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A NEW METHOD OF ASSESSING UNCERTAINTIES IN DESIGNING BUILDING FIRE SAFETY PROVISIONS

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ABSTRACT

New architectural features and special usages of modern buildings can lead to difficulties in complying with prescriptive fire codes. Engineering performance-based fire codes (EPBFC) and application of the fire safety engineering approach (FEA) are important alternatives to prescriptive code in the design of fire safety provisions for those new buildings. However, there are uncertainties associated with these approaches. The uncertainties must be assessed systematically prior to the acceptance of the proposed fire safety provisions design and to assure that public safety is achieved. A new method, using a probability based Monte Carlo approach, is shown to be effective in providing a quantitative assessment of the uncertainties. A general three-step probability based approach is proposed for fire safety provisions design.

1. INTRODUCTION

Fire safety provisions, both passive construction designs and active fire protection systems (known as fire services installation in Hong Kong) are required in buildings as described clearly in the prescriptive codes [e.g. 1,2]. Those codes were developed over a period of many years, as it took time to pass the necessary monetary procedures, such as reading for three times in the Legislative Council of the Special Administrative Region. In recent years, however, there are increasing difficulties for big construction projects with new architectural features [3] or special use of the buildings, to comply with prescriptive fire codes. Upon smooth reunification of Hong Kong to Mainland, more 'open' approach was adopted. Design similar to engineering performance-based fire codes (EPBFC) [4-7] in overseas known as fire safety engineering approach (FEA) [8] has been accepted since 1998. Views from academics were respected in approving those designs. In applying EPBFC or FEA for designing fire safety provisions, the system characteristics should be studied carefully.

For a given design objective with a specific system characteristics, standard procedures are available. An example is the calculation of the required spacing of ceiling-mounted thermal detectors in designing fire detection system [9] if prescriptive codes [10,11] are not complied. Most of the design procedures are deterministic and generally used without an assessment of the uncertainty. Uncertainties, however, are known to exist in the safety system characteristics and they can have a significant impact on system performance in a fire. Currently, the standard design approach to "minimize" the fire risk associated with such uncertainties is to depend on the fire engineer to provide subjectively the appropriate conservatism in the design. For example, a longer response time index might be used in the design of a thermal detection system to eliminate unwanted fire alarm. A bigger heat release rate is used for designing static smoke exhaust systems.

The current "subjective" approach to account for the uncertainty of a fire safety provisions design has many difficulties. First of all, this approach provides no systematic assessment on what "appropriate conservatism" is and how fire risk is "minimized". For example, the "slowest" response time index chosen by a one fire engineer might not be considered as the "slowest" by another. Since both engineers make his/her decision subjectively, it is difficult, if not impossible, to resolve the difference between two "expert opinions". Without a quantitative approach in the assessment of risk, it is also difficult to convince stakeholders (owners, government officials and the general public) that the design has met his/her expected level of risk. There is no systematic approach to determine a level of "conservatism" which is acceptable to different stakeholders. Indeed, the lack of a systematic and quantitative approach to address uncertainties in fire safety provisions design is probably the most significant obstacle preventing

EPBFC, FEA and other non-deterministic approaches from being more widely practiced and accepted by building construction industries and regulatory agencies.

A new method based on probability and the Monte Carlo method proposed earlier in a public lecture to assess the effect of uncertainties in fire safety provisions design [12] will be presented in this paper. In Section 2, a three-step procedure to establish a probabilistic framework for the design is described. Two recent works utilizing the Monte Carlo method [13,14] for fire safety applications are summarized as examples of the probabilistic framework. In Section 3, numerical results of these two examples are presented to illustrate that basic probability concepts (e.g. failure probability, confidence limits) can be used to account for uncertainties in safety consideration. Finally, a probability based EPBFC for fire safety provisions design is formulated and presented in Section 4.

