not to narrow the specifications any more than is required by the choice of the subject of interest. For example, suppose the subject of interest is upholstered furniture sold for use in private homes. In such a case, it would be appropriate to ignore fires in all manner of commercial or public buildings, but it would not be appropriate to narrow the focus to single-family dwellings, because such a focus would either ignore mobile homes, apartments, duplexes, and the like, or treat them as if their fires developed the same as single dwelling fires. Furthermore, it would not be appropriate to narrow the focus to fires begun by cigarettes igniting upholstered furniture because this is only one of the myriad types of fires that can involve upholstered furniture as a significant contributor. It might, however, be appropriate to ignore fires originating in wall spaces and other places where upholstered furniture is not found, on the theory that the contribution of upholstered furniture would be indistinguishable from other late-stage fuels in such a fire.

The common thread here is that for any subject of analysis, the relevant fires are all the fires where that subject of analysis may be involved. Since that will be an infinite number of distinguishable fires, it is necessary to select a manageable number of situations for analysis. Each narrowly defined situation will therefore have to represent a larger set of similar situations. If instead a fire risk analysis were to be constructed based on one fire situation, for example, that would be equivalent to assuming that the estimated severity of that one fire situation is equal to the average severity in all fire situations. That degree of simplification is likely to be untenable. However, if a large number of very different fire situations are used for analysis, then each can be associated with a relatively homogeneous class of fire situations that are all very much like it. Then the assumption that a particular fire situation is representative of its associated class will become more reasonable.

CHARACTERISTICS OF A FIRE SITUATION

The basic definitions given earlier used a term "fire situation" because more familiar terms, like "scenario", have already been used in so many contradictory ways that they are likely to have misleading special connotations for some people. In particular, most familiar terms have come to refer to specialized subsets of fire situations.

For example, in the Fire Risk Assessment Project work sponsored by the National Fire Protection Research Foundation, the term "scenario" is used in the same way I have used

"fire situation". I favor this usage, but there are points of concern. First, there is the need to use "scenario" to refer to both the individual fire situation and to the larger class of fire situations that it is meant to represent. Probabilities must be estimated based on the class, while severity must be calculated on the individual fire situation. Dual usage of the term "scenario" can be confusing.

More problematically, some analysts use "scenario" to refer only to subsets of fire situations defined by the characteristics of initiation, growth and termination of the fire. This meaning of "scenario" would not include such other characteristics as the number, locations, and characteristics of occupants.

Those who use the term "scenario" narrowly often refer to most of the excluded characteristics collectively as "exposure" [3]. In fire risk analysis for nuclear power plants, one of the most advanced applications at present, there may be the added consideration that plant layouts are so tightly controlled that "exposure" dimensions can be treated as standardized. [4] More often "exposure" is contrasted to "hazard" or "potential for harm," possibly with the view that fire effects in a space pose a danger that has meaning apart from the presence of people or property who could be harmed. In principle, everyone agrees that fire risk analysis involves all these elements - a product, its environment, a fire, and exposed people and property - but terminology can become confused because of differing views as to the importance of separating these elements at different stages of analysis.

Another term worth introducing is "context of use". In essence, the subject of analysis may be not just a product (such as carpeting) but a product in a particular environment (such as carpeting designed for and sold only for use on floors in office building occupancies). For purposes of fire risk analysis, then, "context of use" refers to characteristics of what I have called fire situations that shall be fixed because they are part of the definition of the subject of analysis but that are not part of the inherent definition of the product.

It is important to be sure the definition of the subject of the analysis includes context of use considerations, but it also is important not to assume too much under this heading. For example, it must not be assumed that a product, material, assembly, process, activity, building, feature, or fire protection system will always be used appropriately, installed correctly, maintained regularly, operated properly, or otherwise handled as it should. It may be useful to analyze what its fire risk would be if it were not subject to such human errors, but it would be a mistake to exclude by definition the many problems that can degrade performance.

Also, the context of use will rarely imply any reduction in the range of fires that may occur and involve the subject of the analysis. Unless the subject's context of use dictates that it can only be found in a very few places, one must proceed on the basis that fires anywhere in the building(s) could involve and be affected by it.

