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Sensitivity and uncertainty analysis of consequence models

Adrian Kelsey and Simon Gant

30th November and 1st December 2016

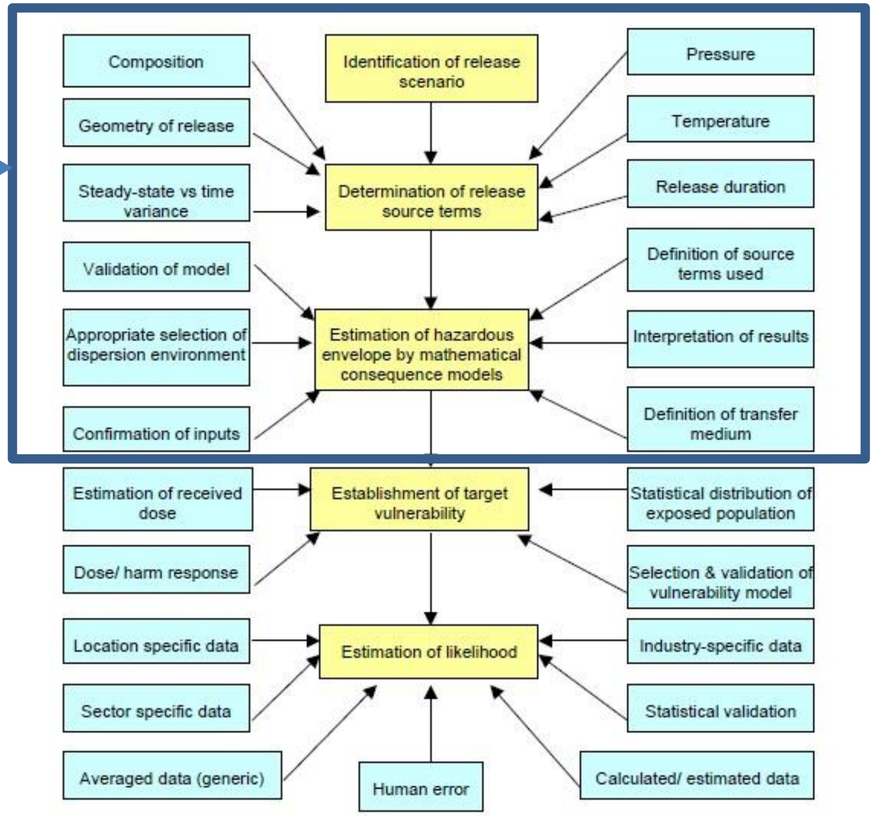
Outline

- Background
- Sensitivity analysis of models
  - Local
  - Global
- Examples
- Conclusions
- Future directions

Background

Consequence modelling

Figure 8: Some sources of risk assessment uncertainty



Guidance on Risk Assessment for Offshore Installations
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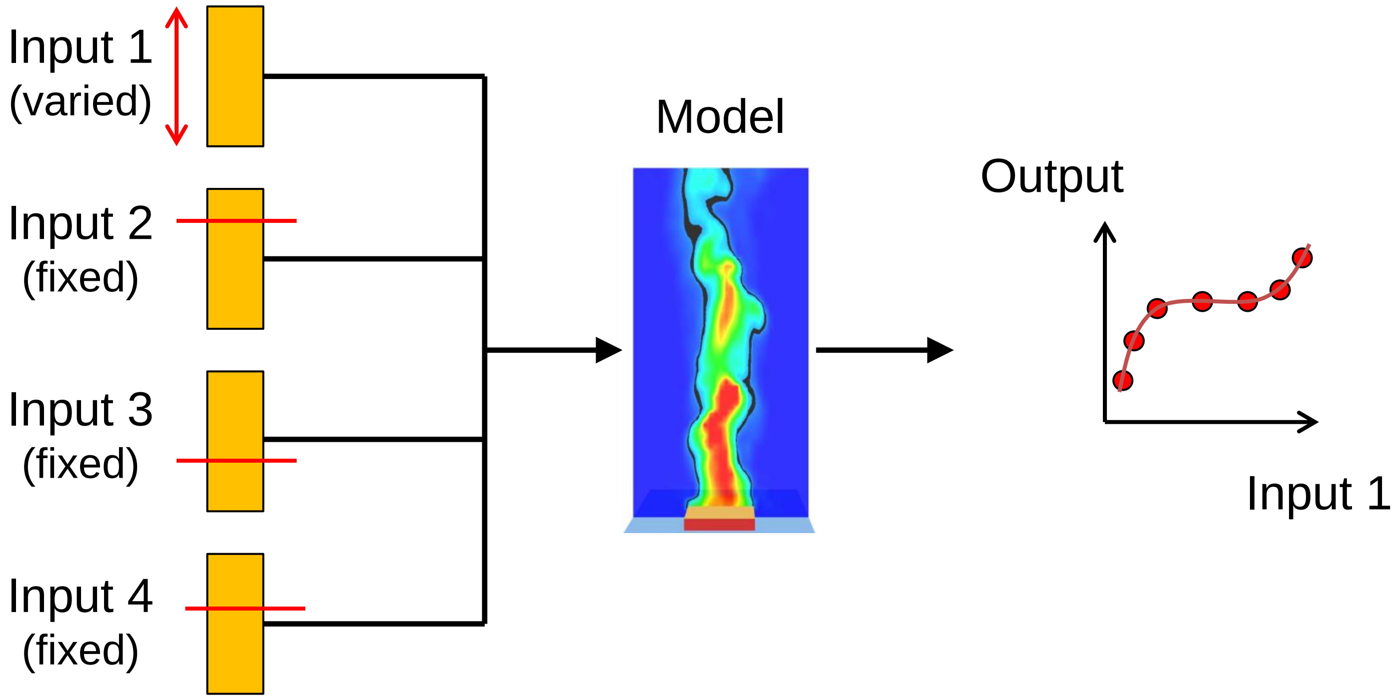
Background

- Consequence models for gas dispersion/fires/explosions have inputs which are often uncertain
  - e.g. gas pressure, hole size, wind speed
- Useful to know:
  - Which inputs have a significant effect on the results
  - How the model results change as the inputs change
  - What combination of inputs gives the worst-case consequence
- Benefits:
  - Prioritise efforts on the most sensitive inputs
  - Improved understanding of the problem




Sensitivity Analysis

- Two approaches for sensitivity analysis:
  1. **Local**: vary one parameter at a time from a "baseline" case