2. A PROBABILISTIC FRAMEWORK FOR FIRE SAFETY PROVISIONS DESIGN

Fundamentally, the design of fire safety provisions is similar to the design of all engineering systems. A certain design objective is known (e.g. the thermal fire detector should be activated within a designated time after the initiation of a fire, the appropriate heat release rate chosen for a design fire), the "best" engineering knowledge is then used to develop a system which meets the design objective. Even though a prescriptive code is often viewed as simplistic and arbitrary (note that most prescriptive codes were set up through long-term discussion such as the karaoke establishment bill), it is one specific engineering approach to meet the design objective. A great deal of practical experience, empirical data, and some engineering analyses were used, together with the assessment and balancing of political, social and economic values in the development of these prescriptive codes. However, with new architectural designs, different building applications and new economic and social values, some of the prescriptive codes might not be applicable, or even giving adverse effect. An obvious example is sprinkler requirement in an atrium of a shopping mall. The prescriptive code, established for older generation of buildings, might not be applicable both from the scientific (following the code for new generation of buildings might give "wrong" regime of the relevant physics) and economic (the cost of building a shopping mall will become prohibitively expensive in following the prescriptive code strictly) perspective.

With the increasing availability of computer, there is an increasing demand to design fire safety provisions based on non-prescriptive approaches such as EPBFC and/or FEA. But it should be noted that the utilization of a more "sophisticated" design procedure (mathematical modeling, computer code, etc.) does not necessarily imply a reduction in uncertainty of the proposed design. There are uncertainties associated with the understanding of the relevant physics, formulation of the mathematical model and the assumptions used in the development of the computer codes. Unless these uncertainties are addressed appropriately, the fire safety provisions design generated by the non-prescriptive approach can have as much uncertainties (if not more) as those generated by prescriptive codes.

To gain acceptance by stakeholders, all non-prescriptive approaches to fire safety provision designs must thus include steps to address uncertainties in a systematic, self-consistent and transparent (i.e. easy to understand) fashion. The present work proposes a three-step process. These steps are:

i. Model formulation and identification of "elemental" parameters
ii. Determination of probabilistic distribution of "elemental" parameters
iii. Assessment with Monte Carlo simulation.

Detailed description of the three steps is provided in the following sections.

3. THE APPROACH

The first step in the development of a probability based EPBFC is the formulation of a mathematical model which describes the relevant physics. The model should be based on the most up-to-date knowledge of the relevant physics (fire dynamics for most cases) and is in sufficient detail so that the required model parameters are "elemental".

An "elemental" parameter is defined to be a parameter which value is either known deterministically or governed by a probabilistic distribution. Statistically, the probabilistic distribution of an "elemental" parameter is assumed to exist as postulated by Bernoulli's "First Limit Theorem" [15], the very basis of probability theory. The probability distribution can be determined based on experimental data or, when data are insufficient to provide a reliable statistical distribution, by "expert opinions". The probability distribution of an "elemental" parameter should be updated regularly when more data are available. It is expected to approach the "fundamental probability set" (FPS). The updating procedure (based on statistically analysis or the well known Bayes Theorem [16]) will be discussed in a later publication.

Consider the problem of designing a thermal fire detection system [13]. A physical model which predicts the fire detection time as a function of the surrounding gas temperature, for example, would not be an effective model formulation since the gas temperature is not an "elemental" parameter. As shown in ref. [13], the gas temperature is a function of parameters such as the heat release rate and the height of the fire base. The gas temperature is thus not well represented by a single probability distribution.

The actual model selected in the proposed design of a thermal fire detection in ref. [13] represents an accumulation of many fundamental studies on various physical phenomena which are important for the thermal detection process (combustion, fluid flow, etc.). In spite of its early publication date, this model [17] can be considered as the current state-of-the-art understanding of the thermal detection process. The model relates fire detection time to parameters such as the ambient temperature, the fire growth constant, the response time index of the detector and the fire location relative to the thermal detector. Each of these parameters is "elemental" and their actual numerical value can be represented by a probability distribution. The model formulation in ref. [13] is thus a good example of model formulation and identification of "elemental" parameters, the first step of a probability based fire safety provisions design.

Ref. [14] provides another example of the model formulation and identification of "elemental" parameters. The concept of "elemental" parameter, in this case, is extended to include a statistical representation of the cumulative probability of fire damage area. The physical model is a characterization of fire damage area as a function of the heat release rate based on the most recent experimental data on the related combustion processes. The "elemental" parameters in this example include the transitional constant for the correlation characterizing the transition of a fuel controlled fire to a ventilation controlled fire, burning rate constant for fuel, heat output rate constant and heat loss constant for the sprinkler spray. The uncertainty in these parameters contributes to the uncertainty of the required heat release rate predicted for a design fire.

