ARUP

Consistent Approaches to Monte Carlo Analyses for Fire Severity

Structures in Fire Forum – September 2025

Yavor Panev, Dr Susan Deeny, Dr Graeme Flint

ARUP

Outline

- Problem overview
- Discussion of various challenges
- Mitigation strategies

What is a structural significant fire ?

Fully developed fire

Temperature throughout space: 900-1200C

Difficult to extinguish and can continue for a very long time

Large amounts of energy absorbed by structure

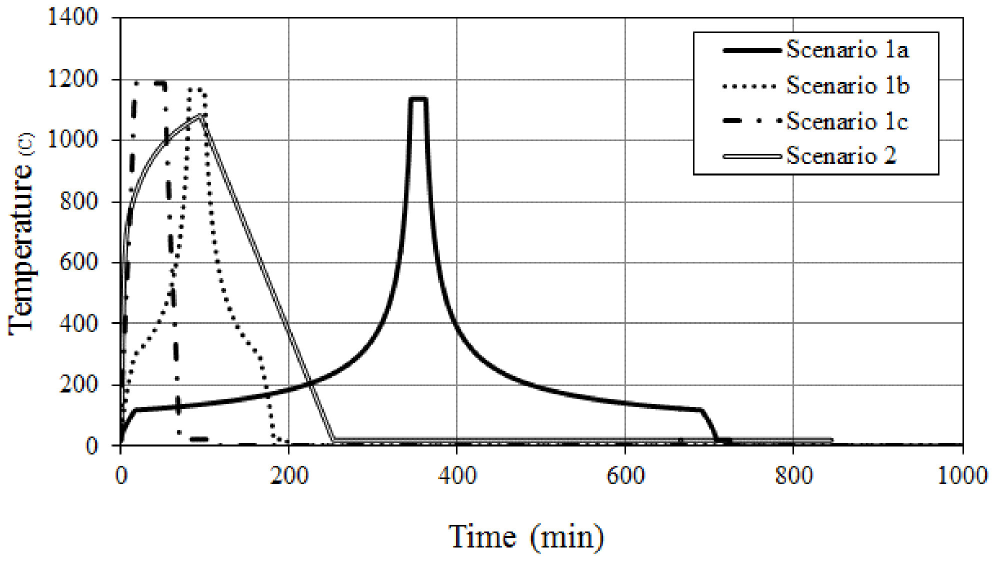
What is Fire Severity?

Introduction

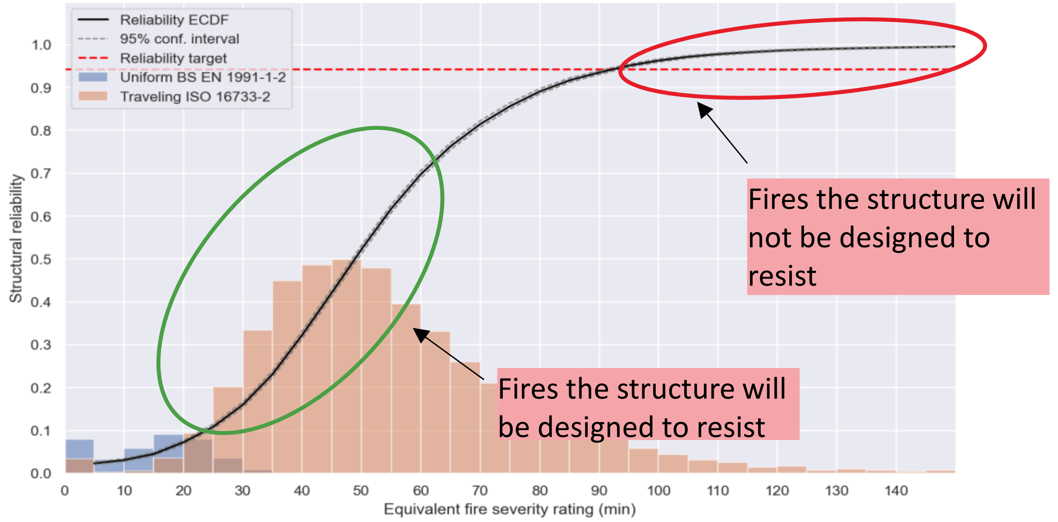
1. Generate a dataset of plausible fires appraising building geometry, functional use, ventilation provisions, fuel load, type of construction, etc

2. Assess the thermomechanical load demand of each scenario to the structure

3. Assess and quantify acceptable level of risk based on established risk targets



Example of gas temperature heating curves from possible fires



Establishing acceptable risk level

What percentage of fires the elements of structure should be designed against ?

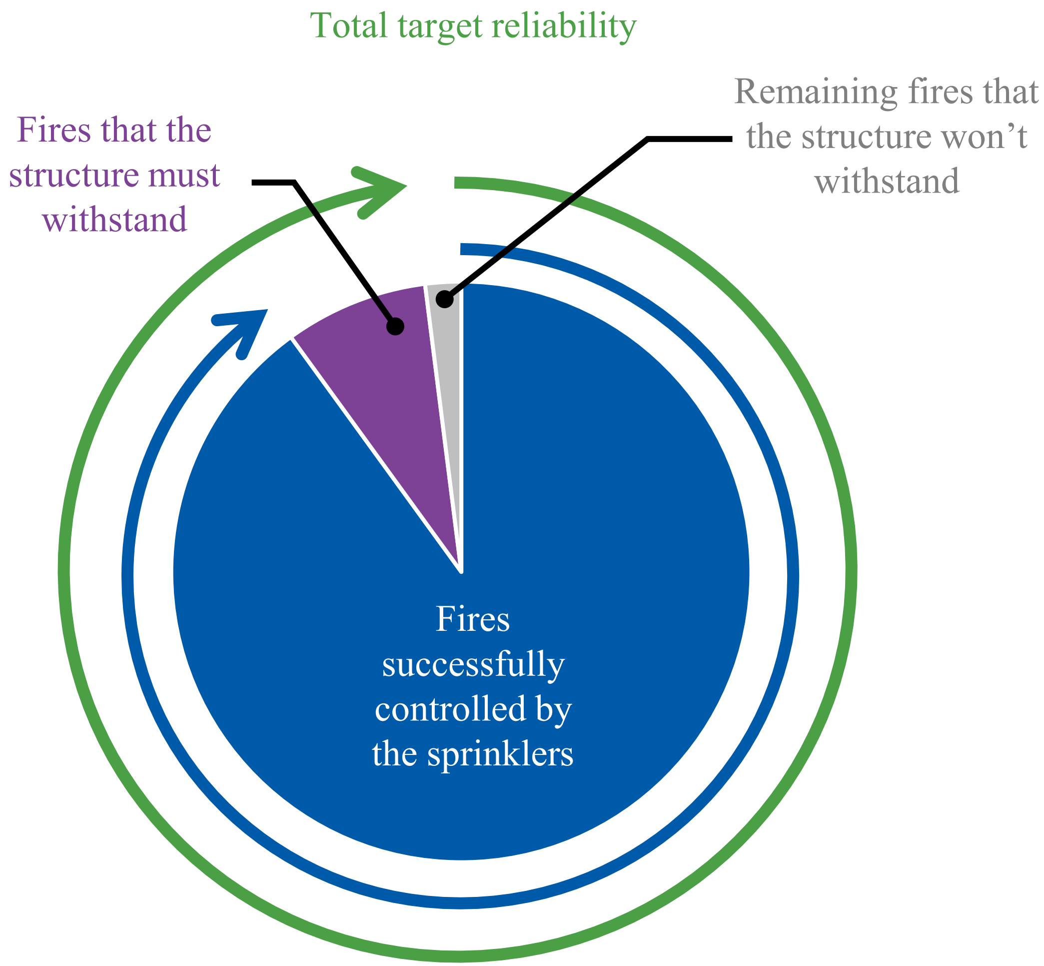
Several method/approaches depending on jurisdiction:

- Likelihood of ignition
- Likelihood of escalation to structural significant fire
- Acceptable rate of structural failure due to fire

BS 9999:2017 approach commonly adopted in UK:

