Fire Risk Analysis: General Conceptual Framework For Describing Models

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ABSTRACT

Despite more than a decade of work in Japan, the U.S., and elsewhere on the development of models and methods for fire risk analysis, the basic terms still are used in many different ways by different modelers, producing confusion over not only best methods but also objectives. In this paper, a fundamental conceptual framework is defined that underlies many different fire risk analysis models. Those models that do not fit this framework may be seen to have different purposes, which should be differentiated by different terms (such as fire hazard analysis), or to be using the term "risk" to refer colloquially to any potentially dangerous situation, however identified or measured. The use of this framework should help to clarify developments in fire risk analysis without excluding any worthwhile method.

1. BACKGROUND

The past decade has seen a proliferation of models and analysis methods labeled as risk analysis tools for fire protection problems. While there has been significant progress along several lines and some practical impact on real decisions, there remains a frustratingly large degree of disagreement and confusion over basic purposes and terminology. In most other areas of fire science, disagreements, however strong, tend to be over the validity of alternative means to achieve a particular modeling objective. In fire risk analysis, disagreements often are more fundamental and involve the basic objectives of modeling.

2. PURPOSE

The field of fire risk analysis would benefit from the development of a conceptual framework sufficiently broad that it can encompass any modeling approach to the analysis of fire risk, however unusual. This framework also should be able to explain how any modeling approach excluded from its broad definition of fire risk analysis fits into the still larger universe of models for generating information on the development and effects of fire. This paper is intended to provide such a framework and to provide summary overviews of known models in the fire risk arena.

3. BASIC CONCEPTS

(a) Let U be the universe of all possible fire situations. That is, each element 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 new term "fire situation". Some of the terms that have been used include the following:

(i) Scenario. A "scenario" is sometimes used to describe a single element of U (that is, a single fire situation). Alternatively, a "scenario" may refer to groups of elements that share those characteristics that define the initiation, growth, and termination of the fire but which may differ with respect to other characteristics. These other characteristics might include the type of building, vehicle, or other property involved; the number and characteristics of occupants; or physical properties of the building, vehicle, or other property that do not affect the fire development but do affect the harm caused to people or property.

(ii) Exposure. The "exposure" in a fire situation refers to those characteristics of an element of U that specify the number of persons and the quantity of property that may be affected by the fire and their characteristics. "Property" may be used broadly to mean not just the asset value of fixed objects but also the functional capacity of property (such as its ability to sustain productive operations or its ability to support human habitation).

(iii) Context of Use. The "context of use" in a fire situation is a second-order grouping of elements of U because it refers to the context of use of something, typically a particular product, material, assembly, process, operation, or building or other property which is to be the focus of the fire risk analysis. The item (product, material, or assembly), activity (process or operation) or property (building or other property) provides a first-order basis for grouping. (Each fire situation either involves some version of that item, activity, or property, or it does not.) Once it is known that the item, activity, or property was involved - and if involved, which version was involved - then one can specify second-order groupings based on the context of use of that item, activity, or property. For example, if the item of primary interest were upholstered furniture, then the context of use would include the specifications of the building in which the furniture is located, the locations of the pieces of upholstered furniture in the building, and other characteristics of the building and occupants (such as interior finishes, types and locations of other contents proportion of smokers among the occupants) that could be factors in the development of a fire involving upholstered furniture.

(b) 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 events (e) or situations. Therefore:

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

(c) Measure of Severity. Let s be a measure of severity, defined so that (i) the measure can be calculated for every element e of U and (ii) 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.