It is important to note that the model formulation and the associated identification of "elemental" parameters is a transient non-static process. Model formulation can be improved as the knowledge base of the relevant physics increases. The set of "elemental" parameters can also be changed as the model formulation is improved. To be effective, a probability base fire safety provisions design must undergo periodic review to ensure that the most current information is utilized in the design process.

4. DETERMINATION OF PROBABILITY DISTRIBUTION OF "ELEMENTAL" PARAMETERS

In the proposed probability based fire safety provisions design, the uncertainty of the design is accounted for by the uncertainty of the "elemental" parameters which is represented by a probability distribution. Statistically, two types of uncertainty can be identified for "elemental" parameters. They are the "aleatory" uncertainty and "epistemic" uncertainty.

Parameters with "aleatory" uncertainty are those for which a large volume of data is already available. These data meet all statistical tests and can be used to generate a stable, well defined probability distribution (i.e. the Fundamental Probability Set). If needed, additional tests can be done to further improve the statistical reliability of the probability distribution. In the example of designing a thermal fire detection system [9], the response time index of the detector chosen is an "elemental" parameter with "aleatory" uncertainty. A probabilistic distribution of the response time index for a specific kind of detector produced by a specific manufacturer can be readily generated by repeated testing.

In fire safety designs, however, many parameters have uncertainties which are due to lack of information. The data base for these parameters is scarce and scientific knowledge is lacking. This type of uncertainty is referred to as "epistemic" and the probability distribution is ultimately determined by some level of "expert judgment". In the example of the thermal fire detection system design [9], the fire location and height relative to the detector are parameters with "epistemic" uncertainty. The probability distributions for these parameters are set by people (e.g. fire fighters, builders, users of the building) who are knowledgeable about the potential fire scenarios in the building under consideration ("expert opinion"), not by repeated testing.

It should be noted that the uncertainty of some parameters can be both "aleatory" and "epistemic". The fire growth rate constant needed in the thermal fire detector design has both aleatory and epistemic uncertainty. For a certain class of fires, the fire growth rate constant has been measured and a probability distribution can be deduced. A probability distribution for the fire growth rate constant in a t^2-fire, for example, is used in the analysis in ref. [13]. But the relative probability of the different types of fire which should be included in the design is "epistemic" and is ultimately determined by the user and designer of the building who are familiar with the potential occupants and functions of the building. Similarly, all of the "elemental" parameters in the determination of heat release rate for a design fire [14] have both epistemic and aleatory uncertainty. While additional experiments can be performed to get better assessment of the various rate constants needed by the physical model and additional data on fire damaged area can be collected, it is likely that these data are still insufficient and some level of "expert judgment" are needed to yield the probability distribution used in the design.

Similar to the model formulation, the probability distributions of "elemental" parameters in the model should also be updated periodically to ensure that they reflect the most up-to-date statistical information available. For parameters with "aleatory" uncertainty, this updating process is straight forward (assessment of new statistical data, etc.). Since a large volume of data already exists for these parameters, result of the updating is expected to only produce a minor modification of the probability distribution. For parameters with "epistemic" uncertainty, on the other hand, significant modification can occur. Bayes Theorem can be used as a systematic, self-consistent approach to provide such updates. A discussion of Bayes Theorem and its role in fire safety design will be presented in a future publication.

It is interesting to note that the "prescriptive code" approach to fire safety design can be considered as a limiting case of the probability based approach. For the same model formulation, the prescriptive approach treats all "elemental" parameters as "epistemic" and assigns to each parameter a single value (i.e. 100% probability). The "expert opinion" is that these values would lead to a "conservative" design.

5. ASSESSMENT WITH MONTE CARLO SIMULATION

After a model is formulated and the probability distributions of the various "elemental" parameters are specified, the Monte Carlo method [18] can be used to determine the statistical behavior of the system outcomes generated by the design. Mathematically, the Monte Carlo method is a sampling procedure which generates multiple system outcomes utilizing values of the "elemental" parameters which are consistent with the given probability distribution. In general, a large number (in the order of 50,000 to 100,000 for examples in refs. [13] and [14]) of repeated calculation is carried out. The result of a Monte Carlo simulation generates a statistical distribution of the design outcome.

