The Next Generation of Performance-Based Fire Safety Engineering in New Zealand

Abstract

The introduction of a new Building Act in New Zealand in 2004 prompted a comprehensive review of the Building Code to ensure that its provisions were both consistent with the new Act, and contained sufficient quantification of performance requirements. The review resulted in new Protection from Fire code clauses, Acceptable Solutions (prescriptive, non-mandatory deemed-to-satisfy provisions), and a Verification Method (based on the structural design process where design loads and performance criteria are specified) being introduced in 2012. This new generation of fire safety regulation is expected to substantially reduce the level of inconsistency and inefficiency that previously existed. The next paradigm shift in the New Zealand building regulatory environment is expected to introduce a risk-informed regime, where probabilistic provisions will be incorporated to address the inherent risk and uncertainty associated with performance-based fire safety engineering design. With this scenario in mind, a collaborative research project involving BRANZ Ltd and the University of Canterbury has recently developed a new fire safety engineering design tool called B-RISK, forming part of the essential underlying research necessary to underpin any such future code change. This paper describes the development of the B-RISK tool and its application to the practice of performance-based fire safety engineering design. Instead of doing calculations in the traditional deterministic manner, B-RISK improves the designer’s risk-informed decision-making by using a physics-based model in conjunction with the probabilistic functionality of Monte-Carlo sampling techniques in an iterative fashion. A design fire generator that populates a room with items and predicts item to item fire spread provides probabilistic families of fire growth curves. User-defined distributions for key input parameters are included, as well as distributions for the reliability of fire protection systems, from which B-RISK samples for each iteration. The resulting model results are presented in the form of cumulative density functions of probability, whereby a risk-informed design decision can be made.

Keywords: performance-based design, fire safety engineering, quantitative risk assessment, systems reliability, design fires.

1. Introduction

1.1 Building controls framework

There are essentially three hierarchical levels to the performance-based building controls framework in New Zealand. The overarching legislation is the Building Act (NZ Govt., 2004), which contains the provisions for regulating building work, and which must be adhered to when buildings are designed and constructed. The purpose of the Building Act is to ensure that people can safely use buildings without endangering their health, they can escape from the building in the event of fire breaking out, the building provides amenity for users, the building promotes principles of sustainable development and Fire Service personnel can undertake fire fighting and rescue functions without undue risk (DBH, 2011a).

The second tier of the overall building controls framework consists of a number of sets of building regulations which provide more specific details relating to administration of the building regulatory system.

The third level of this hierarchy is the New Zealand Building Code (NZBC) which is an annex to one of the sets of building regulations, namely the Building Regulations 1992 (NZ Govt., 1992), which provides the minimum legal requirements for building works. The NZBC contains the mandatory provisions for new building work by stating the required level of building performance but not prescriptively describing how the level of performance should be achieved. The NZBC contains 35 technical clauses that set out the different performance criteria that must be met including structural stability, fire safety, access, moisture control, durability, services and facilities, and energy efficiency.

Each clause of the NZBC stipulates, in a descending hierarchy: (a) Objectives (statements of social objectives in terms of health, safety, amenity and sustainability); (b) Functional Requirements (how a building in general terms could be expected to satisfy the relevant Objectives); and (c) Performance Criteria (qualitative or quantitative criteria to meet the Functional Requirements and Objectives).

There are three possible pathways for demonstrating compliance with the NZBC: (1) Acceptable Solutions (deemed-to-satisfy instructions) that are contained in the Compliance Documents (prescriptive methods to meet Performance Criteria); (2) Verification Methods (calculation or test methods) also contained in the Compliance Documents; or (3), Alternative Solutions (alternative methods, other than those contained in Compliance Documents, to meet Performance Criteria) (DBH, 2011a).

1.2 Fire safety engineering

Performance-based fire safety engineering makes use of calculations and modelling. For example, demonstrating that building occupants can safely evacuate in the event of a fire breaking out is generally done by conducting an ASET/RSET analysis. In this context the available safe egress time (ASET) is the time for conditions to become untenable, while the required safe egress time (RSET) is the time taken to reach a place of safety (Gwynne, 2012).

Focussing on ASET, the starting point for the calculations are design fire scenarios (qualitative descriptions that characterize the key events of a potential fire), which include such aspects as the location of the fire, building characteristics, fire loads, fire protection systems, etc. A design fire scenario also includes a design fire (quantitative description of fire characteristics within the design fire scenario) which is typically defined as a heat release rate (HRR) time history, but will also often include species production rates and the effective heat of combustion (ISO, 2006).