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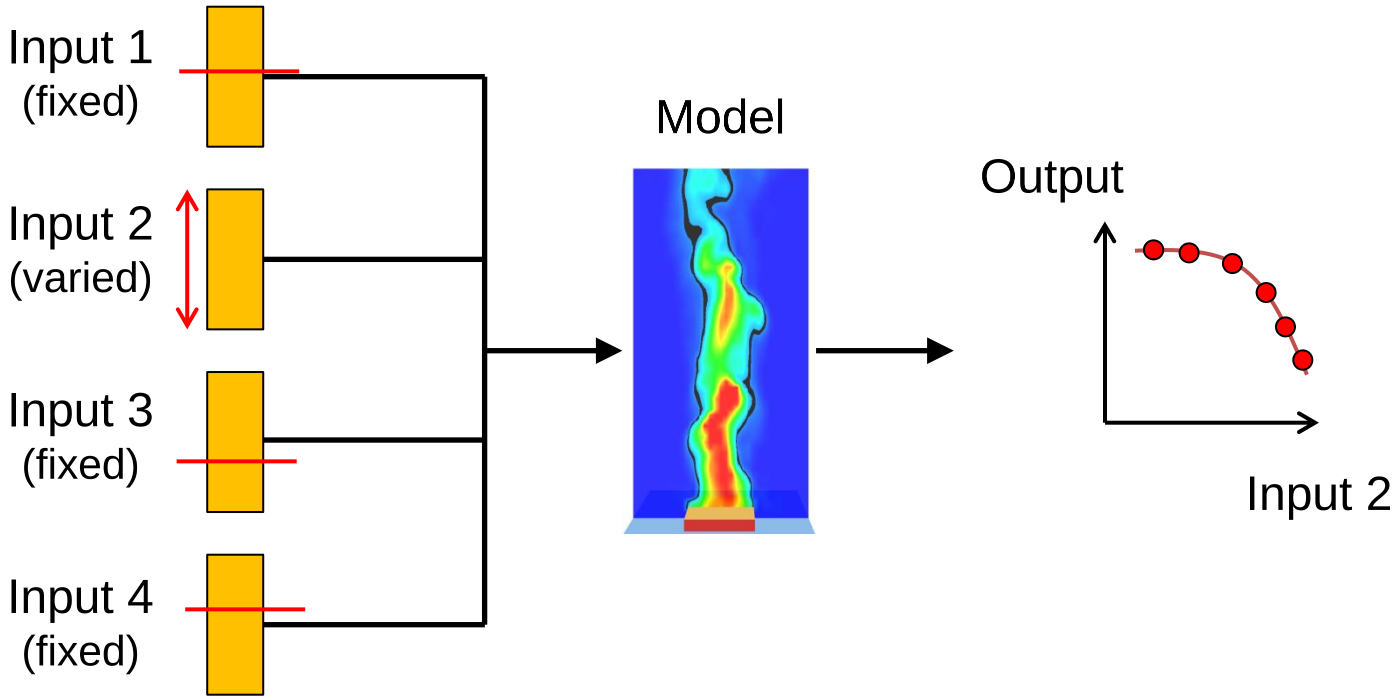

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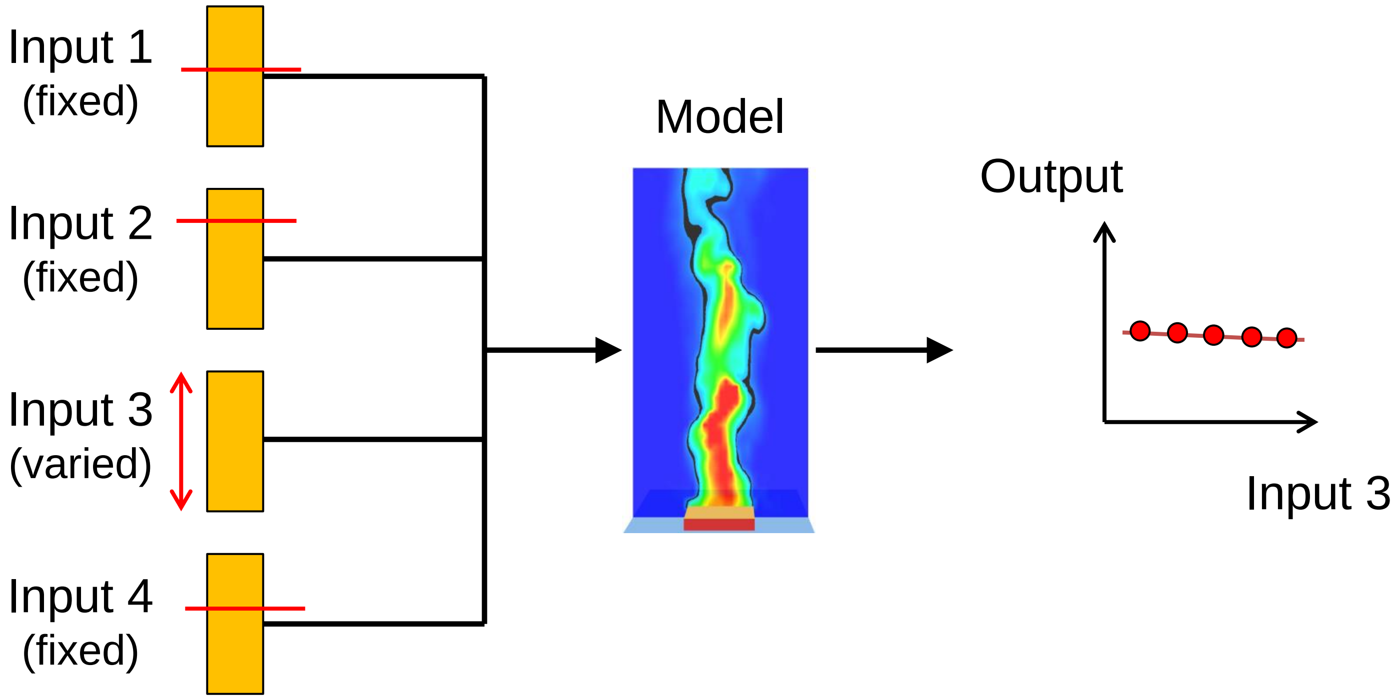

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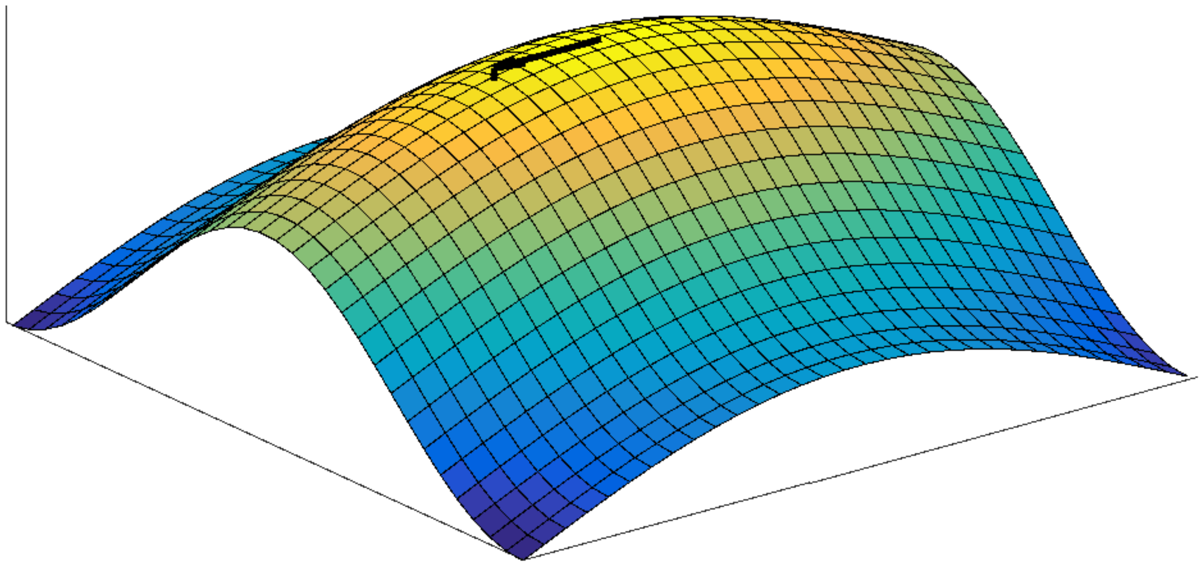