The points made so far may seem merely semantic, so it is worth while to summarize and emphasize the substantive distinctions involved:

- Fire risk analysis involves development and synthesis of information on the probability and severity of every type of fire that can include, affect, or be affected by a particular subject of interest.
- Terminology to refer to a generic type of fire has not been standardized. In part, this reflects the need to refer to both unique fire situations and classes of fire situations and the tendency to use the same term for both. In part, it reflects a desire to distinguish among several classes of fire situation characteristics, such as properties of the fire vs. building environment vs. people or property exposure, and to do so at the most fundamental level of the design of the analysis. These distinctions can be useful as long as it is recognized

that every dimension of variation in fire characteristics must be addressed somewhere in the analysis and that the terms used to do so may not mean the same things to other people.

APPROPRIATE OUTCOME MEASURES

While there are many possible outcome measure functions - that is, choices of $g(s)$ in the earlier definitions - it is useful to distinguish those that favor an "average risk" form and those that favor an "extreme value" form. If $g(s) = s$, for example, then the measure of risk will be the expected value of loss. This is equivalent to the probability that a fire (of any type) will occur multiplied by the average severity if fire occurs. On the other hand, if $g(s) = 1$ if $s \geq s'$ and 0 otherwise, for example, then the measure of risk will be the probability that a fire occurs having a severity of s' or greater.

An expected loss risk measure is the most natural and appropriate measure in most situations. It provides a measure of predicted loss that is suitable for comparison with the costs of achieving it. Expected loss measures sometimes are invalidly criticized because of confusion between average loss and typical loss. A true average will give proper weight to very rare, very large losses and may even be dominated by them. A measure of typical loss - or a method for calculating the average that does not properly capture extreme values - will not give major events their proper weight.

Extreme-value risk measures, such as measures in the form of a "probability of failure" or "probability of large loss", implicitly assume that all fire situations are either major or negligible. There are many specialty areas of engineering where events are either catastrophic (the building loses structural integrity and collapses, the dam breaks, the bridge collapses) or inconsequential (the building, dam, or bridge continues to stand). For many engineers, that view of the world has carried over into fire protection. But for most classes of buildings or products or processes, the majority of fire loss results from an accumulation of small fires. There is simply no justification for a pre-emptive emphasis on major events.

However, there are some situations where such a pre-emptive focus can be defended:

1. In some industrial settings, the largest fire or fires of the decade may dominate the overall loss totals. In nuclear power plants, there may be the added factor that controls are extensive enough to justify the assumption that only a very few types of fire situations are even possible. If these conditions hold, expected loss is essentially equivalent to the probability of a large loss, and the latter may be simpler to calculate.
2. For some purposes, an analyst may be interested only in fires whose losses would be so great that they would drive a company out of business. Under those conditions, a fire risk analysis in terms of the probability of unsustainable loss would be justified.
3. The analyst may have been asked to identify not the risk associated with a product - such as a fire protection system or building feature - but its various failure modes, in which case the need for redesign may depend more on the likelihood than on its consequences. Again, if the problem is defined so that probability of failure is the right measure, it should be used.
4. Recognizing that the press and public tend to place disproportionate emphasis on major fires, it may be considered appropriate - or even necessary - to focus on those incidents. Even then, however, it may be better to use an approach that captures expected loss in large incidents or that includes all fires but uses a non-linear outcome measure function to give greater weight to more severe incidents while still giving some weight to less severe incidents.

The common thread in this discussion is that fire risk must be assessed broadly unless it can be positively demonstrated that a narrow focus is valid for the question at issue.

There may be inappropriate reasons that tempt analysts to use a narrow focus when it is not appropriate. One is concern over computational burden and the cost of analysis, since expected loss measures often require a large number of scenarios or fire situations, which will tend to involve a very large number of calculations.

Another inappropriate reason would be a desire to minimize the use of probabilistic theory and statistics in favor of an emphasis on modeling using physics, chemistry, and laboratory data. An example of a generally inappropriate fire risk formulation that can arise in this way would be a definition of fire risk as the severity of a single event times the probability of that event [3]. While such a definition would satisfy the definitional requirements given earlier for a measure of fire risk, few if any real problems can be validly addressed by a measure limited to one event. Such a measure would be an appropriate outcome measure only in cases where one and only fire situation was relevant.