If the design objective is for a specific design outcome to attain certain numerical value, a probability of failure can be determined from the outcome's statistical distribution generated by the Monte Carlo simulation. For example, if the objective of the design for a thermal fire detection system is to have the detector actuated prior to the heat release rate of the fire reaching a specified critical value, then a failure probability of a specific design (say, for a specific detector spacing), can be calculated by:

$$F = \frac{N_f}{N} \quad (1)$$

where N is the number of simulation and N_f is the number of cases in which the heat release rate of the fire exceeds the spcecified critical value at the time of detector actuation. In the limit of a sufficiently large number of simulations, the failure probability F is expected to be independent of N.

It is important to note that the Monte Carlo simulation generates a statistical description of the system outcome generated by a specific fire safety provisions design. These statistical data allow the stakeholders to accept or reject a specific design based on quantitative considerations. For example, using the same physical model as in ref. [13], a thermal fire detection system with a detector spacing greater than 7 m would be rejected since it does not meet the prescriptive code requirement. But as shown in ref. [13], using some specific probabilistic distribution for the various elemental parameters, the Monte Carlo simulation predicts a failure probability distribution as a function of detector spacing as shown in Fig. 1. With these data, stakeholders can make their choice of the detector spacing based on their acceptance of a specific failure probability. Results in Fig. 1 also allow stakeholders to compare the relative risk of using one detector spacing to another. For example, if stakeholders want to consider the possibility of choosing a detector spacing of 5 m instead of 4 m (due to economic reason, for example), results in Fig. 1 show that the increase in detector spacing would increase the failure probability from 3.7% to 8.3%. This result gives the stakeholder some flexibility in his/her design decision, balancing between economics and risk.

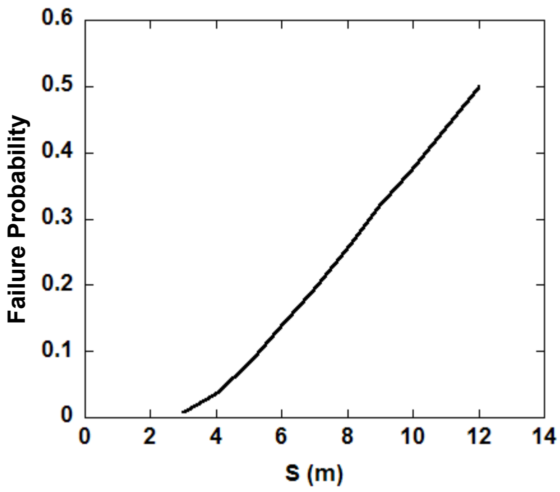

Fig. 1: Results of a Monte Carlo simulation of a thermal fire detection system

In ref. [14], the objective of the design is to determine the appropriate heat release rate for a design fire such that the expected fire damage area is less than some specific value. In Fig. 2, the result generated by a prescriptive approach (Morgan and Hansell [19]) is compared with the Monte Carlo results. For a specific heat release rate (design fire), 90% of the sampling results generated by Monte Carlo have a fire damage area less than that indicated by the line marked 90%. 80% of the sampling results has a fire damage area between the 10% line and the 90% line. These result clearly provide the stakeholders with much more information as basis for more rational decision than the prescriptive approach which yields only one specific value for the fire damage area.

6. EXAMPLES OF THE PROBABILISTIC FRAMEWORK

The two examples cited in the previous sections [13,14] will be presented as an illustration of the application of the proposed three-step approach to non-prescriptive fire safety provisions design.

For the design of a thermal fire detection system [13], the relation between the physical model, the "elemental" parameters, system input and output variables is shown schematically in Fig. 3. A summary of the probabilistic distribution used in the Monte Carlo simulation is shown in Table 1. All of the elemental parameters are assumed to have a uniform probability distribution over the expected range except for the characteristic time for fire growth. Based on a set of data generated by a series of furniture calorimeter tests done at the National Bureau of Standard [20], a probability distribution is generated and is presented in Fig. 4. As discussed in the previous section, a typical result generated by the simulation is shown in Fig. 1.

