PERFORMANCE BASED FIRE SAFETY REGULATION UNDER INTENTIONAL UNCERTAINTY

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INTRODUCTION

Many predictive fire risk models use as inputs the results of complex human decisions. These human decisions can take many forms, with widely varying degrees of predictability. Many performance based analyses interpret or express the output of these decisions as technical phenomena, as if they were physical variables in a well defined natural system, rather then human decisions. However human decision making does not follow the same kind of well understood rules that control the physical science variables used in models. Human decisions represent intentional uncertainty, which requires a separate treatment from traditional model and data uncertainty. Regulating in this environment requires a careful understanding of the limitations and capabilities of both regulators and engineers.

HUMAN DECISIONS AND FIRE SAFETY

Fires are a product of buildings, users, contents, ignition sources and public and private responses. Only some parts of these systems are outputs of traditional engineering principles. Fire protection engineers usually define performance based analysis (PBA) in terms of fire physics, chemistry and toxicology. [1] But almost all the key variables involved in performance based analysis involve the interpretation of the effects of intentional human decisions. Human decisions take place before the accident sequence and during the accident sequence itself.[2] Fire load, number of occupants, system maintenance, clear exit pathways, building condition, arson and exiting behavior all involve human decisions.

Fire engineering does not appear to have well established methodologies for analyzing these fire related human decisions. Even human factors engineering is generally thought of as a last minute adjustment of the technical system to the physical and comprehension needs of the human operator, rather then a comprehensive treatment of man-machine interactions. Fire protection engineers do not receive extensive training in human decision making, and their professional skills in thermodynamics, system design and heat release do not automatically

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stretch to these areas. Many fire safety variables incorporated into PBAs seem to reflect an "engineering" approach to human decisions, as if they were physical phenomena.

This is also a product of the fire engineer's downstream role in product design. Architects translate their perception of the client's human needs into the design strategy and create the formal technical requirements for the various engineering disciplines. However, fire safety represents a special problem. Architects are also not trained to recognize the human decisions relevant to fire. Architects rely on the fire safety codes to provide a safe design, so they have no real need to study the issue of human behavior related to fire.

The proponents of performance based codes claim that better hazard analysis is possible and better and more efficient safety design will result from the use of performance based codes. [3] They also suggest that the fire safety protection can be designed to reflect the specific hazards in the building. But if fire codes are changed to require protection against a specific level of hazard, precision in predicting the human component of the hazard becomes far more important. However precision in predicting human decisions does not come easy.

PERFORMANCE BASED CODES AND HUMAN DECISION MAKING

In Performance Based Codes (PBC) humans are normally analyzed as entities "affected" by the fires. Sometimes this technological approach to human behavior is explicitly stated, e.g. describing humans exiting a fire as a "hydraulic flow". (Like opening a tank of water occupants are released, moved along prescribed pathways and hopefully pour out of the buildings.) While the assumption that people flow like water to an exit is handy for computation, where do engineers **demonstrate** that for the lifetime of the building people will go down the stairs, instead of towards helicopters on the roof?

Measuring human response in fire is difficult enough when the preexisting conditions are known, but predicting human decisions related to the prefire conditions is an even more difficult activity. The ability to predict the future state of a building may be extremely limited, especially in the areas involved in human decision making. The human decisions required for evaluating the fire hazard can change through the entire lifetime of the building. PBA discussions often focus on one time **regulatory approval** even though a single prediction prior to the creation of the building is unlikely to be useful for the entire lifetime of the building. This approach shifts to the occupant of the building any effects of uncertainty in the design process. We believe that the inherent uncertainty in human decisions makes long term prediction of fire hazards very difficult.

UNCERTAINTY

Uncertainty describes the difference between a model and reality.[4] In physical science uncertainties can be described as relating to our knowledge of physical or mechanical laws (**epistemic uncertainty**), or relating to the existence of data (**aleatory uncertainty**). In theory both can be reduced by further research or data collection. But it is not clear that any human decision research or data collection can give the very precise quantitative data needed for fire risk models. There is simply no evidence that human decisions always follow precise knowable rules. We believe that human decisions should be characterized as representing **intentional uncertainty**. (For a greek equivalent we would suggest ***Teleological*** uncertainty. *Teleology* is the study of human intentions.)

The existence of **intentional uncertainty** is not a claim that all future human actions or social decisions are totally unpredictable. Instead, those human decisions which are more predictable can be described as having low **intentional uncertainty**. Some decisions may be more predictable because the actors are highly trained or because the problem is so structured that substantial variation is not to be expected. Some decision making may be predictable because the human action is constrained by technological or similar external factors. Truly random behavior can often be accommodated by proper statistical analysis. However no *a priori* assumptions can be made about human decisions. The ability to predict each category of intentional human decisions must be examined on its own.