In order to demonstrate that the ASET exceeds the RSET, generally with an appropriate safety factor, widespread usage is made of computer models to simulate both compartment fires (ASET) and occupant escape (RSET). Generally, models can be classified as being either deterministic (single values for calculation parameters) or probabilistic (range of possible values for calculation parameters), with the former being the most commonly used in performance-based fire safety engineering. With only a few specific scenarios being considered and single-point values for key design parameters incorporated into the calculation procedures, this approach makes no allowance for the probability of these scenarios occurring or the variability of input parameters (Fleischmann, 2011).

1.3 New safety from fire provisions

During the two decade period in which performance-based fire safety engineering has been carried out in New Zealand, a number of issues have become apparent. One major issue that has hampered the full benefits of a performance-based regime being achieved has been a lack of quantification of performance criteria in the NZBC. This lack of quantified performance criteria has resulted in the unsatisfactory situation of fire designers both proposing and applying their own criteria. In addition, a lack of suitable verification methods has resulted in a general design approach that is not standardised and sensitivity analysis, to address uncertainty, is rarely done. The current process of design and regulatory approval appears to involve a high degree of subjective judgement and has resulted in inconsistency in fire engineering and disputes about fire safety (Wade et al., 2007).

Until recently, the Compliance Document for the fire safety clauses of the NZBC (DBH, 2011b) did not provide quantified guidance for specific performance-based fire safety engineering. In 2006 a project was initiated by the building regulator which in part had the objective of providing more specific guidance to practitioners – this culminated in the publication in 2012 of a new Verification Method (C/VM2) (DBH, 2012) which quantifies design fire scenarios, design fires, pre-travel activity time and acceptance criteria.

1.4 Collaborative research project

The inability to deal in a rational manner with the risk and uncertainty inherent in performance-based fire safety engineering was the catalyst for a collaborative research project that started in 2007. The research project has developed a quantitative risk assessment (QRA) tool called B-RISK, which incorporates deterministic calculations, probabilistic sampling from input parameter distributions, and Monte-Carlo iterative functionality.

At the same time, the building regulator has indicated a desire to move towards more risk-informed building regulations at some point in the future. One possible manifestation of this intent could be probabilistic statements of building performance (PSBP) in future revisions of the NZBC. Notarianni (2000) notes that PSBPs contain a minimum of four elements - probability, time, a performance criterion, and a threshold value.

In the context of the new Verification Method, C/VM2, an example of a PSBP could be:

> *The fractional effective dose (FED) of carbon monoxide (CO) shall have a 90% probability of not exceeding 0.3 at a time of 400 seconds after a fire starts.*

The B-RISK model has been developed for use by fire safety engineering practitioners and regulatory authorities to be able to demonstrate compliance with the requirements of such statements of performance.

2. B-RISK model development

Extensive use is made of computer models in performance-based fire safety engineering. Olenick and Carpenter (2003) classify such models into six types; zone, field, detector response, egress, fire endurance, and miscellaneous. These six classes of models can then be further differentiated as being either deterministic or probabilistic/stochastic (Beard, 1992; Ramachandran, 2008). Compartment fires are generally modelled using either zone (Walton et al., 2008) or field (McGrattan and Miles, 2008) models.

Structurally, B-RISK consists of a User Input Module, a Sampling Module, a Deterministic Calculation Module, an Output Data Module, and an Output Distribution Module. The Deterministic Calculation Module incorporates a Design Fire Generator (DFG) Sub Module and a Systems Effectiveness Sub Module. Figure 1 shows schematically the high-level conceptual structure of B-RISK.