- Limitations:
  - No information provided on interactions between inputs

Sensitivity Analysis

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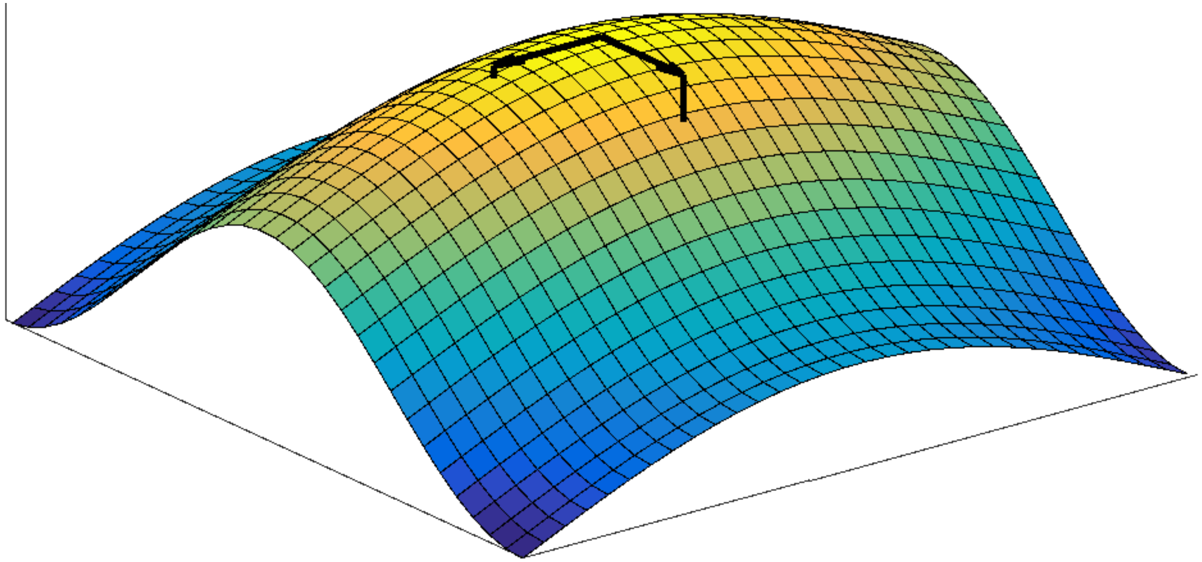

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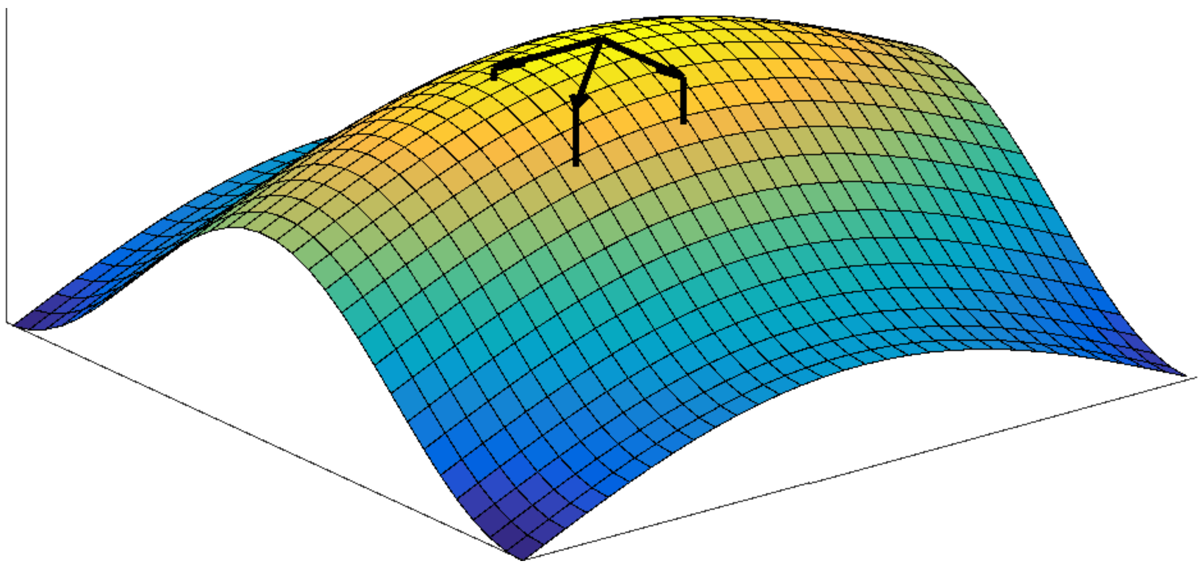

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Sensitivity Analysis

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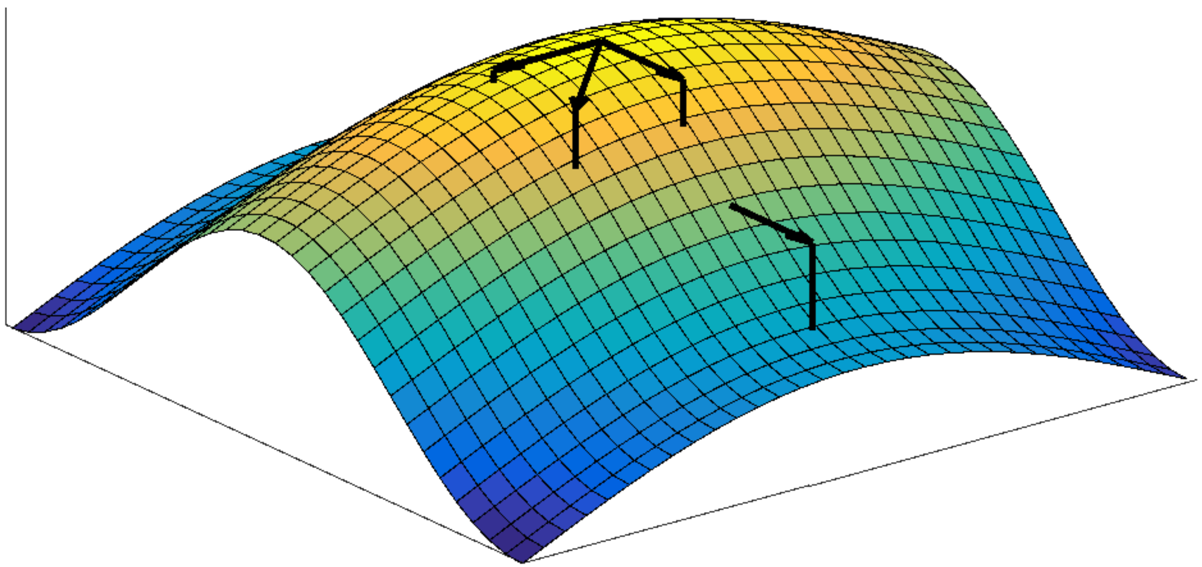

- Limitations:
  – No information provided on interactions between inputs
  – Results depend upon choice of baseline