Another example would be the use of the term "fire risk analysis" to refer to a simple listing of major locations of potential concern to fire protection people [5]. Again, the usage of terms like "risk" and "hazard" is far from standardized. Some people use the terms not to refer to relative scales characterizing all objects but rather as category descriptors of selected objects. In other words, they speak of products or features or buildings as being hazards or risks or as not being hazards or risks rather than as having a certain degree of hazard or risk. The insurance industry's practice of referring to each insured property as "a risk," using the term as a synonym for a customer's property, also adds to the confusion, but this usage is less confusing because it clearly involves no measurement or comparisons.

To recapitulate the major point in this section:

Just as the previous section warned against defining fire risk analysis too narrowly with respect to the possible dimensions of variation in fire situations, so this section warns against defining fire risk too narrowly with respect to the level of severity, for example, by focusing on large fires or on cases of established burning. The burden of proof is always on the fire risk analyst to demonstrate positively that any excluded classes of fire situations are truly irrelevant to an assessment of the fire consequences of the subject of interest.

MODELS, DATA AND VALIDATION

The scope of many fire risk analyses requires the integration of a wide range of models and data sources. Models developed independently often must be combined, and new modeling components must be developed. Data requirements from the laboratory may go beyond existing standard tests, and data requirements from the field may go beyond existing data bases on actual fires and on the distribution of characteristics in actual buildings. Even a fire risk analysis conducted on a specific building will need to draw on extensive data bases, if only to capture the variations in conditions in that building. Parameter estimates by experts often are needed.

One technique that has proven useful in the Fire Risk Assessment Project sponsored by the National Fire Protection Research Foundation involves inferring the necessary detail about the starting conditions for fires from their subsequent development [6]. Such an approach does not attempt to survey large samples of buildings and times to develop a probability distribution for the possible fuel loads and furniture positionings of all rooms in a building, for example, because the cost of such an exercise would be enormous. Instead, a probability is developed for each size a fire might reach, based on the proportion of fires that reached that size during some historical reference period. Then, the description of fire size

(e.g., flame spread confined to part of room of origin) is converted to physical parameters, based on expert judgment. Then, fire growth curves are set to be consistent with these final sizes and with any other known information, such as initial fuels. These fire growth curves contain all the information needed for modeling and can be used in lieu of more detailed information about the specific combinations of furnishings that produced them.

This example illustrates that fire risk analysis models tend to have large data requirements that can only be met by using data sources of widely varying degrees of quality. All data bases carry significant uncertainties, as do the models, and fire risk analysis requires explicit attention to the degree of uncertainty in the estimates. Validation presents an unusual challenge for fire risk analysis, because there will tend to be no experiment or body of documented experience that can be treated as a better representation of the reality the model seeks to capture than the experiments and data that are part of the model. The few external points of reference will at most serve to partially validate the model, not validate it in its entirety and all its details. Under these conditions, validation becomes indistinguishable from the process of estimating the uncertainty of the risk estimates produced by the model [7].

The two previous sections warned against improperly narrowing a fire risk analysis model based on the exclusion of certain sizes of fires or certain dimensions of variation in fire situations that may be relevant to the subject of interest. This section warns against biasing a fire risk analysis model toward certain favored types of component models or data sources. Also, because conventional validation tends to be possible only for parts of a full-scale fire risk analysis model, it is essential that the uncertainties of the model be explicitly estimated.

CONCLUSIONS

The term "fire risk analysis" can be used to refer to any systematic estimation of patterns in the probability and severity of fires involving or affected by a particular subject of interest. However, a valid fire risk analysis needs to encompass all the relevant fires, which dictates considerable care in translating the problem to be solved into model specifications. Both the burdens of computation and the understandable desire of building managers, product manufacturers, and the like for certainty will create pressures to narrow the focus of the fire risk analysis model. Even the terms used to describe elements of fire risk analysis have taken on connotations that reflect this pressure to narrow the focus. It is especially important, therefore, that the design of a fire risk analysis model for a particular problem, decision, or issue reflect the needs of that situation explicitly and in detail.

Sound fire risk analysis depends upon the selection of appropriate severity measures, appropriate outcome functions for those severity measures, and a suitably comprehensive and detailed structuring of the universe of fire situations. By designing fire risk analyses around these key elements and assessing the value of existing models in terms of their choices for these elements, we can produce models that assemble the best information possible for the decision at hand, including a clear sense of the uncertainties attending that information. That is the measure of a fire risk analysis.

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