The success of the PBC effort depends in no small part on the ability of the fire protection engineers to anticipate and properly allow for the effects of uncertain human decisions. Performing an engineering analysis of the overall fire safety situation in a building will require applying engineering techniques to the product of human decisions. In addition regulatory systems will have to be changed to deal with the problem of intentional uncertainty.[5]

ANALYTICAL APPROACH

The engineering approach to PBA clearly indicates a inclination to focus on technical instead of human variables involved in fire safety. The fire's growth and products of combustion are treated as the centerpiece of the analysis, despite the importance of the human factors. There are many historical examples of highly qualified engineers making totally untoward assumptions involving the human interaction with technology. For example, there was an engineering/regulatory failure in the case of the ATR-72 aircraft that crashed in icing conditions in Roselawn Indiana. In that case engineering developments in unpowered control surfaces on thin wings caused a revival of an old airline hazard, in-flight icing. Engineers were lulled by the wing's compliance with a performance based standard into thinking that they were coping with the real world problem. However icing on thin wings with unpowered controls produces sudden "loss of control problems" that had not existed on the older thicker wings in use when the performance standard was developed. Engineers continued to rely on pilots exiting icing conditions but pilots could no longer reliably detect icing conditions before they lost control of the aircraft. Pushing the technology against a performance based regulation had to the limit had produced an entirely new human intentional uncertainty.

Most fire models deal with development of conditions in a compartment, or series of compartments, after assuming the size of the initial fire. The focus on the compartment fire development instead of the building hazard analysis may be a result of the initial use of fire safety models in explaining fire growth and development in specific fire environments. In these environments, as in laboratory tests, the actual values of critical pre fire variables were known. In such an environment the "hard part" of the task was the thermodynamics. Engineers who were successful in explaining these fires began to believe that they could predict fires. The hidden caveat is that they may only be able to predict a fire if all the variables are known to the same degree of precision as in the explained fire.[6]

REGULATION: POLITICAL OR TECHNICAL DECISION MAKING?

The next step was claiming that these explanatory models were valid enough for prediction in the regulatory environment. The original proposal for performance based codes suggested total elimination of regulatory participation in final design approval. [7] The suggestion was that regulators would set a level of safety, and fire engineers could use "any technology" that promised the needed level of safety. The explicit goal was to restate the social fire decision in fire protection engineering terms. Traditional codes were not disfavored because they were "prescriptive", they were disfavored because the technical requirements were the result of political, rather then fire protection engineering judgement.

But political acceptance is a substitute for technical validation, not a competitor. Political decisions are a traditional social method of dealing with both technical and human uncertainty. Replacing political with technical decision making require a very high level of technical validation because without such validation engineers are simply usurping the public's right to decide what risk it will tolerate.[8] However, in the attempt to transform fire safety from the political to an engineering focus, the effects of human decisions on the hazard were simply not analyzed, possibly because it is intractable in the engineering analysis. This effort required the maximum claim for the predictive quality of the fire models, and minimization of other influences on the fire problem. As it happens, most of these "other" variables seem to be those related to human intentional decision making.

Scenario fires illustrate the problem. Many authors suggest that "fire scenarios" are the technical prerogative of building designers, rather then a political decision by regulators. To make an engineering analysis decisions have to be made as to the anticipated fire. But unlike wind or earthquake scenario fires are the product of human decisions.[9] Statistical analysis of fire loads may be of little help, since fire disasters are often the result of excessive fire loads. Terms like "reasonable worst case scenario" are actually public policy judgments presented as technical analysis. In the end elimination of the regulators proved to be impossible and the emphasis shifted to maximizing the portion of the decision process that was under the control of the fire engineers rather then regulators. Pre-fire human decisions which affect the fire are usually ignored in the analytical process. Instead data reflecting human decisions is simply put into the engineering models as technical variables.

GETTING HUMAN DECISION DATA FOR FIRE MODELS

The sophisticated computer models may have seemed so powerful that it seemed trivial to "nail down" these behavioral variables to complete the analysis. The term "nail down" is used deliberately. A value for a variable can be produced for use in the model, without a great deal of analysis as to how human behavior might differ from physical responses. For example exiting conditions which humans are "willing" to enter would appear to fall in this category. A small number of tests and limited real world experience are combined into a "hard" number that gets put into the fire models just as if it was a physical reality. The problem of arbitrary data appears to be aggravated if the goal is regulatory approval rather then published analysis, since regulators may be in a much poorer position to challenge the underlying assumptions. Compared to the precision asserted for the thermodynamic variables, the reliability tests for the human decision variables seem almost trivial, especially since they have to be valid for the lifetime of the building. Among the various techniques, a few stand out as critical.