- Risk target increases with building height
- Depends on occupancy profile
- Considers effects of sprinkler system
- Firefighting intervention not considered

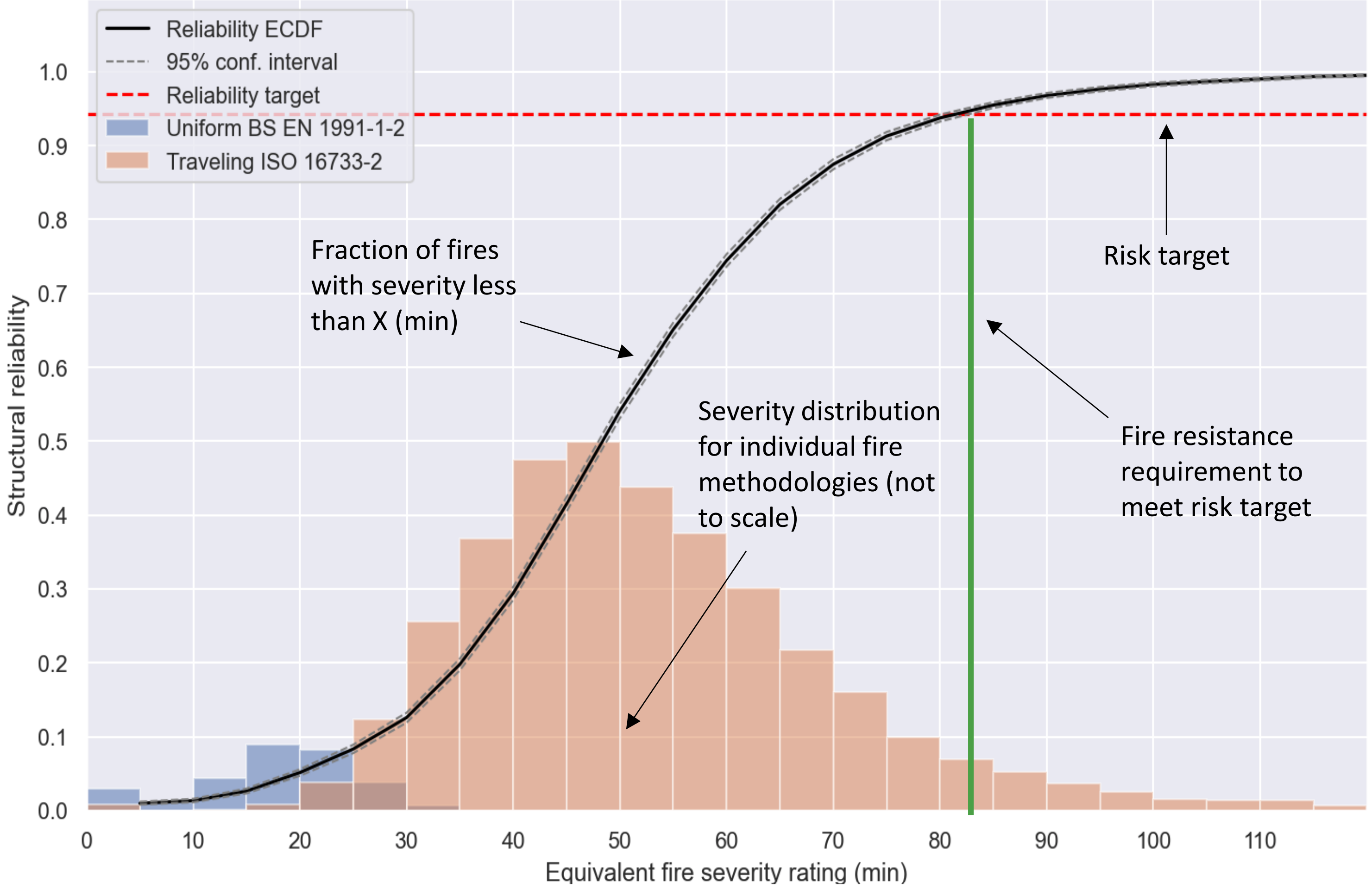
<u>Acceptable risk level usually can be expressed as a fraction between 0 and 1</u>



Problem Review

ARUP

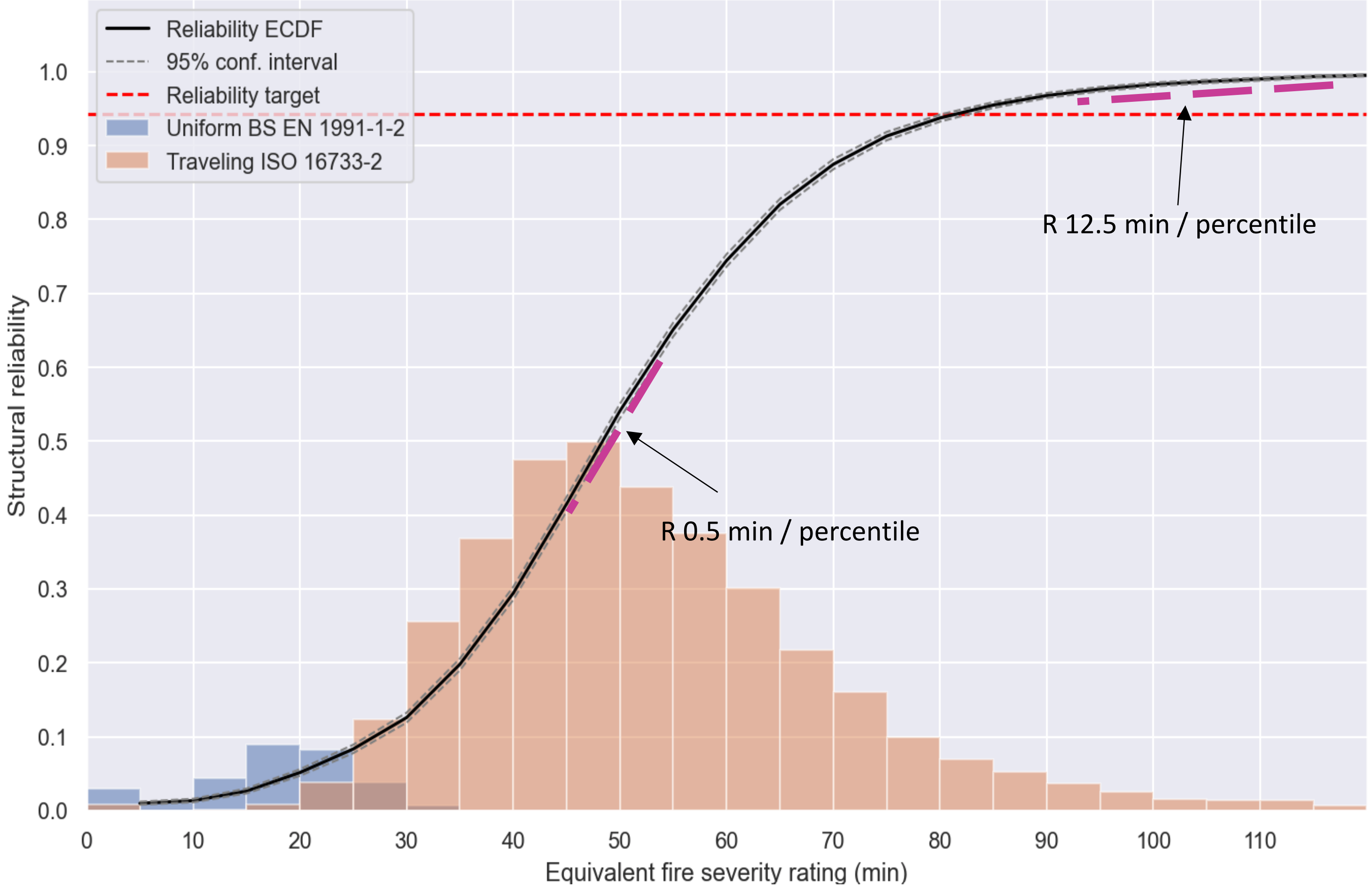
Introduction



- Cumulative density function (CDF) of plausible design fire severities is the main input of a fire severity study
- Severity expressed as equivalent rating to standard testing
- CDF benchmarked against risk target to determine acceptable level of fire protection