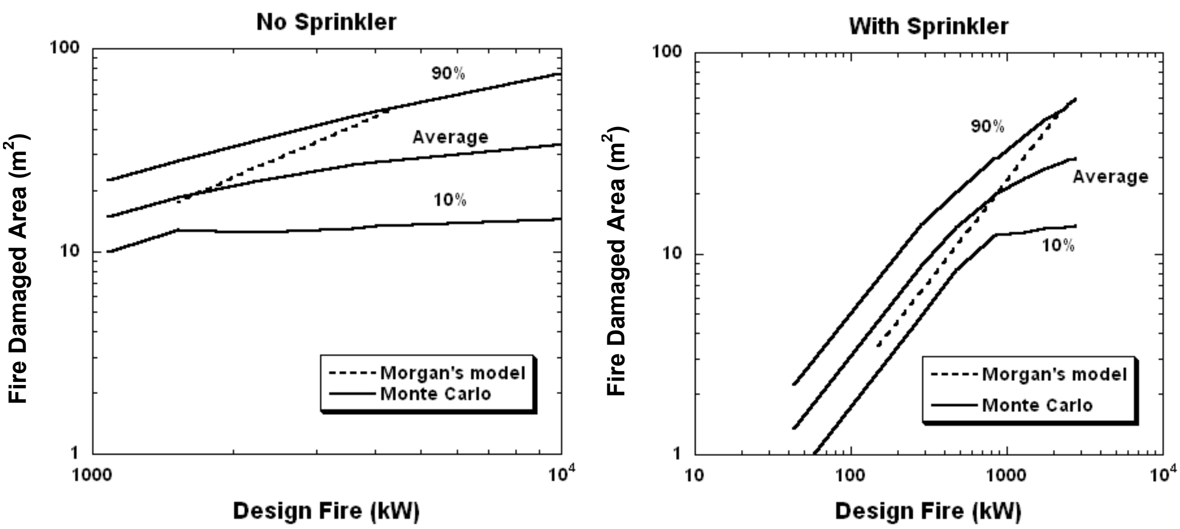

Fig. 2: The variation of fire damage area with design fires generated by the Monte Carlo method and a prescriptive approach (Morgan's model)