Some measures of severity include the following:

(i) Fire deaths
(ii) Fire injuries
(iii) Direct monetary damages to property
(iv) Damage to specific equipment involved in the productive operations of the property
(v) Damage to specific equipment involved in the protection of the property from some non-fire hazard, such as a core meltdown at a nuclear power plant
(vi) Area damaged by fire
(vii) Number of rooms damaged by fire or smoke
(viii) Whether or not fire extended beyond the designated compartmentation space for enclosing, confining, or isolating fires originating in that fire's initial location
(ix) Whether or not the structural integrity of the building was lost
(x) Time for room of fire origin to reach flashover
(xi) Time for first occupied room to reach untenable conditions for human occupation
(xii) Point score, based on assignment of points to various characteristics related to fire development and damage but for which the point scores have no direct physical interpretation

(d) 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:

$$P(s=s') = \int_U p(e \mid s(e) = s')\, de.$$

(e) Fire Hazard Analysis. A method for analysis of fire hazard is a method for calculating one or more severity measures, given a specified fire event, e, from the universe of fire situations. The purpose of a fire hazard analysis is to identify patterns in the changes in the severity measure(s) produced by changes in the specified fire event.

(f) 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).

The purpose of a fire risk analysis is to measure changes in the outcome measure(s) produced by changes in the underlying probability density function of fire events. The mathematical modeling of these changes may represent the changes as either or both of the following: (a) the probabilities of some fire events are changed, or (b) the characteristics of some fire events, including their severities, are changed.

Some outcome measures that could be used include the following:

(i) Expected loss (that is, the expected value or arithmetic average), such as expected number of deaths or injuries or average monetary property damage.

(ii) Probability of failure (that is, cumulative probability that some qualitative outcome measure is satisfied), such as probability that structural integrity is lost or that fire extends beyond designated containment area or that essential equipment is damaged.

(iii) Expected utility (that is, the expected value of a function that reflects any nonlinear aspects in the evaluation of a particular value of the severity measure).

(iv) Perceived risk (similar to expected utility but incorporating nonlinear phenomena arising from the processing of risk information rather than the evaluation of it).

(v) Expected cost or benefit (or expected value). These are terms used for outcome measures that are expressed in monetary terms. Expected cost might be calculated from the three severity measures of fire deaths, fire injuries, and direct property damage in three steps: (a) Calculate expected loss separately in terms of fire deaths, fire injuries, and direct property damage. (b) Convert the expected loss values for fire deaths and fire injuries to monetary terms by using assumed values for value of a life saved and value of an injury averted. (c) Sum the three expected loss values, now all expressed in commensurable monetary terms.

4. DISCUSSION OF THE BASIC CONCEPTS

In both Japan and the U.S., some of the distinctions embodied in these general definitions are not yet universally employed and some of the possibilities cited are still rare or non-existent. In Japan, there are not yet different words to distinguish the concepts of risk and hazard; the word "kiken" is used for all such concepts. In the U.S., the use of "hazard" for a specific mathematical family of analyses is still rare. "Risk" is often used to refer to both concepts and to other, less precise concepts as well. As noted earlier, the conceptual framework described here is proposed as a means of clarifying discussion, but it is not merely a codification of generally accepted practices.

Major differences among fire risk models or methods typically involve either or both of these two aspects: (1) the choice of severity and outcome measures to be used and (2) the methods proposed for calculation of probabilities and severity measures. The latter tends to be a more traditional area of model differentiation, in which different models will reflect their designers' views on the most valid data sources, the most valid models, the most essential phenomena to be addressed, and the trade-off between the sophistication of the estimate and the cost or time required for calculation. The former choice, however, can reflect more than these technical differences. It may reflect the values and purposes of the users of the analysis.

For example, engineers are accustomed to problems in which 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). In such situations, appropriate severity measures are inevitably qualitative (whether or not a catastrophic failure occurs) and outcome measures are limited to the cumulative probability that such severe failures occur. Fault tree analysis is a classic example of the application of this view to the risks of fire. This model tends to underlie most of the fire risk analysis methods developed by or for engineers.

In fire, however, this approach is at best a simplification. Meaningful quantitative measures of fire effects do exist and show that fire severity is inherently a matter of degree. At the same time, there are some settings in which an approach using qualitative severity measures will provide a close approximation of the full richness of the real universe of fire situations. In some industrial settings, for example, the management controls may be sufficiently strict that the overall probability of fire is very low, while the likely severity of a catastrophic fire, if it occurred, would be orders of magnitude greater than the severity of even the worst non-catastrophic fire. (For example, in some industrial properties, the most costly fire of the decade involves more loss than all other fires combined in that type of property and that decade.) In such a situation, an analysis based on expected loss and an analysis based on the probability of a catastrophic fire would tend to produce the same results, and the latter might be preferable because it would be much less cumbersome and so would permit analysis of the details of the catastrophic fire situations in greater detail.