Problem Review

Introduction

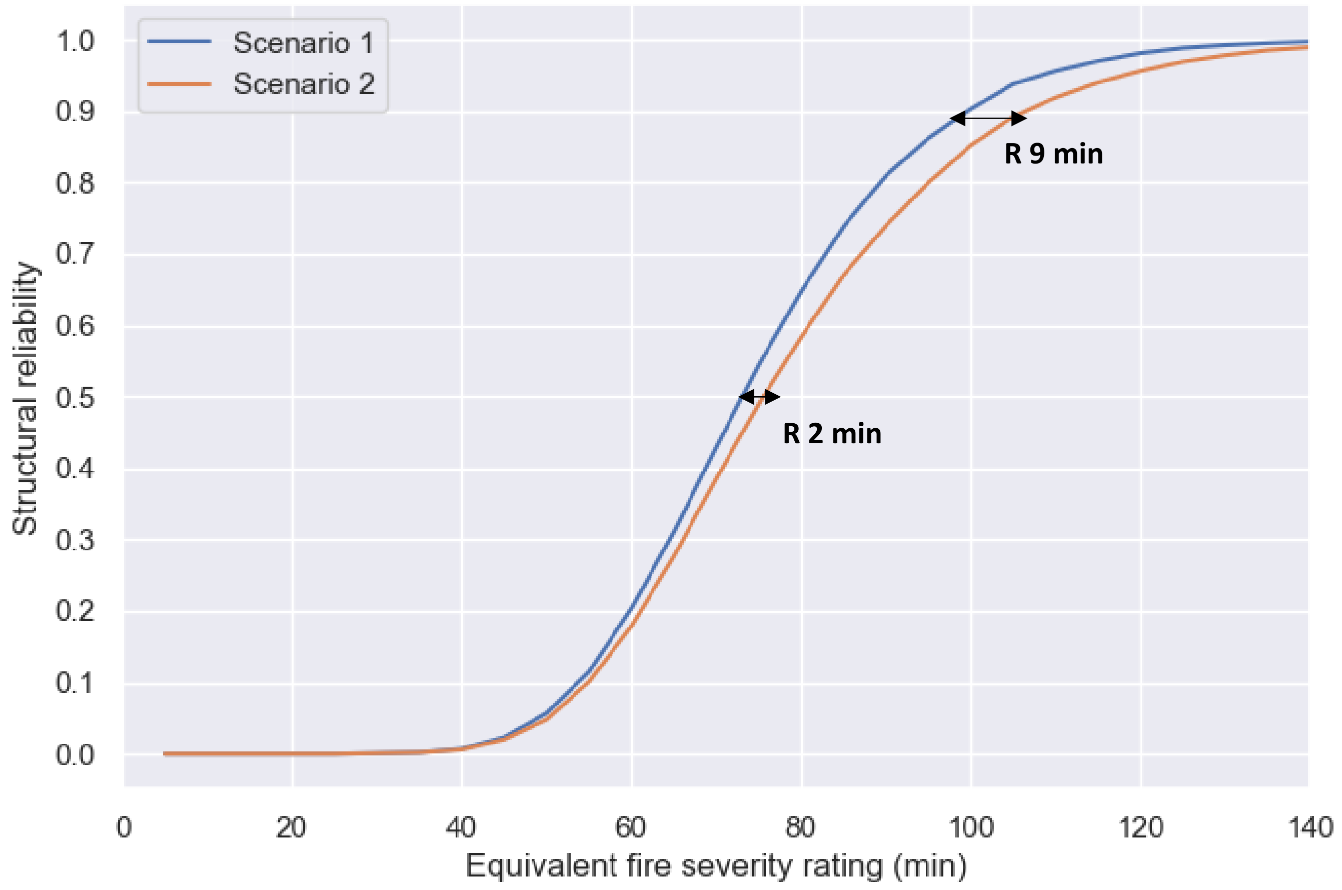


For high-risk applications:

- Outcome 20x more sensitive in extreme regions of the CDF compared to median regions
- Outcome informed by the fires in the extreme region of the initial distribution
- Elevated sensitivity to simulation inputs

Problem Review

Example of input sensitivity at high risk



Scenario 1
Fire spread rate [5.0; 19.3] mm/s

Scenario 2
Fire spread rate [2.5; 19.3] mm/s

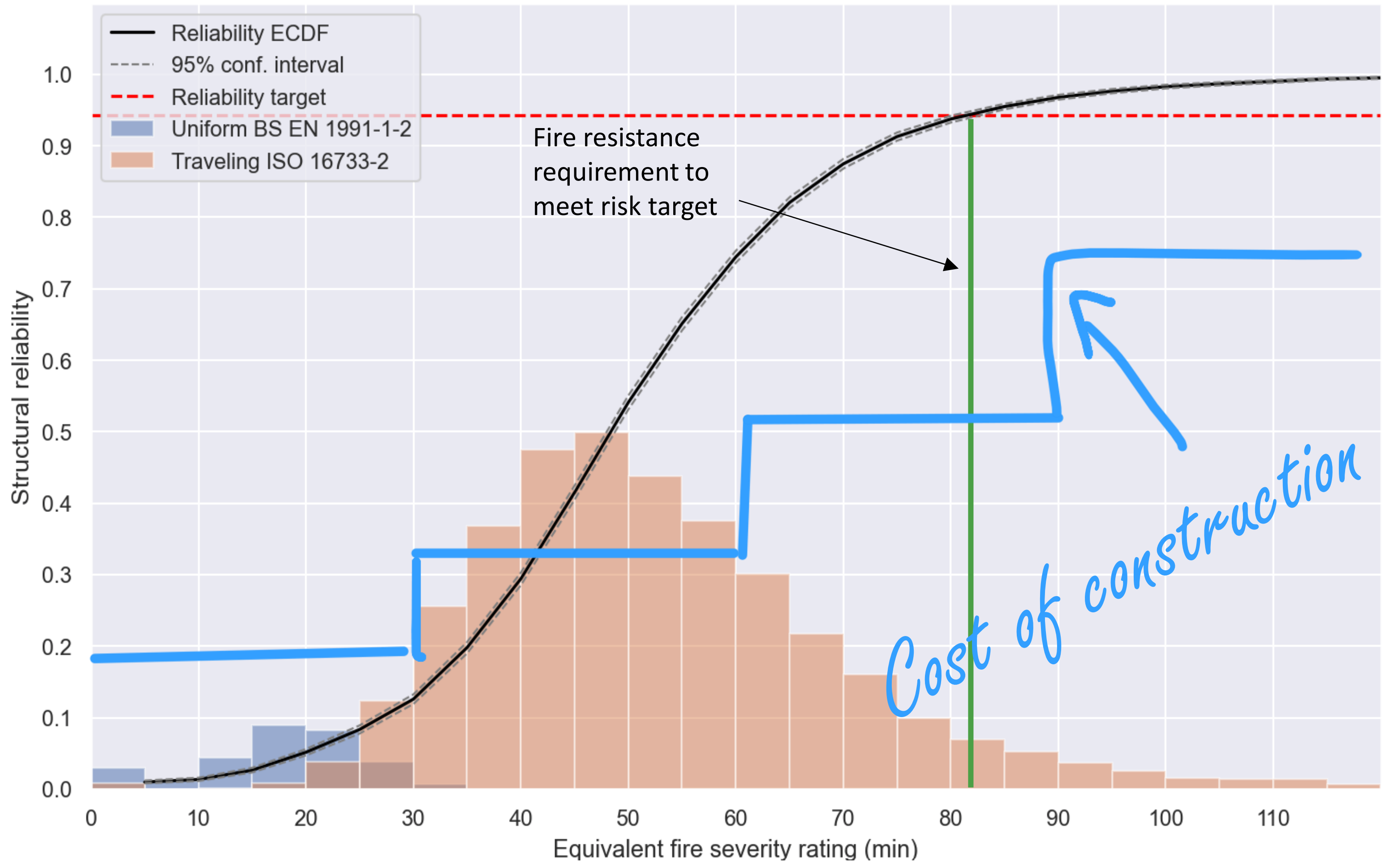
Results difference:
~ R 2 min @ 50 percentile
~ R 9 min @ 90 percentile