Sensitivity Analysis

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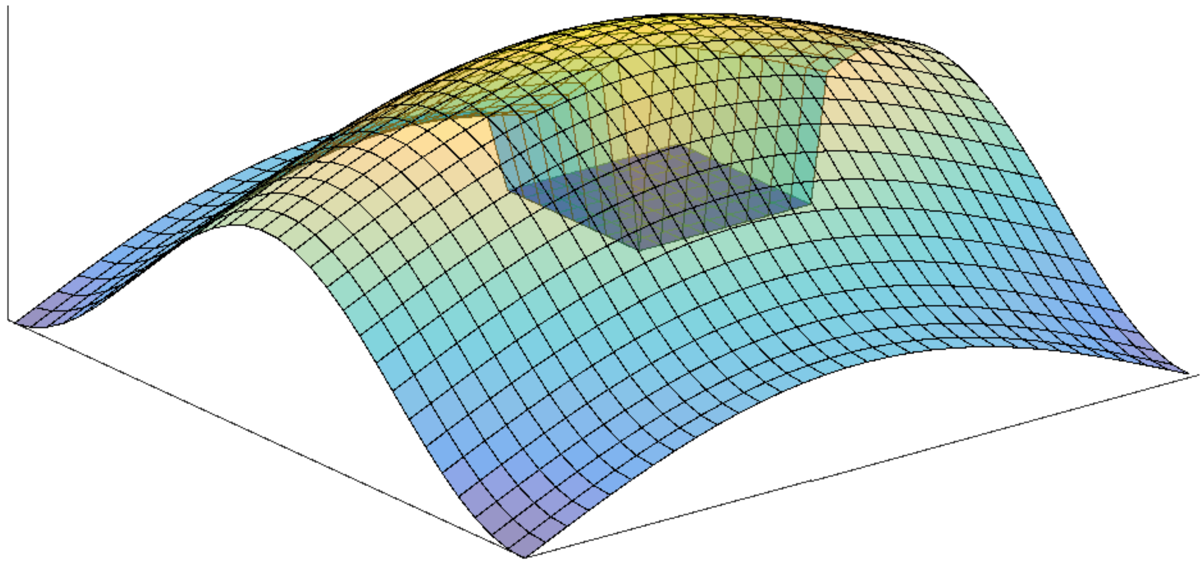
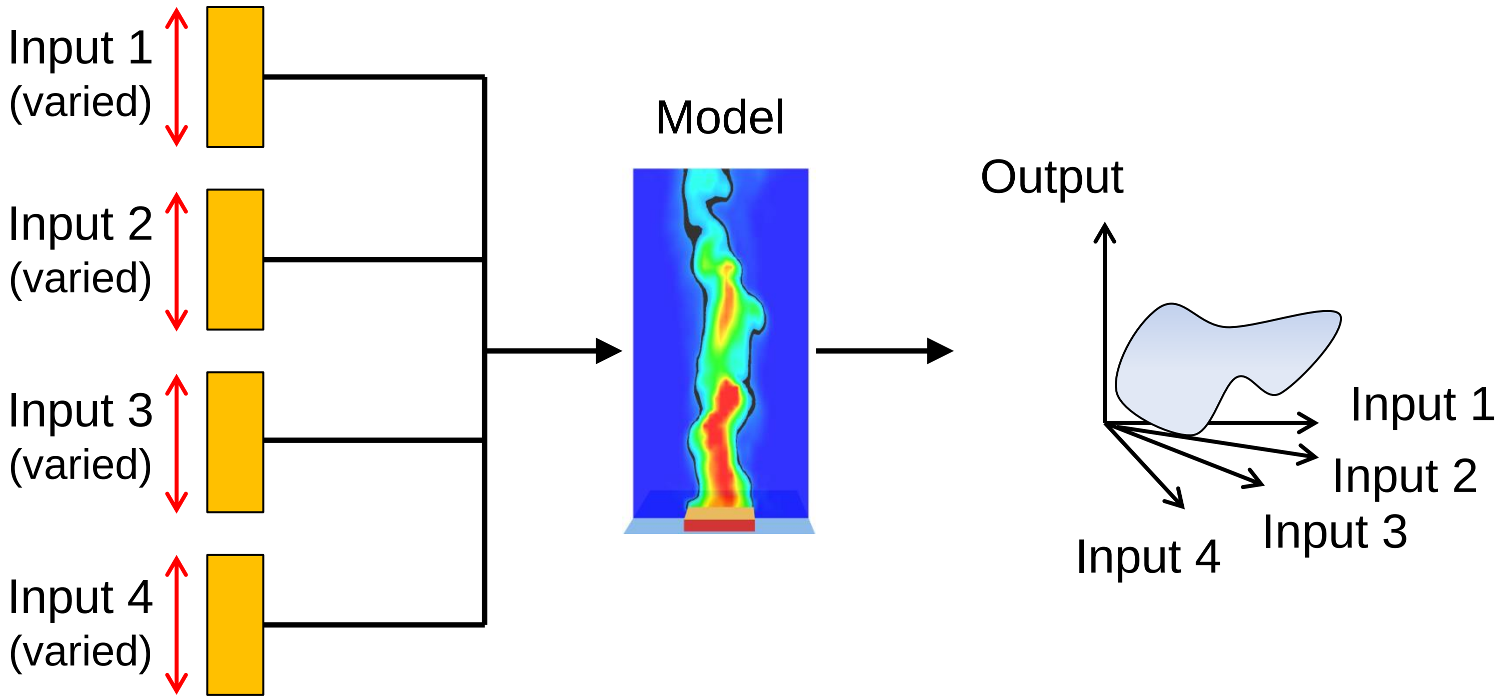


- Limitations:
  - No information provided on interactions between inputs
  - Results depend upon choice of baseline
  - Analysis may miss important effects (e.g. cliff edges)

Sensitivity Analysis

- Two approaches for sensitivity analysis:
  1. **Local**: vary one parameter at a time from a "baseline" case
  2. **Global**: vary all parameters simultaneously



Sensitivity Analysis

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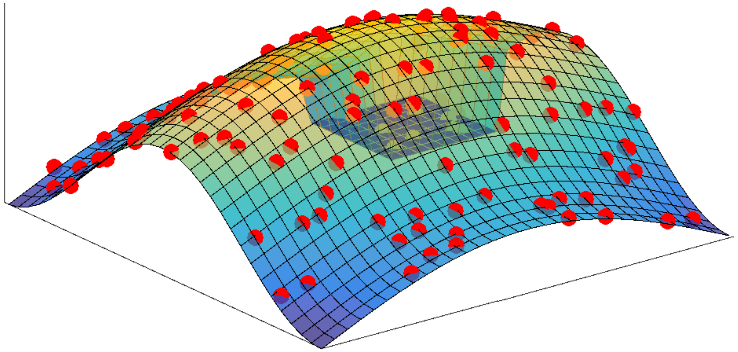

- Benefits:
  - Results do not depend upon choice of baseline
  - Information provided on interactions between inputs
- Problem:
  - Many thousands of model calculations required to cover combinations of all inputs
  - Computing time can be prohibitive