Fire Scenarios

Fire scenarios are the linchpin of the effort to develop performance based codes. Since a scenario is heavily dependant on the human decisions related to the contents and condition of the building, it is one of the more important intentional uncertainties. The credibility of fire scenarios depends heavily on correctly estimating all the human decision factors related to the fire hazard. A recent published PBA for the Luxor Hotel in Las Vegas states:

> A key part of this agreement was that the fire size expected within the atrium would not exceed 2110 kW (2000 BTU/s) maximum heat release rate [10]

Given that this is a very large unsprinklered casino and show area it is worth mentioning that the fire load control was described as "*most of the decorative items and furnishings included in uncovered areas of the attractions level are non combustible or minimally combustible*". No enforcement mechanism is described.

Data borrowing from components of prescriptive codes

This approach involves borrowing data from prescriptive codes, such as the occupancy load of a building. The number and condition of people in a building is clearly the result of intentional decision making. Component borrowing (also known as mix & match) suggests that prescriptive codes are divisible into hazard and response, and that the engineers can simply adopt the human decisions implicated in the hazard component. However, the key complaint about prescriptive codes is that they do not have any analytical foundation. A claim that an overall existing code is a proper standard for "equivalency" does not support a claim that portions of that code can be extracted and used in a different protective system. Engineers cannot assume values for occupancy or fire loads based on a prescriptive category such as mercantile or assembly. They have to actually investigate the real conditions, which involves understanding the human decisions. Borrowing data from prescriptive codes simply emphasizes that the engineers may have no real knowledge of the true data, and are simply trying to obtain satisfactory values for a model.

Data projection

The use of existing statistical data about past fires for predicting future fires requires special attention to the human decisions involved in such fires. Projection problems are substantial even in purely physical systems, such as earthquakes or hurricanes. All evidence suggests that human systems are much less predictable then physical systems, particularly if high precision is required. The ability to use data sets to predict the future is an attribute of some but not all systems. The utility of even accurate data in predicting the future cannot be assumed, but must be demonstrated.

ASSUMPTIONS: ESTIMATIONS OR CONDITIONS?

Some models simply contain "assumptions" about human decisions such as system maintenance, interior finish, code enforcement, occupant characteristics, fire department response or system failures. Is assuming the sprinklers are maintained an acceptable modeling technique? What happens if they are not? Exactly what assumptions about human decisions are part of the model and which ones are not? Intentional uncertainties can be divided into two categories:

Internal Intentional Uncertainty is a component of intentional human decisions whose output is included in the model itself. For example if fire load is included in the model, even indirectly, it has to be evaluated as an internal intentional uncertainty.

External Intentional uncertainty is a component of those intentional human decisions that determine the basic "rules of the game". In physical models these are the laws of gravity, thermodynamics and so forth. Models of social systems operate in environments constrained by organized rules or prescribed behaviors. But unlike physical laws, the social constraints for decision making are not fixed. Society changes the basic rules, and individuals change their fundamental behaviors. Arson rates are not the same thing as earthquake rates. In general a change in external environment invalidates a model. The most obvious external intentional uncertainty involves changes in fire codes themselves.

There is a necessary imprecision in language. Since models currently do not have to meet any minimum criteria, no hard and fast rule can be created as to whether a given uncertainty in the real world should be described as internal or external. For example fire department response can either be included in the model, or set up as external to the model. What is clear is that any model is only valid as long as the external environment is kept constant. As a result assumptions used in modelling have to be divided into two categories, which we describe as **estimations** and **conditions.**

Estimations represent a technically credible value for a real data point, and can be included in the model.

Conditions are a requirement for the validity of the model itself.

Quantitative **estimates** must normally disclose the range over which they are valid since it is normally a **condition** of a model that the true value lie within the accepted estimation range. Values for external intentional uncertainties would be stated as a **condition** for the model. If the **conditions** change, the model needs to be abandoned or reworked. In some cases variables have to be treated as **conditions**, simply because of there is insufficient data to create an estimation.