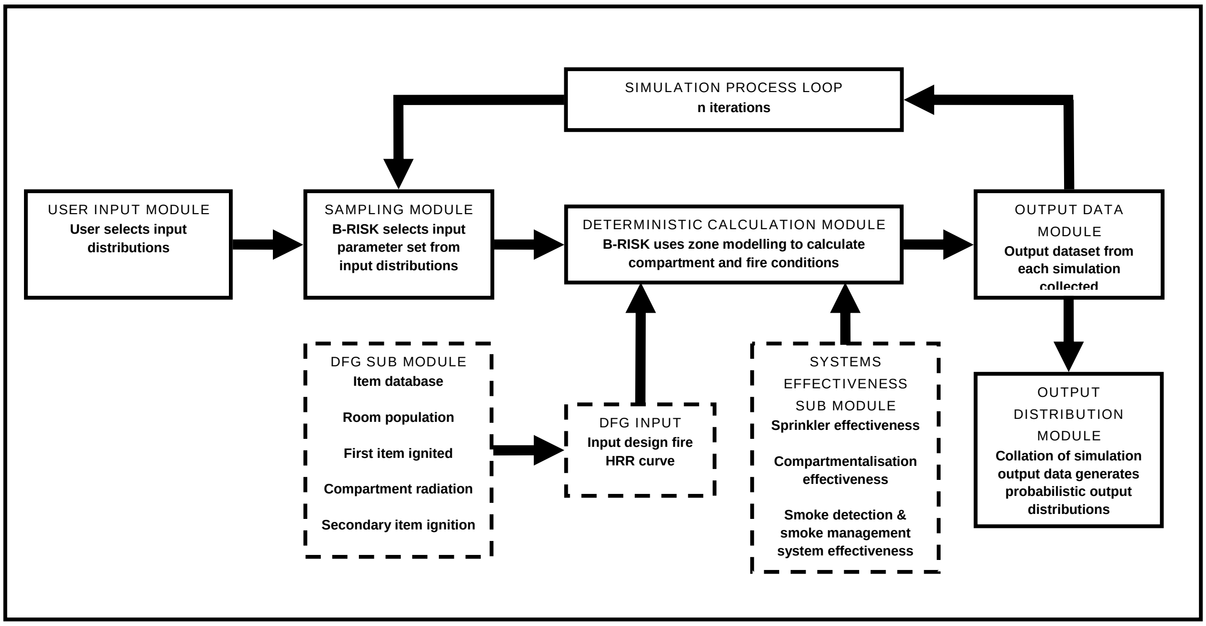


Figure 1: Schematic structure of B-RISK modules.

The User Input Module deals with the variability and uncertainty associated with the modelling inputs by assigning probability distributions to key input parameters. Next, the Sampling Module uses iterative Monte-Carlo sampling techniques to select a set of input values from the user-defined input distributions.

The Deterministic Calculation Module uses zone modelling principles to determine the fire environment. Two important sub modules contribute to the Deterministic Calculation Module - the Design Fire Generator Sub Module provides an input HRR curve for each simulation loop, while the Systems Effectiveness Sub Module provides the ability to incorporate fire safety systems reliability and efficacy into the B-RISK modelling predictions.

Each of the *n* iterations of the Simulation Process Loop provides a set of output data to the Output Data Module and then the Output Distribution Module collates these datasets into output distributions, which take the form of cumulative density functions of probability. The fire safety engineering practitioner is then able to compare these outputs to the applicable PSBP.

2.1 Design Fire Generator

The starting point for any performance-based fire safety engineering design is to characterise the severity of the fire that may occur in the building. For traditional deterministic modelling, the model user manually inputs a HRR curve for a theoretical design fire. The HRR curve is a plot of heat output vs. time, and generally will have growth, fully-developed and decay phases. The growth phase is typically represented in a parabolic “t-squared” form (Karlsson and Quintiere, 2000).

In order to be able to efficiently input hundreds, or even thousands, of unique HRR curves for each individual iteration of the B-RISK calculation process, a sub model was developed within B-RISK for this purpose, termed a “design fire generator” (DFG).

2.1.1 Room population functionality

The starting point for the DFG is a database of combustible items. The items represent typical objects that are likely to be found in the occupancy under consideration, such as chairs, desks, armchairs, sofas, televisions, bookcases, etc. As shown in Figure 2(a), each item has various geometric, chemical, ignition and HRR properties assigned to it.

Once the physical dimensions of the compartment of fire origin have been defined in B-RISK, the DFG randomly selects items from the item database and populates the space with combustible objects. The total number of objects is governed by one, or a combination, of the following:

1. The physical space available in the compartment, i.e. once an area is occupied by one item, another object cannot overlap the first item,

2. The maximum number of that type of object permitted,

3. The fire load density, which can be either a distribution, or a single value.

With regard to item 2, the B-RISK user may want to limit the number of items – an example may be televisions, where there is likely to be only a single item of that type in any one room.