Solution: emulators

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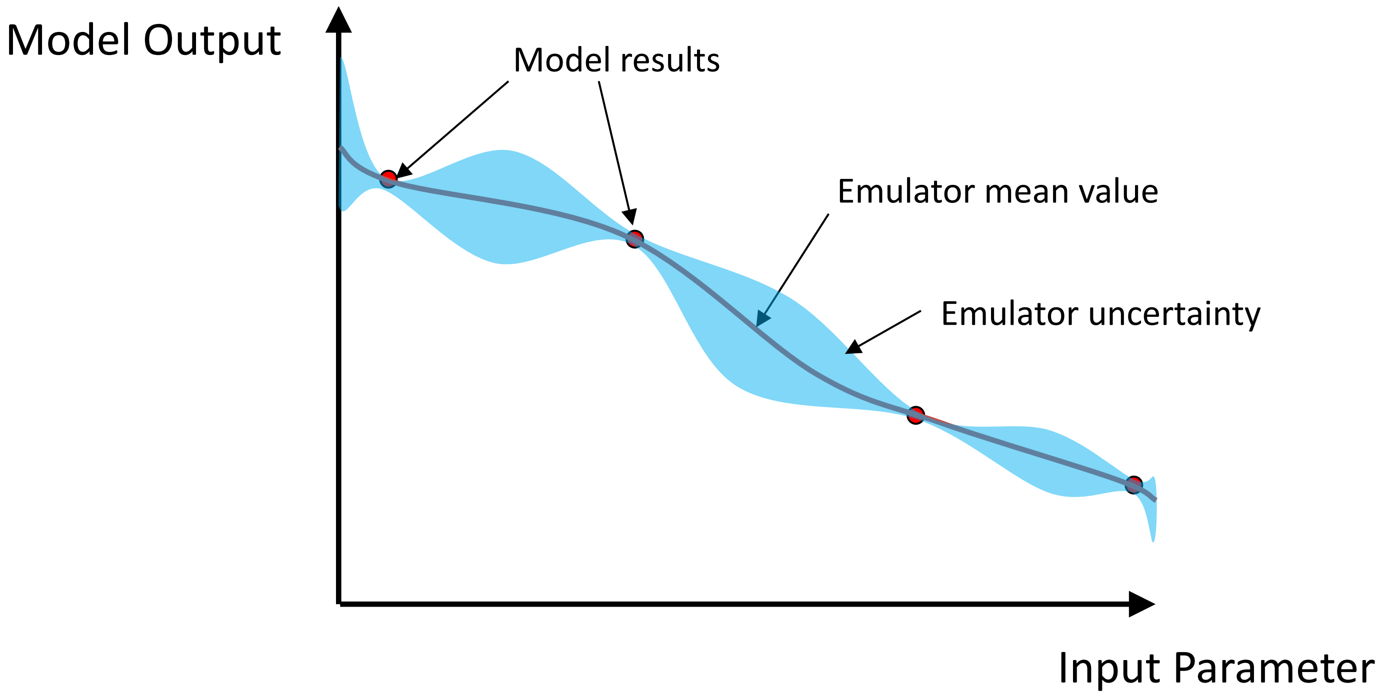
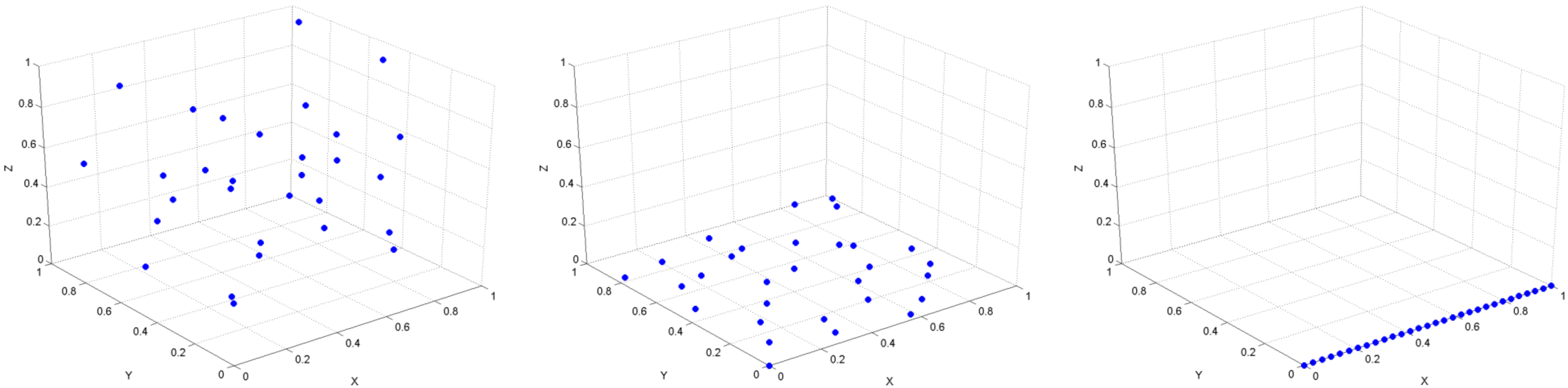
- Fit a statistical emulator to a few hundred model results
- Run the sensitivity analysis using the emulator (much faster)



- Underlying assumption of emulator: output is a smooth, continuous function of the input parameters

Maximin Latin Hypercube

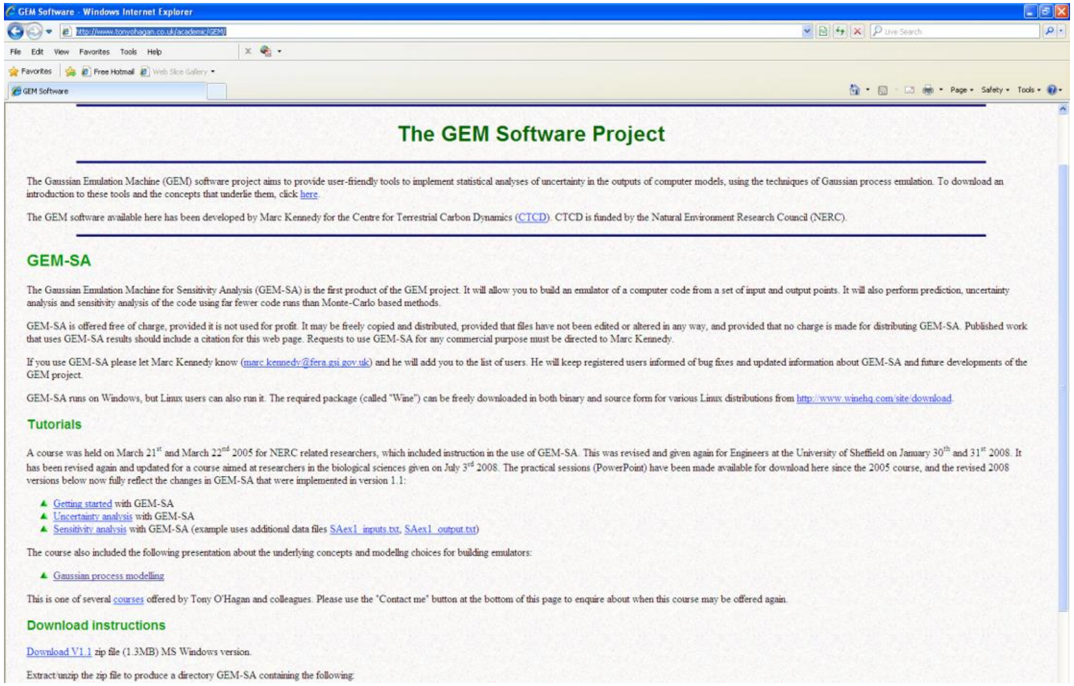
- Example: 3 input variables, 30 samples



- If Parameters Y and Z had no effect on the results, all 30 samples are equispaced across Parameter X sample space
- Often, just 1 or 2 input parameters dominate model predictions : Latin hypercube maximises coverage from limited number of points

Sensitivity Analysis: GEM

- Gaussian Emulation Machine (GEM)
- Free software (for non-commercial use) developed by Marc Kennedy and colleagues at Sheffield University http://www.tonyohagan.co.uk/academic/GEM/



The GEM Software Project

The Gaussian Emulation Machine (GEM) software project aims to provide user-friendly tools to implement statistical analyses of uncertainty in the outputs of computer models, using the techniques of Gaussian process emulation. To download an introduction to these tools and the concepts that underlie them, click here.