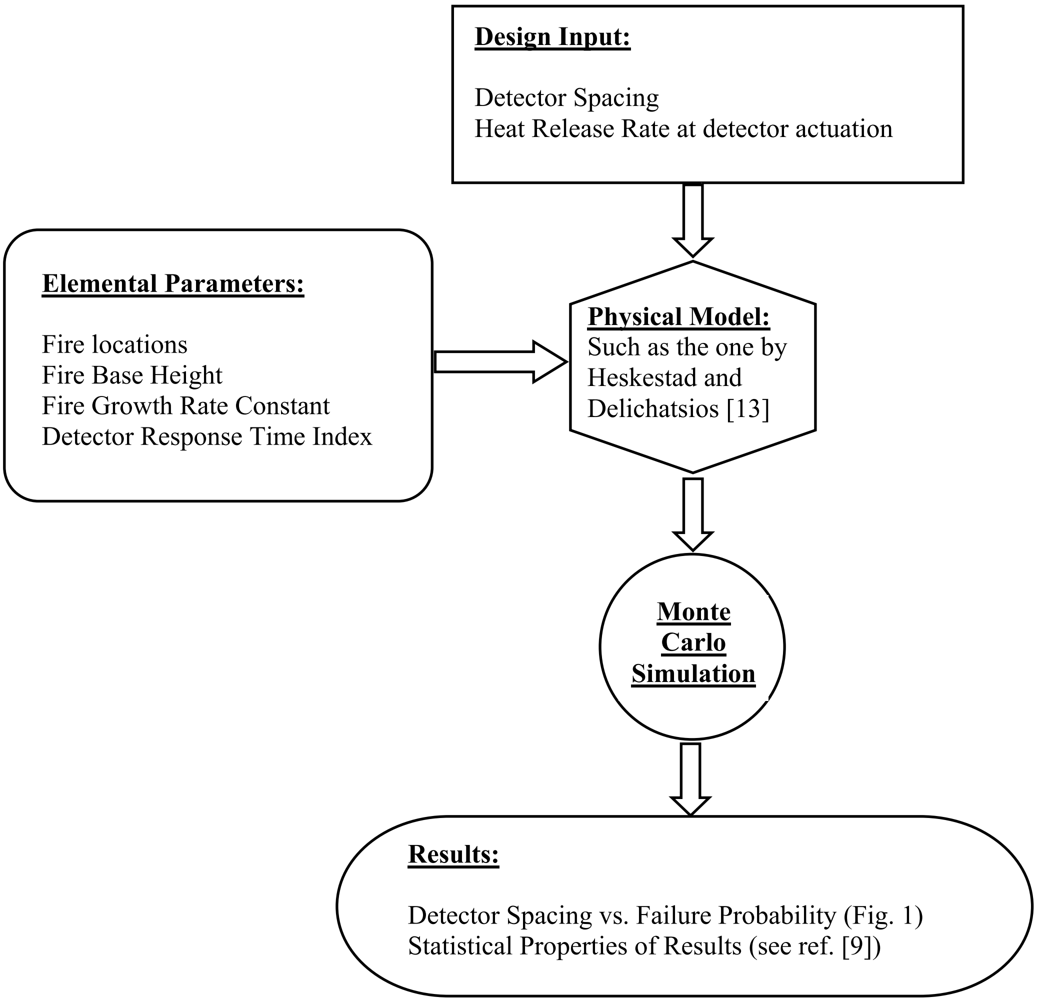

Fig. 3: Schematics of the probability based Monte Carlo approach to the design of a thermal fire detection system

Table 1: A list of the elemental parameters and the associated probability distribution used in the design of a thermal fire detection system

Elemental Parameters	Probability Distribution
Fire location	Uniform
Fire base height	Uniform
Detector response time index	Deterministic
Fire growth rate constant	Fig. 4

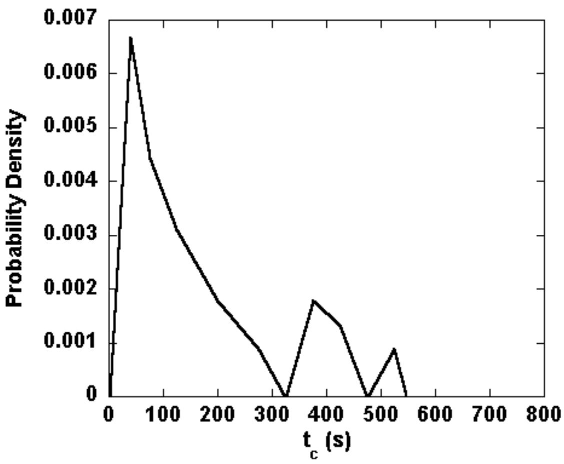

Fig. 4: Discrete probability and probability density for the range of the characteristic time of fire growth (t_c) generated by the furniture calorimeter tests of NBS

In the determination of heat release rate in a design fire using the probability based Monte Carlo approach [14], a schematic of the relation between the physical model and "elemental" parameters is shown in Fig. 5. A summary of the elemental parameters and the probability distribution used in the Monte Carlo simulation is shown in Table 2. Result generated by the Monte Carlo calculation is shown in Fig. 2.

The difference between the two examples (both in terms of its objectives and the level of physics involved) illustrates the generality of the proposed probabilistic framework.