Small changes in input distribution might lead to significant changes at extreme ends of the output distribution

ARUP

Problem Review

Commercial aspect



Fire severity assessments inform both:

- Fire resistance requirement for structural fire protection
- Fire resistance requirement for non-loadbearing members (compartmentation construction, fire stoppings etc)

Fire protection products marketed of bands at R(EI) of 15 to 30 min with costs increasing for higher ratings

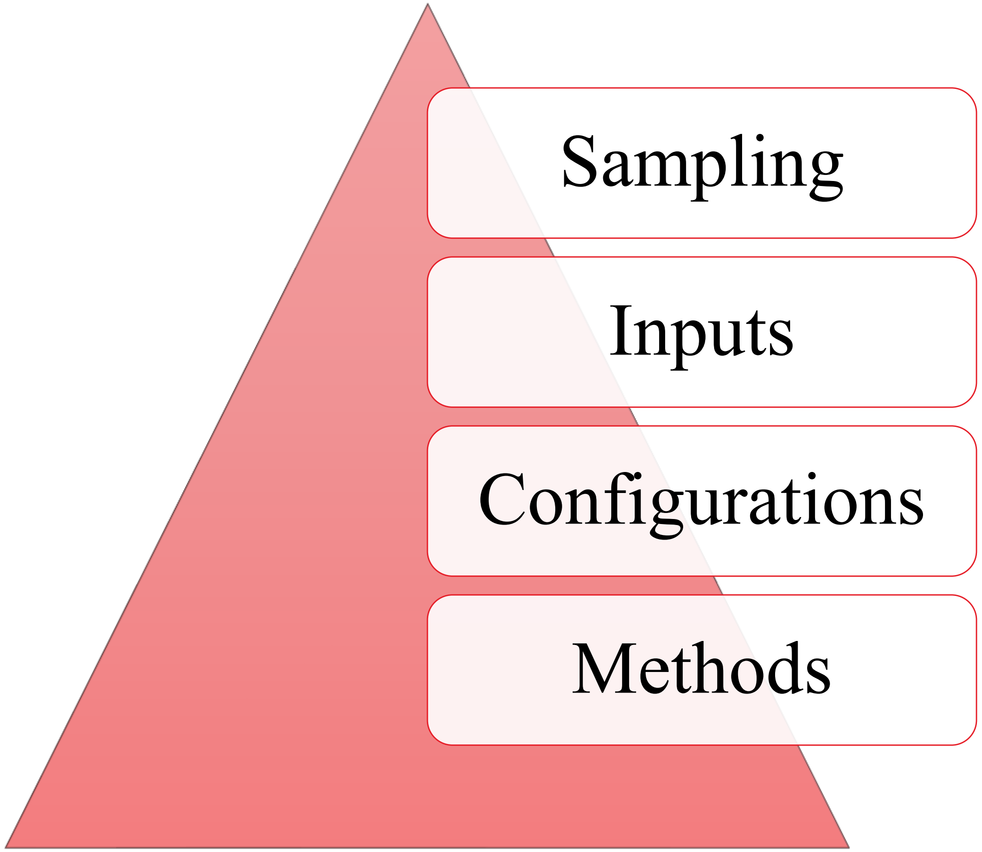
ARUP

Problem Review

- Analysis challenges increase when addressing high risk profile buildings
- Significant design and cost implications due to fire products rating banding
- Elevated burden on designer for accurate fire severity assessment

Challenges

Overview

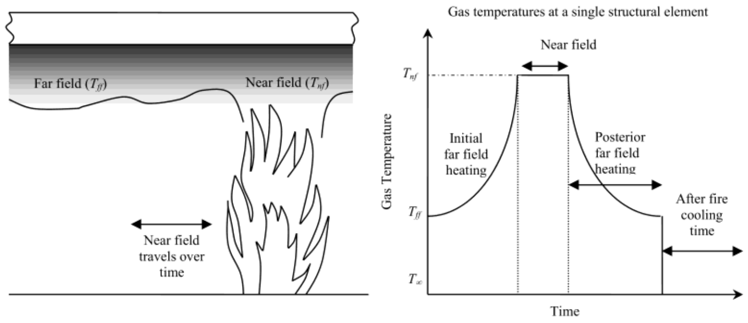


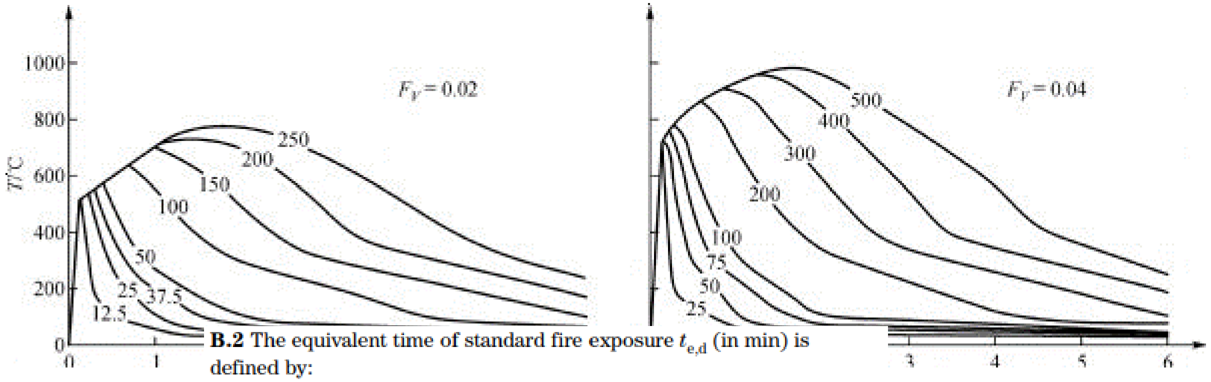
Typical fire severity analysis can be represented as hierarchical structure where the adopted assessment methods are placed at the bottom and associated input assumptions at the top

Specific challenges persist at each level

Methods

ARUP





B.2 The equivalent time of standard fire exposure $t_{e,d}$ (in min) is defined by:

$t_{e,d} = q_{f,d} k_b w_f$; or

$t_{e,d} = q_{t,d} k_b w_t$

where

$q_{f,d}$ is the design fire load density according to the UK guidance set out in Annex A;

k_b is the conversion factor according to **B.3**;