The GEM software available here has been developed by Marc Kennedy for the Centre for Terrestrial Carbon Dynamics (CTCD). CTCD is funded by the Natural Environment Research Council (NERC).

GEM-SA

The Gaussian Emulation Machine for Sensitivity Analysis (GEM-SA) is the first product of the GEM project. It will allow you to build an emulator of a computer code from a set of input and output points. It will also perform prediction, uncertainty analysis and sensitivity analysis of the code using far fewer code runs than Monte-Carlo based methods.

GEM-SA is offered free of charge, provided it is not used for profit. It may be freely copied and distributed, provided that files have not been edited or altered in any way, and provided that no charge is made for distributing GEM-SA. Published work that uses GEM-SA results should include a citation for this web page. Requests to use GEM-SA for any commercial purpose must be directed to Marc Kennedy.

If you use GEM-SA please let Marc Kennedy know (marc.kennedy@fera.gsi.gov.uk) and he will add you to the list of users. He will keep registered users informed of bug fixes and updated information about GEM-SA and future developments of the GEM project.

GEM-SA runs on Windows, but Linux users can also run it. The required package (called "Wine") can be freely downloaded in both binary and source form for various Linux distributions from http://www.winehq.com/site/download.

Tutorials

A course was held on March 21st and March 22nd 2005 for NERC related researchers, which included instruction in the use of GEM-SA. This was revised and given again for Engineers at the University of Sheffield on January 30th and 31st 2008. It has been revised again and updated for a course aimed at researchers in the biological sciences given on July 3rd 2008. The practical sessions (PowerPoint) have been made available for download here since the 2005 course, and the revised 2008 versions below now fully reflect the changes in GEM-SA that were implemented in version 1.1:

- Getting started with GEM-SA
- Uncertainty analysis with GEM-SA
- Sensitivity analysis with GEM-SA (example uses additional data files SAex1_inputs.txt, SAex1_output.txt)

The course also included the following presentation about the underlying concepts and modelling choices for building emulators:

- Gaussian process modelling

This is one of several courses offered by Tony O'Hagan and colleagues. Please use the "Contact me" button at the bottom of this page to enquire about when this course may be offered again.

Download instructions

Download V1.1 zip file (1.3MB) MS Windows version.

Extract/unzip the zip file to produce a directory GEM-SA containing the following:

Example: CO_2 release

- Which of these inputs (or combinations of inputs) has a significant effect on the results?

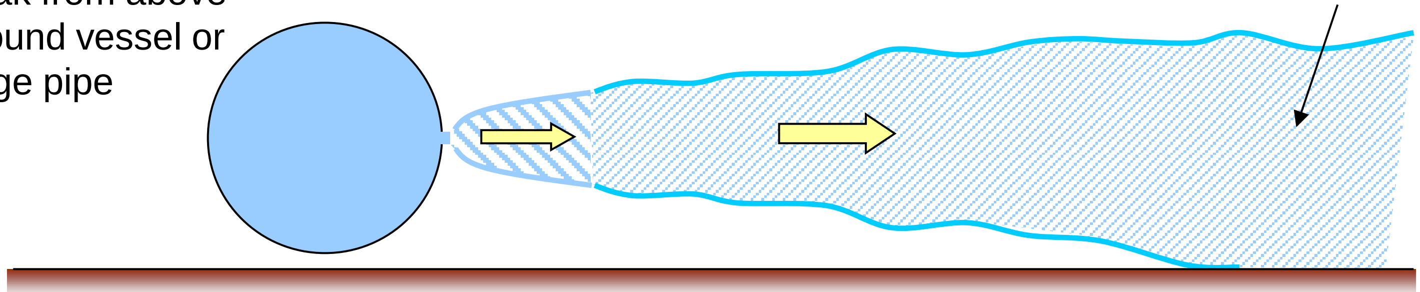
<u>Sample Inputs:</u>

1. Reservoir temperature: 5 – 30 ºC
2. Reservoir pressure: 100 – 150 barg
3. Orifice size: ½ – 2 inch
4. Wind speed: 0.5 – 50 m/s
5. Ambient humidity: 0 – 100% RH
6. Ground roughness: 0.0001 – 1 m
7. Release height: 0.5 – 3 m

Output of interest:

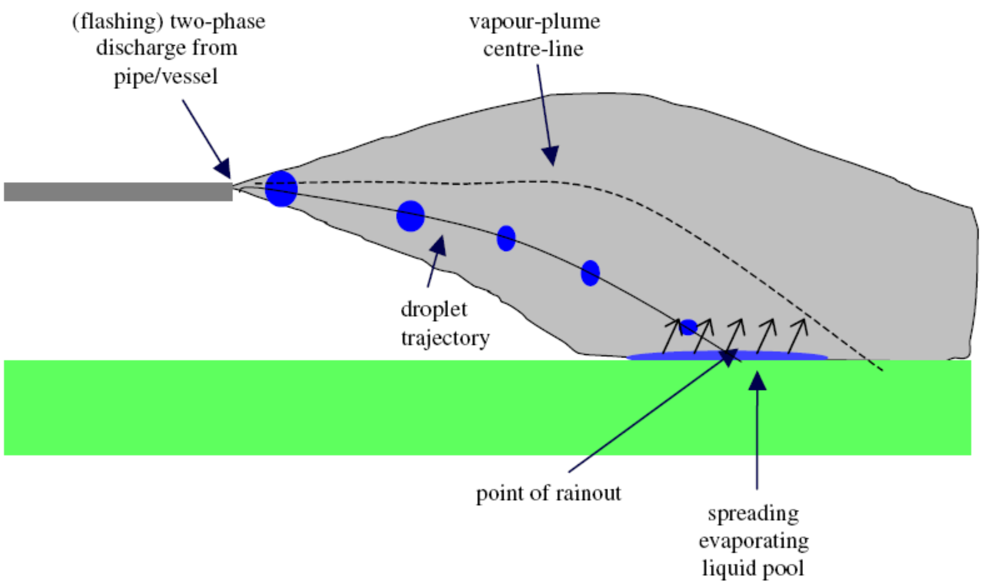
"Dispersion distance" where concentration reaches 6.9% v/v CO_2

Leak from above-ground vessel or large pipe



Consequence model: Phast

- Integral release and dispersion model produced by DNV-GL Software
- Validated against CO_2 dispersion experiments conducted by Shell and BP