In contrast to engineers, economists are accustomed to problems in which all consequences can be reduced to expected monetary values so that changes to reduce fire risk can be evaluated simply by comparing costs saved to costs incurred to effect the changes. In such situations, severity measures should be quantitative and should involve consequences that have value to the owners and occupants of a property. Numbers of fire deaths would qualify, but area damaged by fire would not (unless it could be translated into estimated monetary damages). In the fields of statistics and operations research, such models are collectively referred to as decision analysis.

This approach is also a simplification, not because of the properties of fire but because of the concerns of individuals and organizations with risk. Individuals are concerned about expected loss, but they tend to be disproportionately concerned about the possibility of catastrophic events. Insurance companies are concerned about expected loss because it affects their costs of doing business, but they are unusually concerned about the possibility of catastrophic events that might overwhelm their reserves and drive them out of business. Building owners and property managers are concerned with the effects of expected risk on their costs, but they are even more concerned about the possibility of catastrophic events that will destroy their assets or businesses with no hope of recovery.

In addition to its being a simplification, this approach is also controversial to the extent that it involves the establishment of any equivalence between damage to people (deaths or injuries) and monetary values. Such equivalences are considered unacceptable by large segments of the population of potential users of fire risk analysis. In fact, parts of the U.S. risk analysis

community (that is, those individuals whose jobs involve performing risk analyses for a wide diversity of users) and certain regulatory agencies are among the few groups who use such monetary equivalences. They are all but non-existent in Japan. It is therefore important to emphasize that expected loss is a useful approach even if no monetary equivalences for deaths or injuries are used and is particularly appropriate in any setting where overall fire loss tends to be dominated by the cumulative effect of large numbers of non-catastrophic events. This point is especially important in Japan, where fire risk models are much less likely to use any monetary loss severity measures of any kind, in part because the decision-makers (such as insurance companies) who find monetary loss measures in fire risk analysis most useful in the U.S. play a different role in Japan.

To summarize, most users of fire risk analysis will want two kinds of information - information on the expected quantity of loss by some measure and information on the relative likelihood of a catastrophic or unacceptably high level of loss. In some properties (such as tightly controlled industrial properties handling large quantities of hazardous materials), it may be sufficient to address only the relative likelihood of catastrophic loss. For some analyses of national programs, where large numbers of people or properties would be affected and a catastrophic event would have no more weight than many smaller losses, it may be sufficient to address only the expected loss.

5. REVIEW OF SELECTED MODELS

In the full paper, this framework is used to describe and compare the purposes and methods of these models:

(a) Fire Risk Assessment Method sponsored by the National Fire Protection Research Foundation (U.S.)

(b) Fire Safety Design Method of Buildings by the Ministry of Construction (Japan)

(c) Probabilistic Risk Analysis such as is used in the U.S. nuclear power industry (U.S.)

(d) Decision Analysis Method such as is used by U.S. decision analysts (U.S.)

(e) Estimation Method of Life Risk in Hospital Fires by Tsujimoto and Shida (Japan)

(f) Firesafety Concepts Tree by the National Fire Protection Association Technical Committee on Systems Concepts for Fire Protection in Structures (U.S.)

(g) Network Model for Quantitative Risk Analysis by Ling and Williamson (U.S.)

(h) Building Fire Simulation Model by Berlin, Swartz, Fahy, and others (U.S.)

(i) Fire Risk Evaluation Method for Multi-Occupancy Buildings by the Ministry of Home Affairs (Japan)

(j) Commercial Fire Rating Schedule by the Insurance Services Office (U.S.)

(k) Fire Brigade Fire Risk Assessment Method by Strickland (U.S.)