With regard to item 3, when the distribution option is used for the fire load density, a value will be randomly sampled for each iteration, and hence the number of items in the space could vary from iteration to iteration.

Having populated the enclosure with items, the DFG randomly assigns an object to be the first item ignited in the scenario being modelled, as illustrated by the notation “I (ignition) 0s” in Figure 2(b).

Short Description: Sofa
User Label: Sofa
Detailed Description: CBUF item 1.1 3-seater sofa
Type: 3 Seater Sofa

Geometry — **Units**

Length 1.75 m
Width 0.88 m
Height 0.6 m
Elevation 0 m
x-coord (left edge of item) 0.15 m
y-coord (bottom edge of item) 0.9 m
Combustible Mass 48.975 kg
Max Number Permitted in Room 4
Prob Near Wall 1 -

Chemistry

Heat of Combustion 17.1 kJ/g
Soot Yield 0.14 g/g
CO2 Yield 1.68 g/g
Latent Heat of Gasification 0 kJ/g
Radiant Loss Fraction 0.5 -
Constant A 0 mdot"= A qdote" + B
Constant B 0 mdot"= A qdote" + B
HRR per unit area 0 kW/m2

Target Ignition

FTP limit pilot 480 kWs^n /m^2
FTP index pilot, n 1
Critical Flux pilot 10 kW/m2
FTP limit auto 430 kWs^n /m^2
FTP index auto, n 1
Critical Flux auto 22 kW/m2

Wind Effects
● Undisturbed Plume
○ Disturbed Plume

Heat Release Rate
Time (s), HRR (kW)
0,0
152,1959
750,0

FLED (MJ/m2) 247.32
No. of Items 9
Grid Size (m) 0.1
Vent Clearance (m) 1
Show Vectors ☐
Show Grid ☐
Show Sprinklers ☐
Show Smoke Detectors ☐

Show Item Labels
Show ID Number ○
Show User Label ●

Population Method
Auto Populate Items ●
Manual Positioning of Items ○

Recall layout by iteration 1

(a) (b)

Figure 2: Room population: (a) Typical item from B-RISK item database; (b) random population with items.

As well as the stochastic populate room functionality, the DFG also has the option to locate items in a pre-determined location, so that validation comparisons are possible.

2.1.2 Compartment radiation and secondary item ignition

The ignition of the secondary items in the compartment of fire origin is modelled on the basis of the radiation received from other burning objects in the compartment. The radiation is either directly from the flames of burning items, or from the underside of the hot upper layer that forms during the pre-flashover stage of the growing fire.

Based on work conducted by Fleury (Fleury et al., 2011), the flame radiation is modelled as emanating from a point at the centre of a sphere, the so-called "point source model" (Modak, 1977).

The underside of the hot upper layer is modelled in the DFG as a uniform, isothermal surface that emits diffuse (directionally-uniform) and gray (wavelength-independent) radiation (Tien et al., 2008), while the emissivity is based on the soot and gases in the upper layer.

To calculate the point at which secondary items will ignite, the Flux-Time Product (FTP) methodology (Baker et al., 2011) is utilised by the DFG sub model. When the incident radiation exceeds a critical value, radiation is assumed to accumulate at the surface of an object until a threshold value is exceeded, at which point ignition is deemed to have occurred

- Figure 2(a) shows an example of the FTP parameters that are assigned to an item in the DFG item database.

2.2 Systems effectiveness

Once potential fires have been characterised for a building, measures to mitigate the risk may be required. The primary tools available for fire safety engineering practitioners to manage fire risk are fire safety systems such as automatic suppression (sprinklers), compartmentalisation, and smoke management systems. However, it has been observed in New Zealand and elsewhere that the lack of ability to account for the reliability and efficacy of fire safety systems has been a major limiting factor in performance-based fire safety engineering solutions (DBH, 2005). The ability to include system reliability and efficacy is integrated with the B-RISK modules for sprinkler systems, detection systems, compartmentalisation, and smoke management.

2.2.1 Sprinkler effectiveness

B-RISK includes the capability to consider the effectiveness of sprinkler systems on fire development in three stages: the first assumes the sprinkler system has no effect on the fire development; the second assumes the HRR is constant after the sprinkler system activates; and the third assumes the HRR is suppressed once the sprinkler system activates using an exponential decay model developed by NIST (Evans, 1993). Probability distributions can be entered for the first and second stages, with the remaining fires included in the third stage. An additional distribution can be added for the number of sprinklers activated before the HRR rate is affected by the sprinkler system.