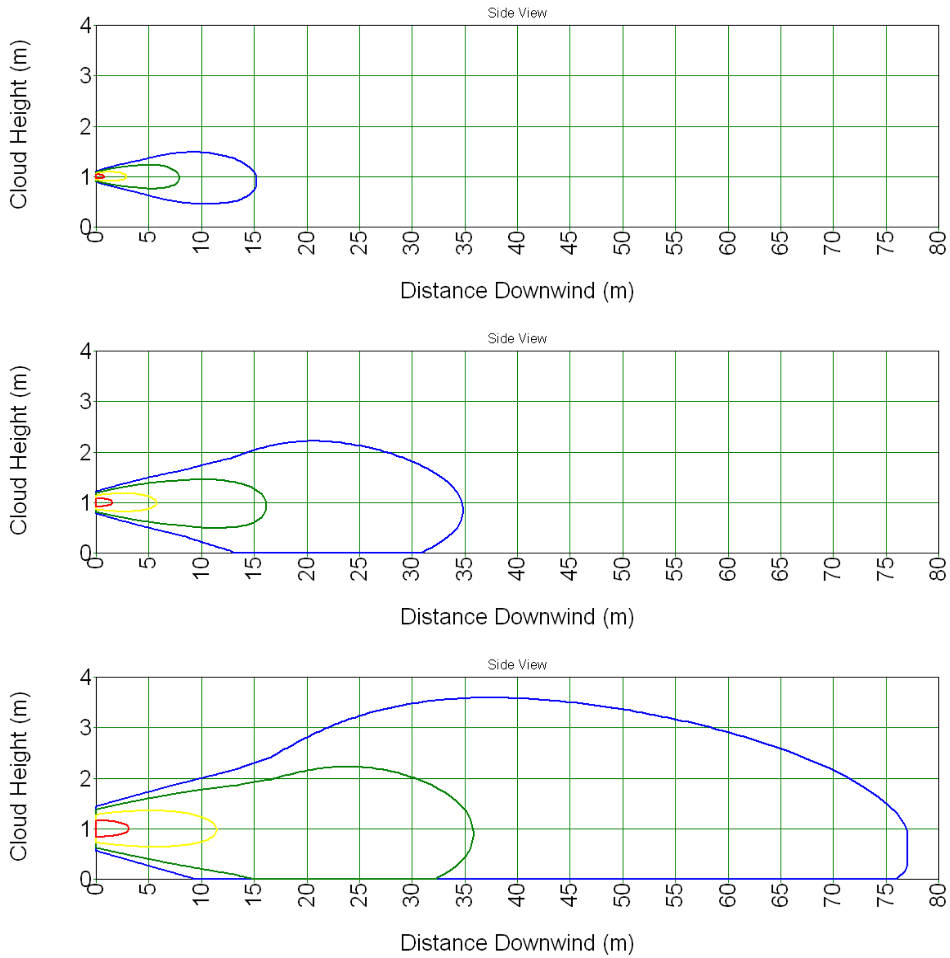
Phast results

Orifice diameter

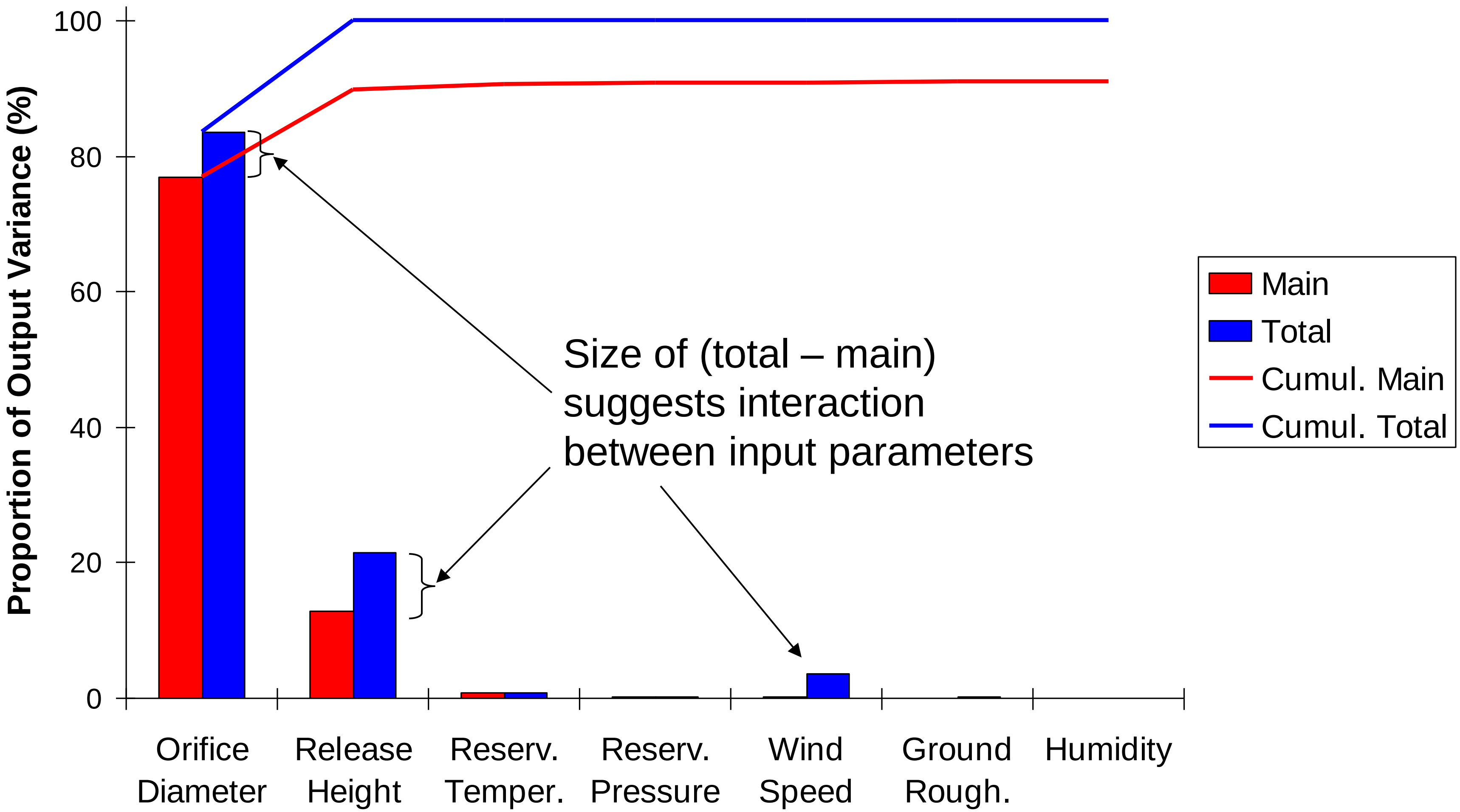
½ inch

1 inch

2 inch



Sensitivity analysis results



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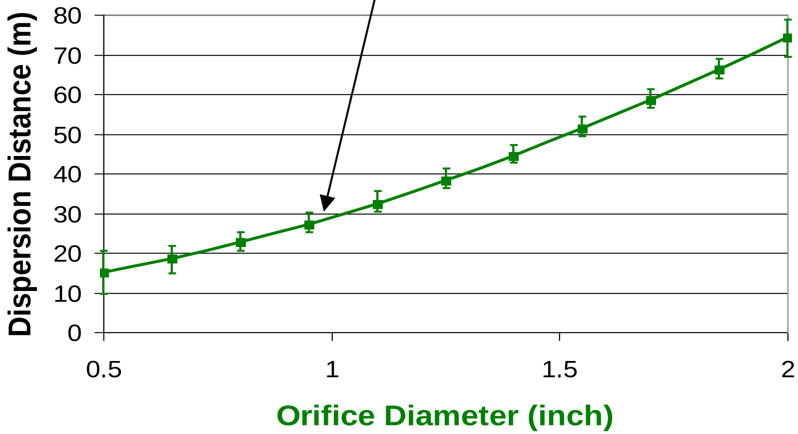
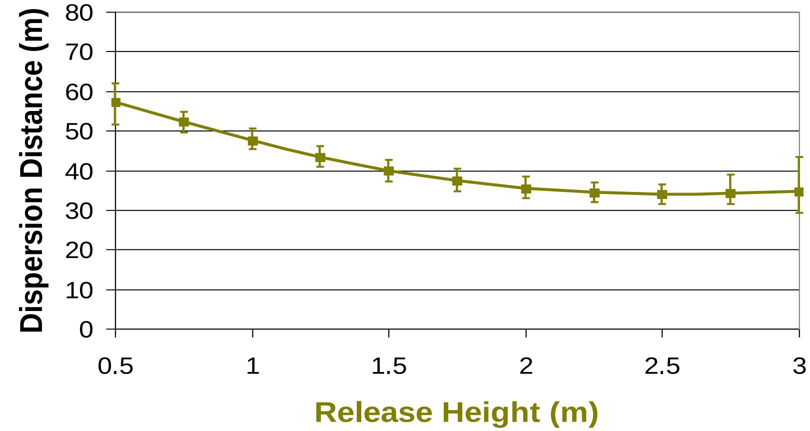