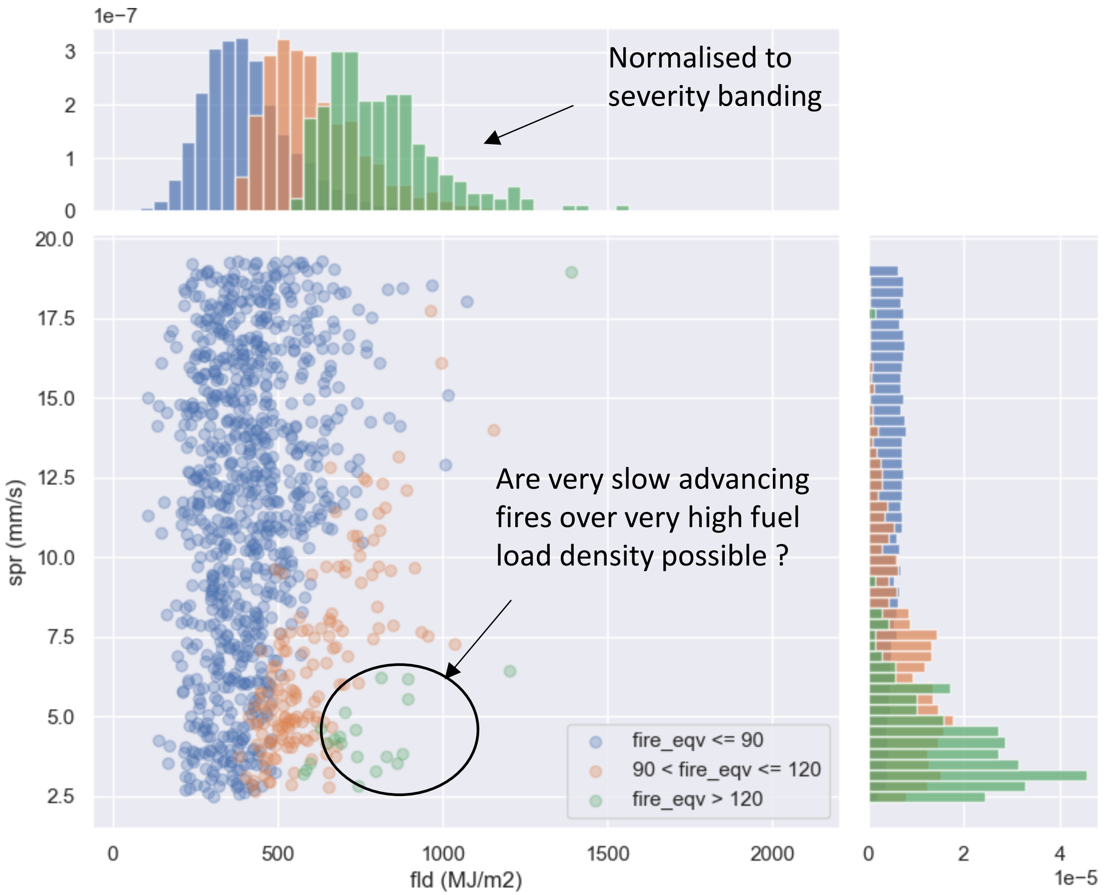
w_f is the ventilation factor according to **B.4**, whereby $w_t = w_f(A_t/A_f)$.

- Adopted design fire methodologies should be representative of expected burning regimes
- Equivalence method should capture the governing failure mechanism and specification standards
- Should the risk evaluation method be decided on individual project basis ? Who is responsible for this ?
- Adoption of legacy methods (e.g. PD 6688-1-2)
- Cross industry agreement and discussion on which methods are applicable

ARUP

Configurations

Method robustness



Scatterplot between fuel load density and fire spread for generated traveling fires. Colour represents severity banding.

Design fire methods are often based on limited experimental evidence against typical (median) but not extreme inputs.

No guarantee that the method will always produce physically valid or numerically stable results

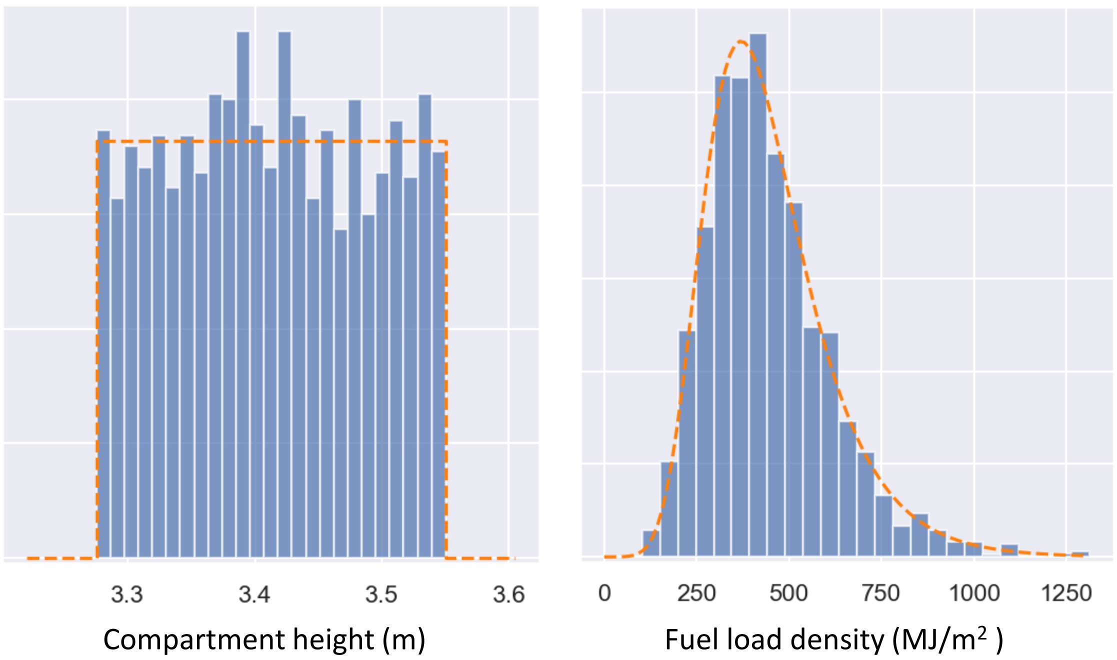
Ad-hoc removal of rogue cases not advised:

- Fudge output results
- Distorts input distributions

Develop a robust handling procedure:

- Systematically applies technically justified modification to a well-researched anomaly
- Tracks prevalence

Inputs



Typical fire severity calculation includes 10 to 11 inputs with varying degree of confidence:

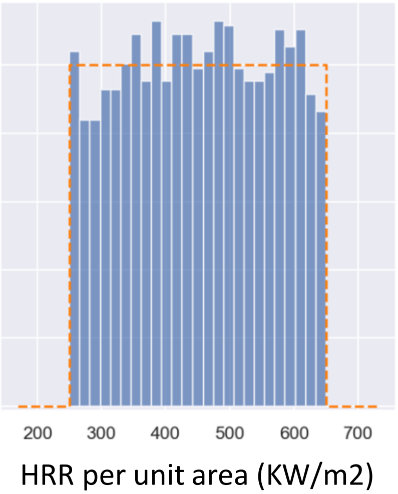
- High confidence – geometric design parameters (e.g. compartment height)
- Medium confidence – code prescribed distribution (e.g. fuel load)
- Low confidence – based on ranges of empirically observed measurements (e.g. fire spread rate, HRRPUA)

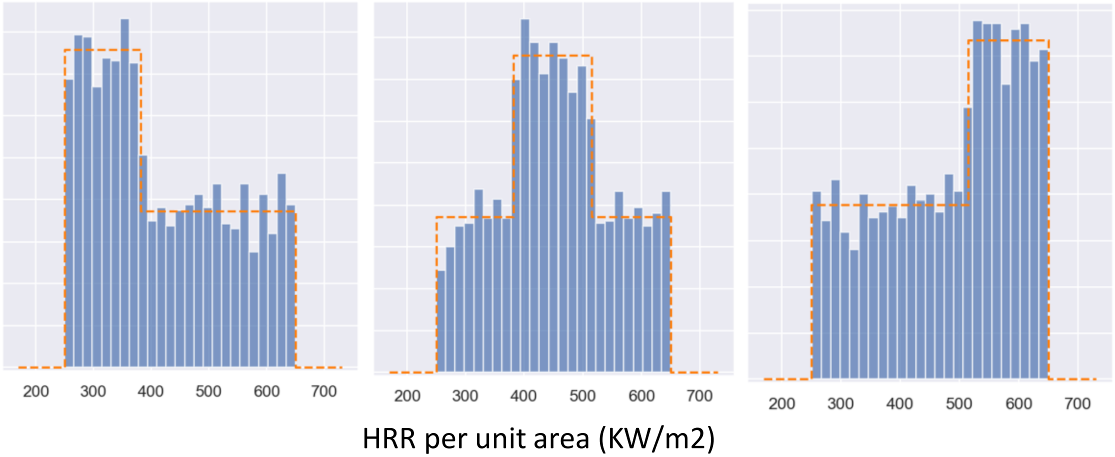
The designer is responsible to appraise if input confidence is appropriate with respect to:

- Sensitivity to end result
- Margin of safety to the risk target

ARUP

Inputs



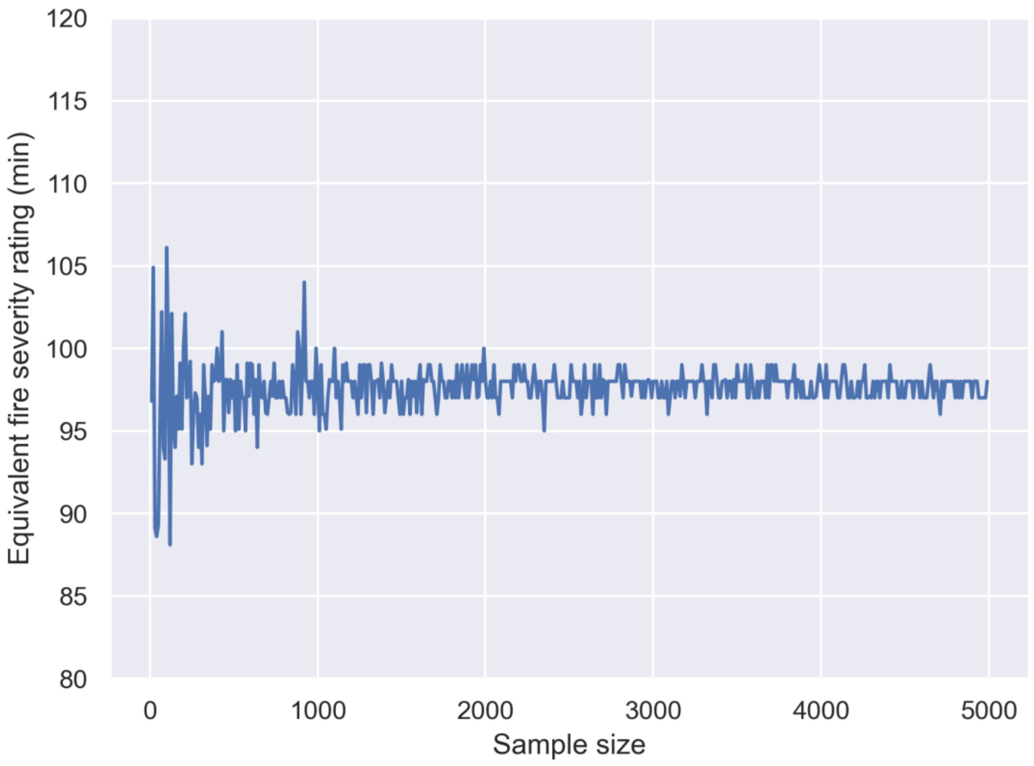


Dealing with low–confidence range input:

- ➢ Uniform distribution is appropriate in absence of further evidence as it conveys the least amount of additional assumptions
- ➢ Sensitivity study with a contra - assumption (e.g. weighted distribution) recommended to explore the consequences of uniform assumption being wrong.

Sample size

ARUP



All outputs of a probabilistic study are also random variables.

Low sample size reduces confidence in the final result:

Consider increasing sample size when:

- Working with high (>0.9) percentile risk targets
- Output sensitive inputs can likely return extreme values (e.g. unbounded thin tailed distributions)