The physics-based Systems Effectiveness Sub Module within the Deterministic Calculation Module (refer to Figure 1) is used to determine when sprinklers activate. Distributions for the sprinkler thermal response parameters allow uncertainty in sprinkler response to be included. Due to the nature of the DFG which allows the fire to be located at random in the fire room, all of the sprinklers in the fire room can be included in the simulation. The activation of multiple sprinklers can be simulated (Frank et al., 2012).

A question that often arises with zone fire physics models is whether they provide a close enough representation to realistic fire behaviour. A study using B-RISK to compare model uncertainty and natural scenario variability uncertainty in sprinkler activation time showed that the zone approach was sufficient to provide a “consistent level of crudeness” with the uncertainty in input parameters for the scenarios considered, particularly in design conditions where more uncertainty is present compared with a reconstruction scenario (Frank et al., 2011).

2.2.2 Compartmentalisation

B-RISK can include compartmentalisation effectiveness using vents in the compartment boundary. Probability distributions can be entered for the probability that a vent is open when the simulation starts (a propped open door, for example) and also for the width and height of vents to include the potential effects of compartment leakage. A study has been undertaken to collect data on the probability for fire and smoke doors being open in shared means of escape routes.

2.2.3 Smoke detection and smoke management system effectiveness

Both passive and active smoke management strategies can be included probabilistically in B-RISK. Detectors can be used to activate vents or fans. A distribution for smoke detector reliability can be used, as well as distributions for optical density at alarm and the detector characteristic length. The ability to enter a distribution for optical density at activation can be used to account for the uncertainty in photoelectric or ionisation detector detection time due to the discrepancy between the physics of the response of these types of detectors and light obscuration (Milke, 2012). Distributions can also be used to include uncertainty in fan reliability and flow characteristics.

3. Discussion

3.1 Design fire generator output

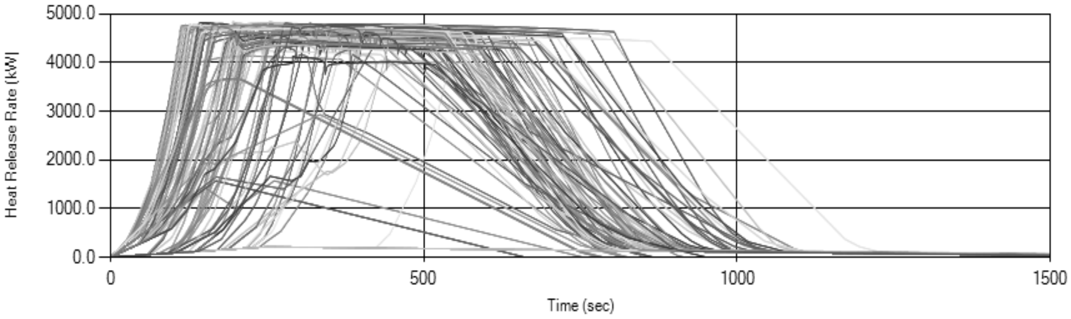
With reference to Figure 2(a), each item in the DFG item database is assigned a free-burning HRR curve. At the start of each DFG iteration, the HRR for the entire compartment consists of the individual HRR curve for the first item ignited. As subsequent items are deemed to have ignited, the individual HRR curves for the secondary items are added in a cumulative fashion to the HRR curve for the entire compartment. As the fire spreads from item to item, and the fire growth starts to accelerate, the total combined HRR curve will go through a transition from a growing fire to a fully-developed fire, akin to flashover (Karlsson and Quintiere, 2000). While initially the growing fire is fuel-controlled in the pre-flashover phase, the fire will quickly become ventilation-controlled as it transitions into the post-flashover, fully-developed, phase. The HRR curves that are the output from the DFG sub model simulations constitute the design fire input for B-RISK calculations, with Figure 3(a) illustrating the subsequent HRR curve output from B-RISK, in this case for 100 iterations. Of these 100 iterations, the fire did not spread beyond the first item ignited in 7 of the 100 iterations. The remaining 93 iterations all reached flashover (deemed to be when the average upper layer temperature reached 500 ºC).