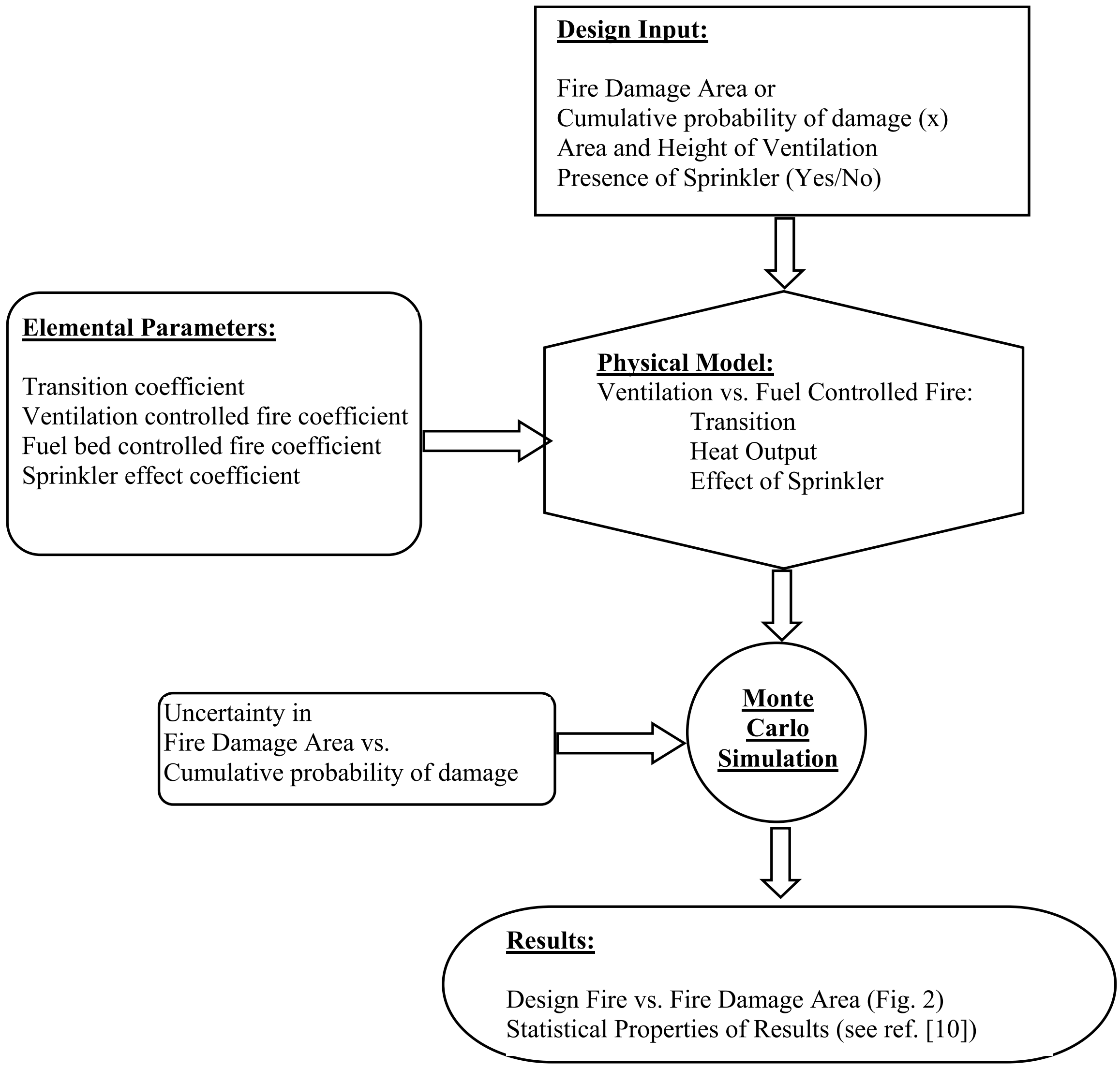

Fig. 5: Schematics of the probability based Monte Carlo approach to determine the heat release rate for a design fire

Table 2: A list of the elemental parameters and the associated probability distribution used in the determination of heat release rate for a design fire

Elemental Parameters	**Probability Distribution**
Coefficient of transition from fuel controlled to ventilation controlled fire	Uniform (from 0.3 to 5)
Coefficient for heat release in a ventilation controlled fire	Uniform (from 0.4 to 0.6)
Coefficient for heat release in a fuel controlled fire	Uniform (from 90 to 360)
Coefficient for the sprinkler effect	Uniform (from 0.4 to 0.6)
Uncertainty in the fire damage area vs. cumulative probability of damage data	Uniform (between lower and upper limit)

7. CONCLUSION

The present work proposes a probability based Monte Carlo method as a basis for EPBFC and other non-prescriptive approach to fire safety design. A three-step approach is proposed as a systematic and self-consistent method to account for the various uncertainties expected in a safety design. Results from two examples [13,14] are presented to illustrate the feasibility of the approach for fire safety applications.