Guidance on selecting right sample size:

- Rules of thumb: variance $\propto \sqrt{n}$
- PD 7974 – 7 section 6.2.5
- Numerical methods (e.g. bootstrapping)

Strategies and Techniques

ARUP

Structural Appraisal

- *Building design at locations where performance risk target is adopted should align with all assumptions of the analysis*
- Guidance on limiting temperature
- Consider introducing additional redundancy for structural members:
  - ➢ Supporting firefighting shafts and risers containing fire safety systems
  - ➢ Which are critical for stability (e.g. transfer beams)
- Coordination exercise between architect, structural engineer, and fire engineer

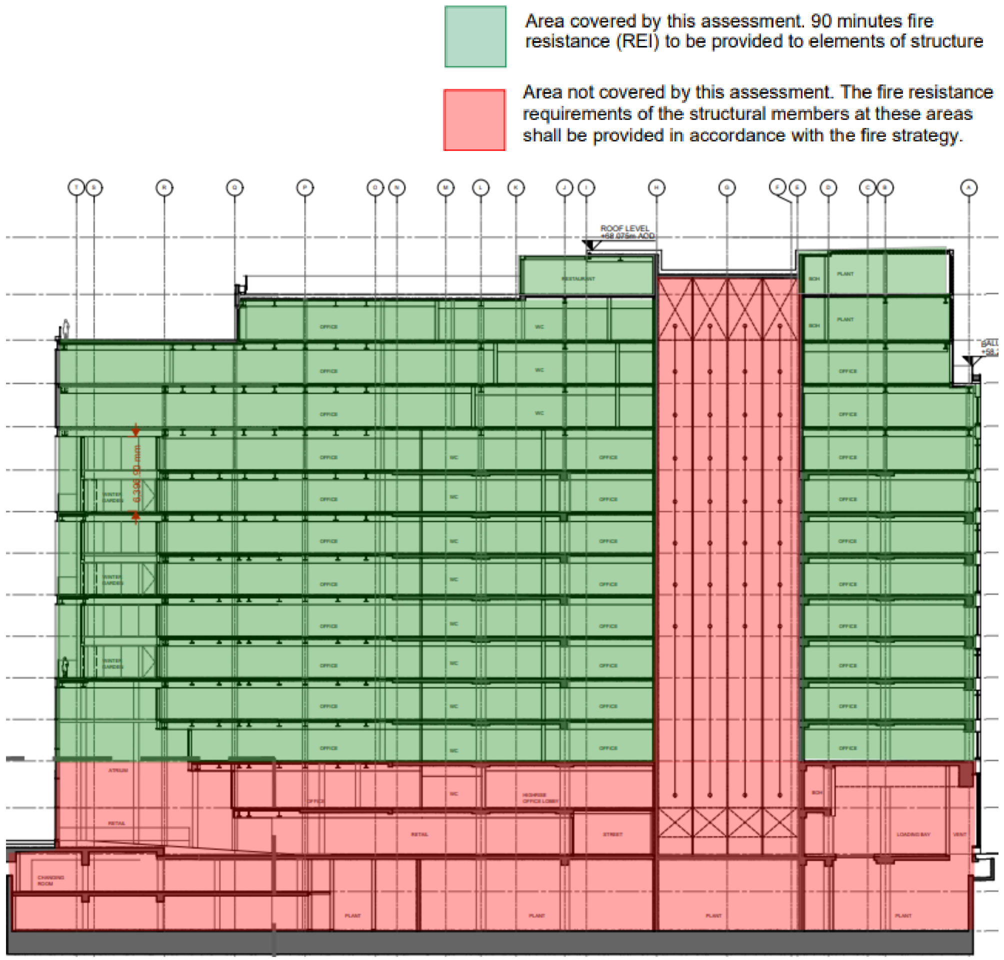
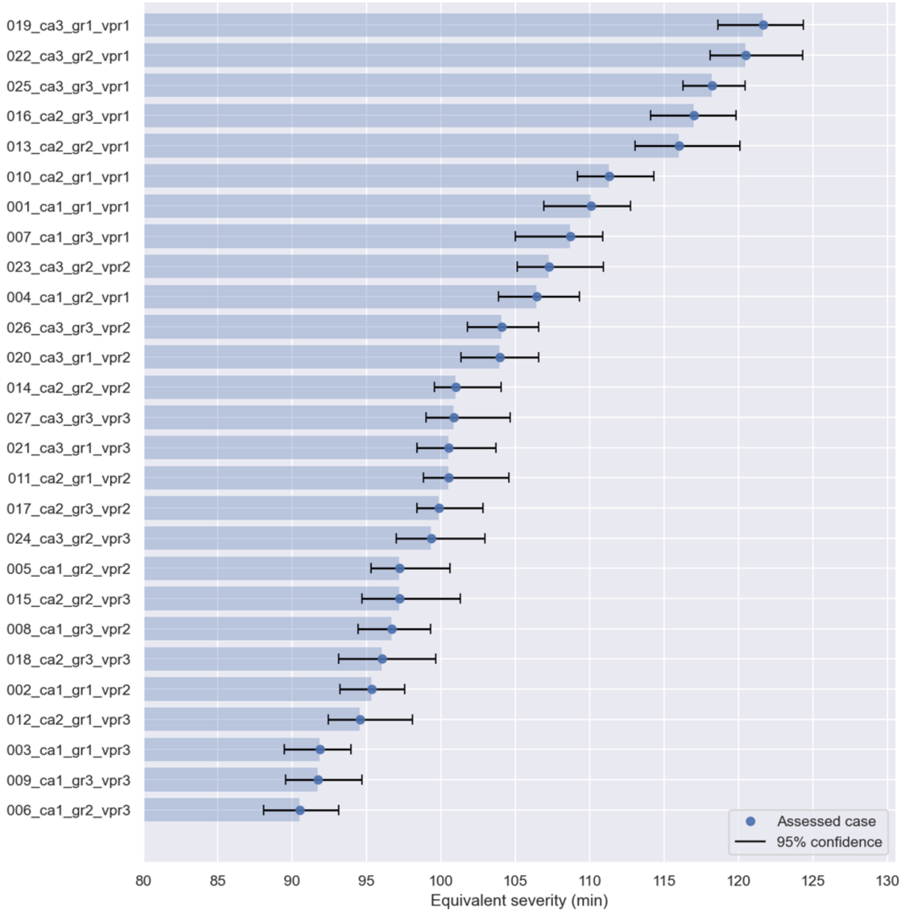
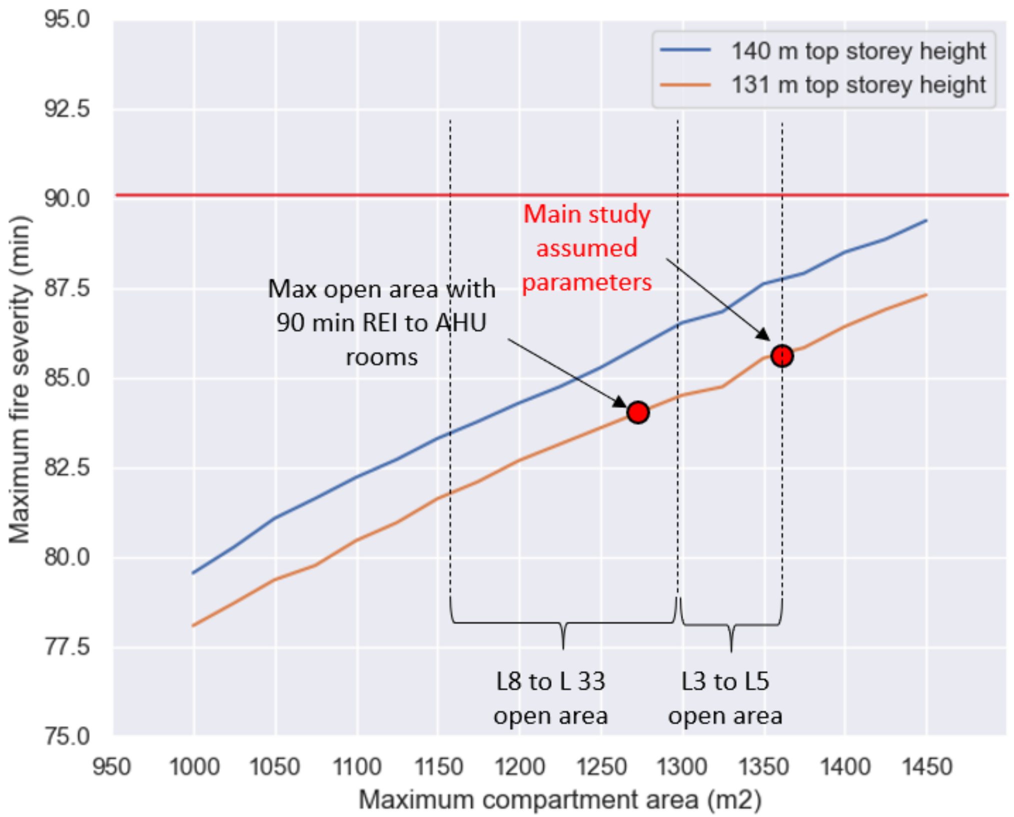