3.2 Comparison to experimental and parametric data

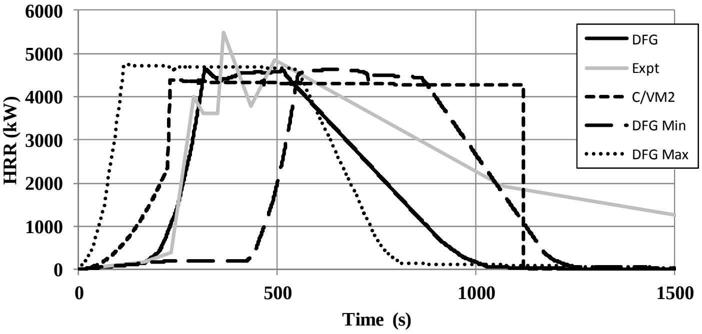
In order to compare the HRR curve predictions of the DFG, B-RISK was used to simulate some existing residential-scale experiments (Blomqvist et al., 2004) in an “a posteriori” manner. The combustible object layout and ignition source scenario were replicated in the DFG – the resulting comparison is shown in Figure 3(b), labelled as “DFG” and “Expt”.

It should be noted that the actual experiment conducted by Blomqvist and colleagues, shown in Figure 3(b), had a long (≈ 750 s) incipient phase. The start of the growth phase is set at the same time between the “DFG” and “Expt” datasets, so the resulting comparison shown in Figure 3(b) is a comparison of the growth, fully-developed, and decay phases only. The experimental data also include post-flashover flaming out through the room doorway, which would give HRR values higher than the compartment-only values generated by B-RISK.

Figure 3(b) also includes the design fire curve (labelled “C/VM2”) that would be required by the new C/VM2 verification method in New Zealand, noting that this HRR curve is based on a “fast t-squared” fire growth (DBH, 2012). For further comparative purposes, the curves with both the fastest and slowest growth rates for the 93 flashover iterations illustrated in Figure 3(a) are also plotted in Figure 3(b), labelled as “DFG Max” and “DFG Min” respectively. The “C/VM2” curve equates to the lower 23 percentile of the 93 flashover iterations.



(a)



(b)

Figure 3: HRR output curves: (a) 100 DFG iterations; (b) comparative.

Further validation experiments are in progress in which two multiple item fire spread scenarios are being set up in an ISO room. Each scenario will be replicated three times and the results compared to B-RISK simulations. The flammability properties of the materials used to construct the combustible items has been determined from cone calorimeter tests and the free burn HRR of each item has been measured under the furniture calorimeter. For the ISO room experiments the item to item ignition sequence and total HRR will be monitored. In addition, it is intended that the response of sprinklers and smoke detectors will be recorded.

3.3 Influence of fire load density

The B-RISK HRR curves shown in Figure 3(b) are each individually based on a unique value sampled from an assigned fire load density distribution. Although it is not immediately obvious from the cluster of overlapping HRR curves shown in Figure 3(a), the extracted curves in Figure 3(b) (labelled “DFG Min” and “DFG Max”) demonstrate different fire load density values (in the form of different durations for the ventilation-controlled peak HRR plateau) when compared to the HRR curve labelled “DFG”, which has a lower fire load density value.

4. Conclusion

This paper has described the development of new fire modelling software called B-RISK. B-RISK combines probabilistic/deterministic functionality with stochastic Monte-Carlo sampling algorithms so as to deal with the risk and uncertainty inherent in performance-based fire safety engineering in a rational manner.

B-RISK includes a design fire generator (DFG) sub model in its calculation module that can generate a unique design fire HRR input for each calculation cycle (iteration) that the model performs. On this basis, B-RISK produces HRR data that compare favourably with experimental and parametric design fire curves.

B-RISK also incorporates functionality that quantifies systems effectiveness, which until now has hampered the robustness of performance-based fire safety engineering, by including metrics for sprinkler, compartmentalisation, and smoke detection and smoke management system efficacy.

Instead of the traditional single point outputs that deterministic models produce, B-RISK produces tenability outputs in the form of cumulative density functions of probability, which quantify the likelihood of values occurring over the range of the output domain.

In conjunction with recent regulatory changes to the Protection from Fire clauses of the New Zealand Building Code, it is expected that B-RISK will help to minimise the subjectivity and inconsistency that has affected the full benefits of performance-based fire safety engineering being realised in the New Zealand building and construction industry.

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