As the world community moves toward an "information age" in the 21st century and beyond, and as all citizens become better informed and educated, there will be an increasing demand that fire safety provisions should be designed based on non-prescriptive, information based scientific approaches. There will also be an increasing demand to account for all uncertainties in a rational, objective basis. Decisions by the public to accept fire safety provisions must be made in a quantitative, self-consistent and transparent manner. The probability based Monte Carlo approach proposed in this work is ideally suited for these expectations. Accepting it as the standard design approach for fire safety provisions is strongly recommended.

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REFERENCES

1. BS 5588 Part 0 Fire precautions in the design, construction and use of buildings: Guide to fire safety codes of practice for particular premises/applications, British Standards Institution, UK (1996).
2. NFPA 5000 Building Construction and Safety Code, National Fire Protection Association, Quincy, Mass, USA (2003).
3. W.Y. Hung and W.K. Chow, "Architecture features for the environmental friendly century", Sustainable Building 2002: 3rd International Conference on Sustainable Building, 23-25 September 2002, Oslo, Norway – Paper 011 presented at the Session on New Symbiotic Building and Environmental Technology – The Future Scope in Subtropical Region (2002).
4. CIBSE Guide E, Fire engineering, The Chartered Institution of Building Services Engineers, London, UK (1997).
5. G.V. Hadjisophocleous, N. Bénichou and A.S. Tamin, "Literature review of performance-based codes and design environment", Journal of Fire Protection Engineering, Vol. 9, No. 1, pp. 12-40 (1998).
6. BS 7974 Application of fire safety engineering principles to the design of buildings – Code of practice, British Standard Institute, UK (2001).
7. SFPE Engineering guide to performance-based fire protection analysis and design of buildings, Quincy, MA, Society of Fire Protection Engineers and National Fire Protection Association (2000).
8. W.K. Chow, "Fire safety in green or sustainable buildings: Application of the fire engineering approach in Hong Kong", Architectural Science Review, Vol. 46, No. 3, pp. 297-303 (2003).
9. R.P. Schifiliti, B.J. Meacham and R.L.P. Custer, "Design of detection systems", SFPE Handbook of Fire Protection Engineering, 3rd edition, Section 4, Chapter 1, pp. 4-1– 4-44, Society of Fire Protection Engineers, National Fire Protection Association Inc., Quincy, Ma, USA (2002).
10. P. Burry, "Fire detection and alarm systems", A guide to the BS Code, BS 5839: Part 1, 2nd edition, Paramount Publishing Ltd (1996).
11. W.D. Moore, "Automatic fire detectors," Section 5, Chapter 2, Fire Protection Handbook, 18th Edition, Edited by A.E. Cote, National Fire Protection Association, Quincy, Massachusetts (1997).
12. W.K. Chow and W.W. Yuen, Lecture notes for CPD lecture "Risk assessment and management of fire safety," 30 December 2002, Research Centre for Fire Engineering, The Hong Kong Polytechnic University, Hong Kong (2002).
13. W.W. Yuen and W.K. Chow, "A Monte Carlo approach for the design of thermal fire detection system", Submitted for publication to Fire Technology (2002).
14. W.W. Yuen and W.K. Chow, "On the design fire for safety provision", Submitted for publication in Fire Safety Journal (2002).
15. I. Hacking, The emergence of probability, Cambridge University Press (1975).
16. D.V. Lindley, "Theory and practice of Bayesian Statistics", The Statistician, Vol. 32, pp. 1-11 (1983).
17. G. Heskestad and M.A. Delichatsios, "Environment of fire detectors Phase I: Effects of fire size, ceiling height and material", Volume II – Analysis, Technical Report Serial No. 22427, RC 77-T-11, Factory Mutual Research Corporation, MA (1977).
18. "The Monte Carlo Method", International series of monographs in pure and applied mathematics, Vol. 87, General editors: I.N. Sneddon, M. Stark and S. Ulam (1966).

19. H.P. Morgan and G.O. Hansell, "Fire sizes and sprinkler effectiveness in offices – Implications for smoke control design", Fire Safety Journal, Vol. 8, pp. 187-198 (1984).

20. D.W. Stroup, D.D. Evans and P. Martin, NBS Special Publication 712, National Bureau of Standard, Gaithersburg (1986).