Figure shows building areas where fire severity assessment has been applied

Detailed Sensitivity Studies

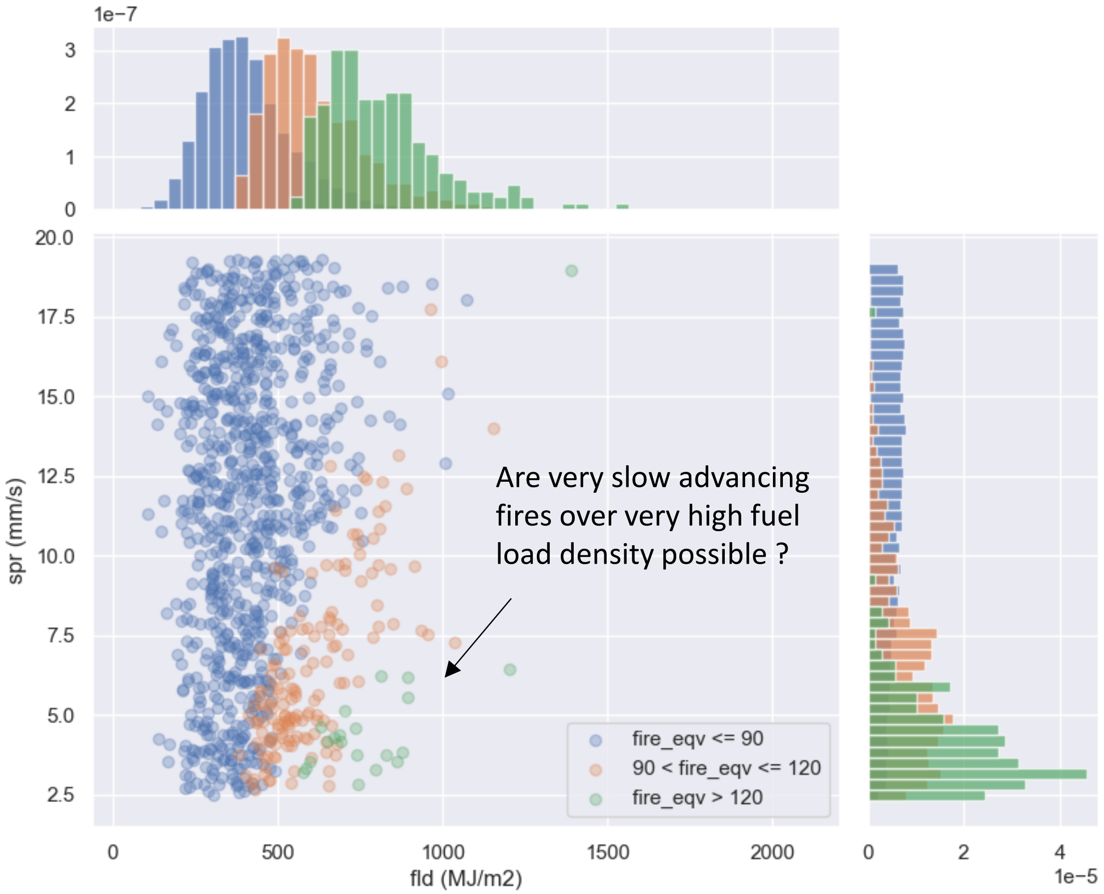


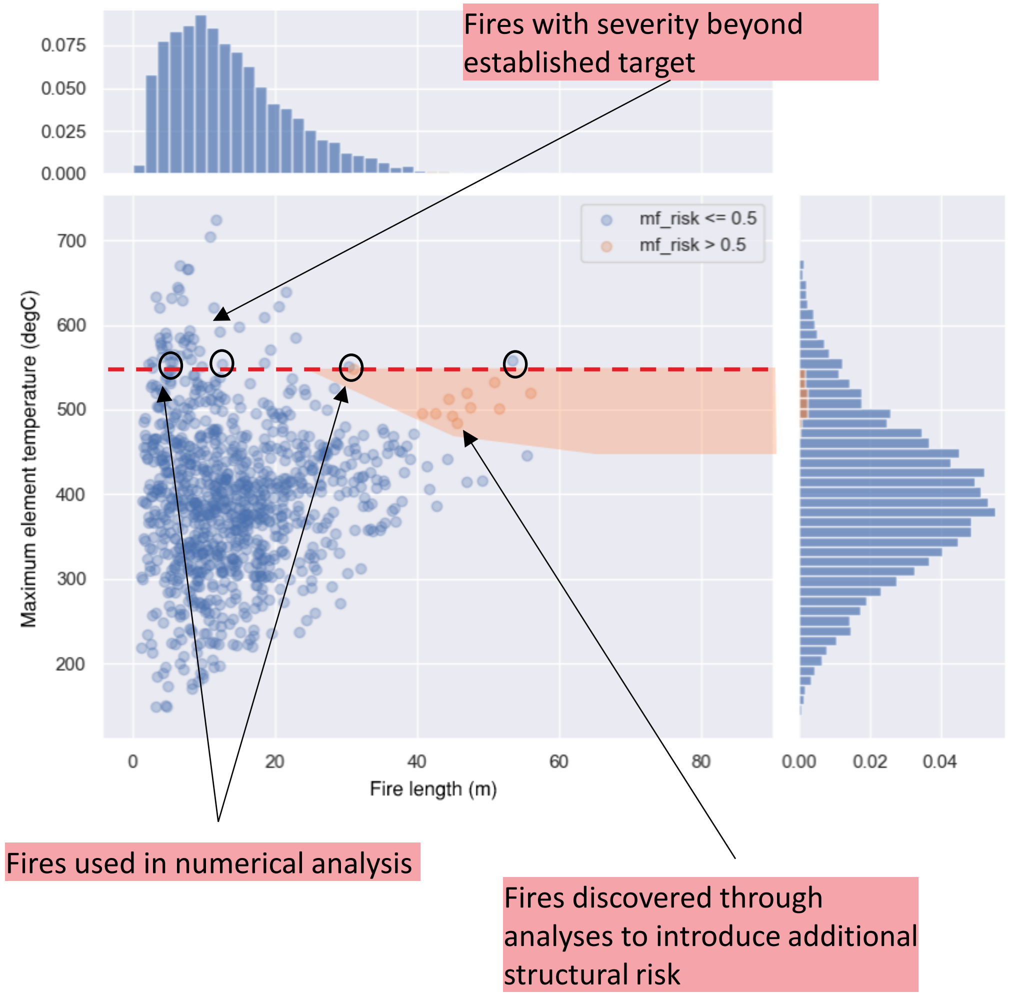
Grid type sensitivity study exploring all combinations between weighted parameters



Project bespoke study exploring sensitivity to critical design parameters in early stages of design

Dataset Exploration

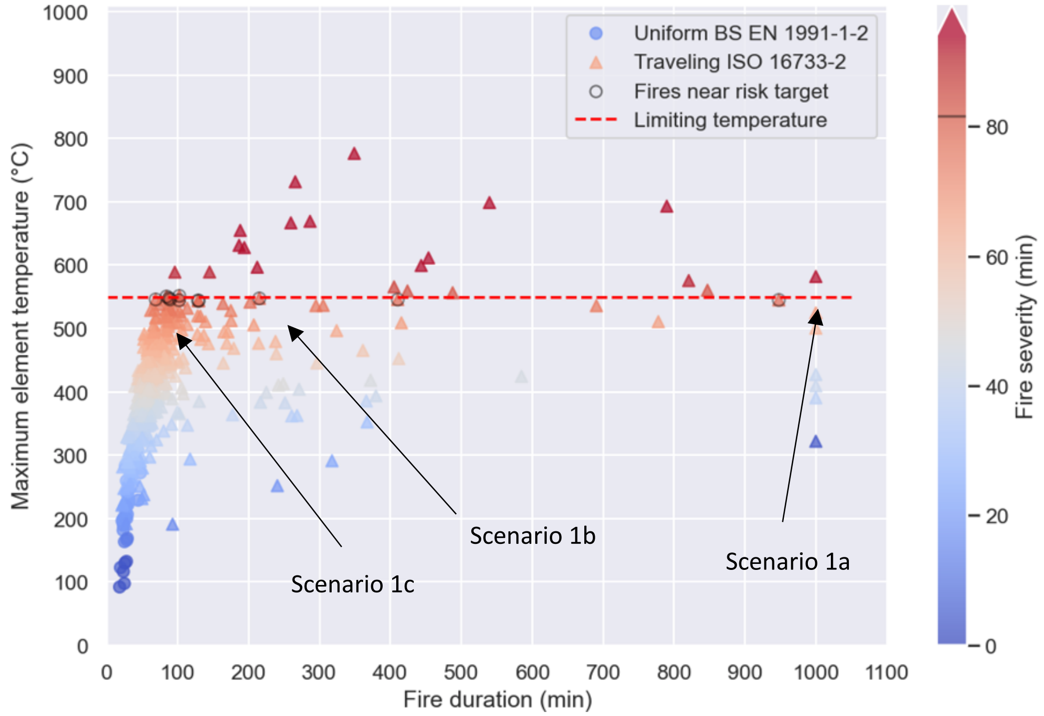


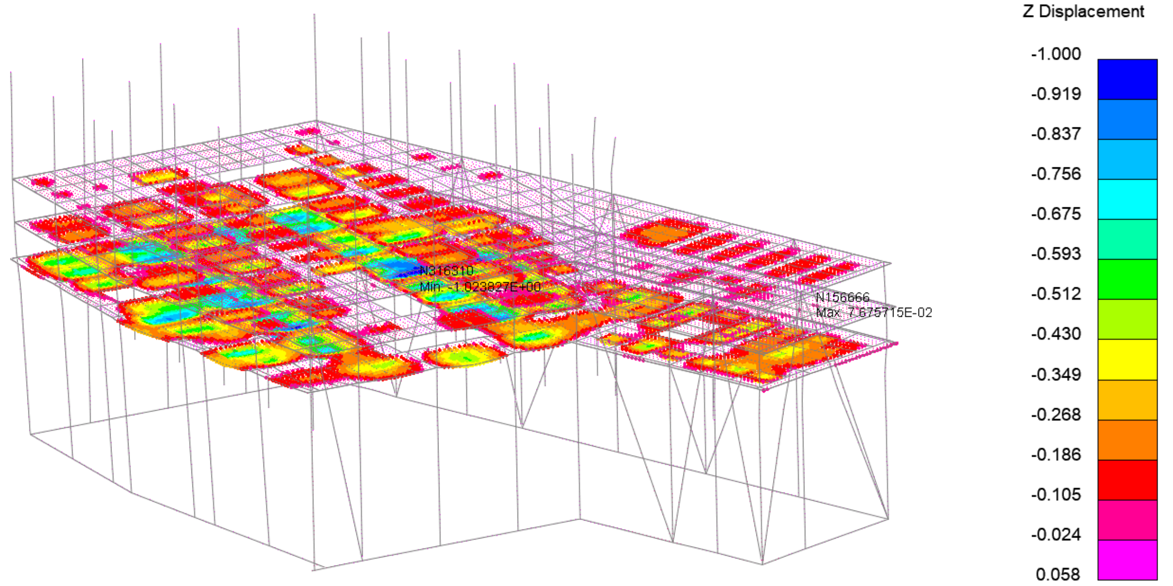


Advanced SFE Analysis

ARUP

Overview





- Boundary conditions based on representative design fires
- Allows for bespoke design of individual members capturing full floorplate performance

ARUP

Conclusions and Recommendations

- Fire severity analysis method is based on simple individual models but grouped together to produce a complex system

- Caution is advised when assessing high risk targets:
    - Review *all* assumptions to align with proposed design intent
    - Conduct extensive sensitivity and dataset exploration studies to confirm analysis robustness
    - Conduct a structural appraisal

- Current implementations likely not be suitable for risk targets higher than 0.95 due to reduced confidence in results

- Always review the numerical outputs in the context of the overall fire and structural design to provide the optimal design specification

ARUP