The validity of an estimation variable is a separate issue from the acceptability of a conclusion. For example if a model of a building can successfully predict the spread of fire in the absence of the sprinkler system, then the state of the sprinkler system can be **estimated**, but if the model is incapable of predicting the fire development if the sprinkler system is not working then the system is a condition for the model. Sensitivity analysis is appropriate for testing **estimations**, but not **conditions**. Improperly stating a condition as an estimation can create a false sense of confidence in a model.

From a regulatory point of view the distinction between credible estimations and required conditions is critical. If a model has too many conditions, it raises significant questions as to whether the model is complete enough for use in the regulatory process. As a practical matter the Authority Having Jurisdiction (AHJ) must set out which conditions are acceptable.

MANAGEMENT OF INTENTIONAL UNCERTAINTY

Because modelers dealing in physical systems are used to a system of stable model conditions, **Conditions** involving intentional uncertainty may be mistakenly treated as **estimations.** But external intentional uncertainty is inherent in social building regulation. Society is not required to set out all its expectations in advance of construction, and regulation is designed only to supervise the fundamental obligation of the owner to create and maintain a safe structure. [11] Society can and does change its requirements during the lifetime of a building. In the case of performance based codes, designers can expect continuous change based on new and developing understanding of the actual hazards represented by building configurations. Therefore current regulatory approval of a building design cannot be the key goal of a performance based analysis. Providing safety over the lifetime of the building must be the focus.

One approach is simply be to use political decision making to set the values for the human decision variables to be used in the models. This approach is useful for intractable technical variables such as the size of an anticipated arson attack. There is no engineering methodology that supports any given level of arson scenario, it is ultimately a political choice.

We propose an approach based on continuous analysis of both the building and the model in the context of a coordinated risk-regulatory management approach. We propose that instead of trying to estimate intentional variables for the indefinite future, at a single point in time, it is a better strategy to use the model to define the required range for the variables. If the range can be specified and a method created for keeping the variables within that range the model can be valid for an extended period of time.

One of the most important advantages of an over-time risk management approach is flexibility in dealing with **conditions.** There are many variables which are not easily estimated and would have to be left outside the model. Such a model would be so incomplete as to be useless. However many of these variables might be directly controlled, thus allowing **external** variables to be included in the risk management strategy, at the same level of confidence as the other variables.

We believe that the key response to the problem is not to ignore human intentional uncertainty but to develop a system for incorporating appropriate control systems into the performance based analysis. In this approach the model is thought of as a series of rules and variables. In any given model the rules are constant over time. But the values assigned to the variables, instead of being estimated, would be continuously controlled. We propose the following rule

> **Any risk model which purports to describe the reaction of a technical system in a future environment that includes unpredictable human action must be accompanied by a regulatory system capable of keeping the human decisions within the *conditions* of the model or simulation.**

IMPLEMENTATION

Using this approach requires a three step process. The first step is to set up a matrix which identifies the key variables whose intentional uncertainty affects the overall model. The second step is to articulate control strategies for conforming the variables with the requirements of the model. The third step is to determine which variables must be left external to the model, because of the lack of a control strategy. The AHJ then decides whether the model is complete enough to use and what structure has to be set up to implement the control systems.

As an example of such an approach consider the "occupant load" of a building. Current prescriptive codes simply set out the permissible occupant load, and demand exits for that number. A performance based analysis would propose an occupancy load, under specified conditions (e.g. blocked exits) and estimations relating to the space and the exits. Sensitivity analysis of the estimates would identify particularly important issues.

The second step would be to articulate a control strategy for keeping the occupancy within the acceptable limits. In the case of occupancy limits this would normally be some kind of capacity control system, supervised by an appropriate regulatory enforcement system. The final step is a determination by the AHJ that the model, the conditions and the estimations are adequate for a regulatory decision.

This formulation turns the original proposal for performance based codes "inside out". Instead of trying to use models to replace regulatory decision making, it recognizes that only political regulators can support the use of necessary variables in predictive fire models, by setting up a system to control those variables in the future. It is therefore not merely a question of using fire models in regulation, but without regulation the models cannot even be created.

CONCLUSION

Human intentional decision making is a significant limitation of predictive fire models. Many technical variables in fire models are actually the output of uncertain human decisions. Human intentional uncertainty is not captured in traditional models of aleatory and epistemic uncertainty. The product of human decisions can be put into the model as **estimations** only if they are supported by adequate data and the model is valid over the full range of decisions. Otherwise uncertainties have to be treated as **conditions** of the model. Violation of a condition invalidates the output of the model. Many human decisions which cannot be predicted might be controlled. With control strategies the values of the variables could kept within the range required for the model. Performance based regulation will requires a regulatory system capable of keeping all variables required by the model within bounds of the model's conditions.

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