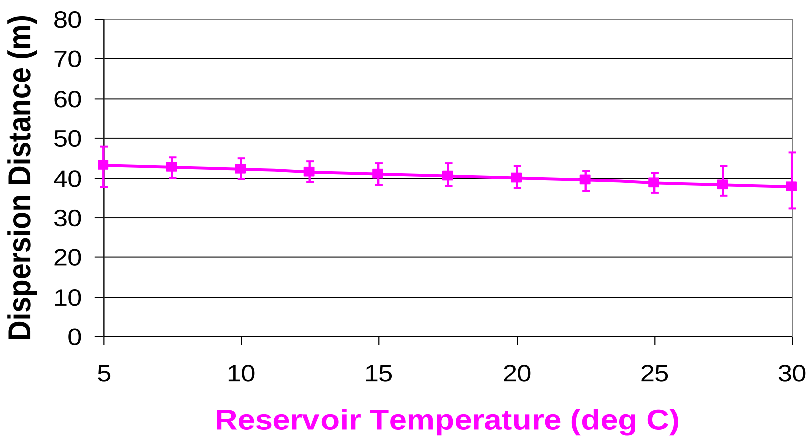
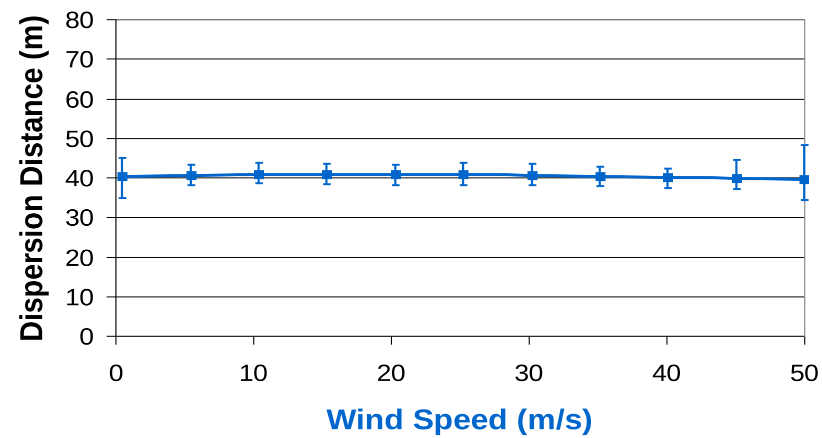
Model behaviour

e.g. fix orifice diameter at 1 inch and average over range of all other input parameters









Joint effects

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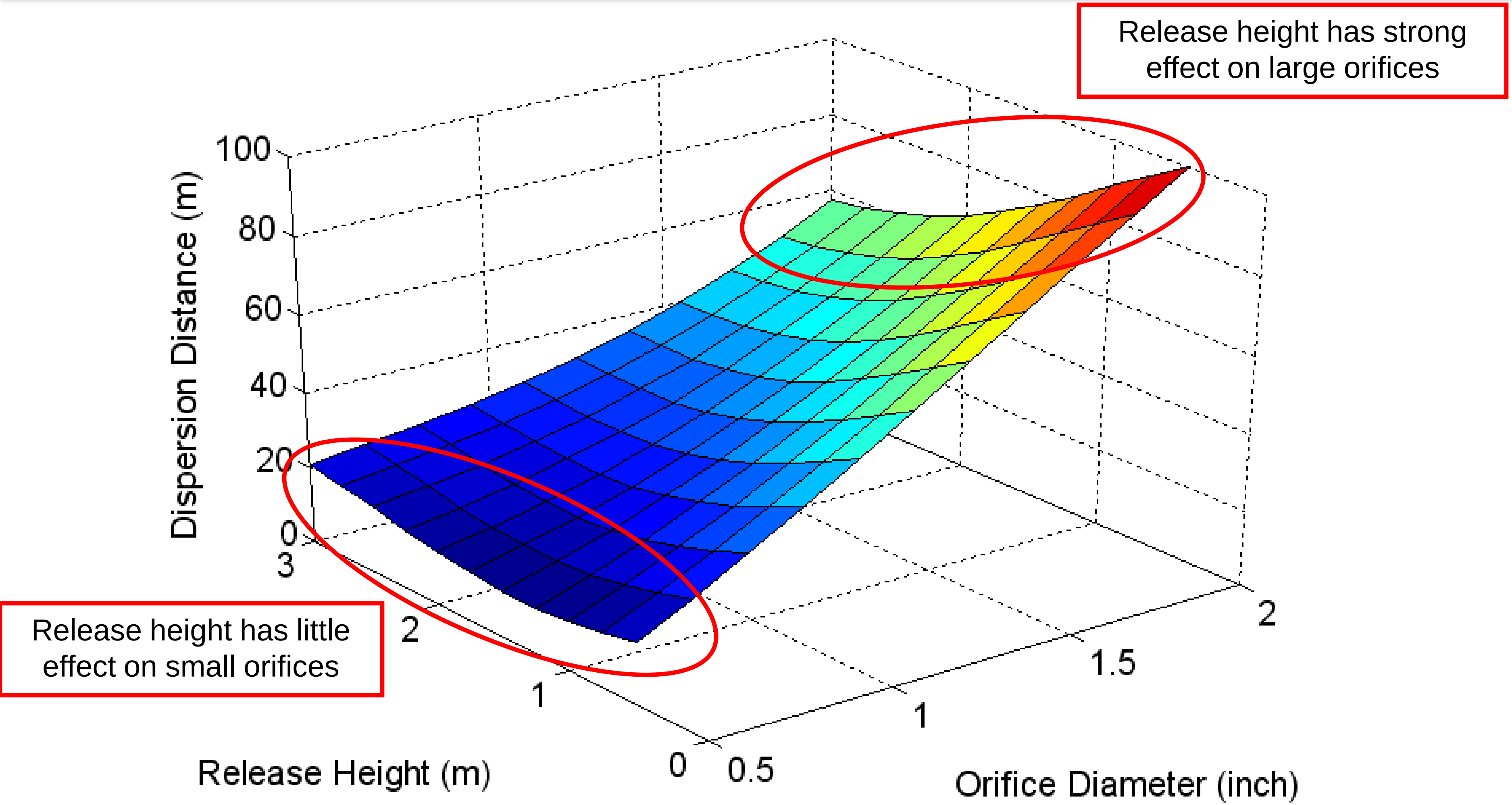
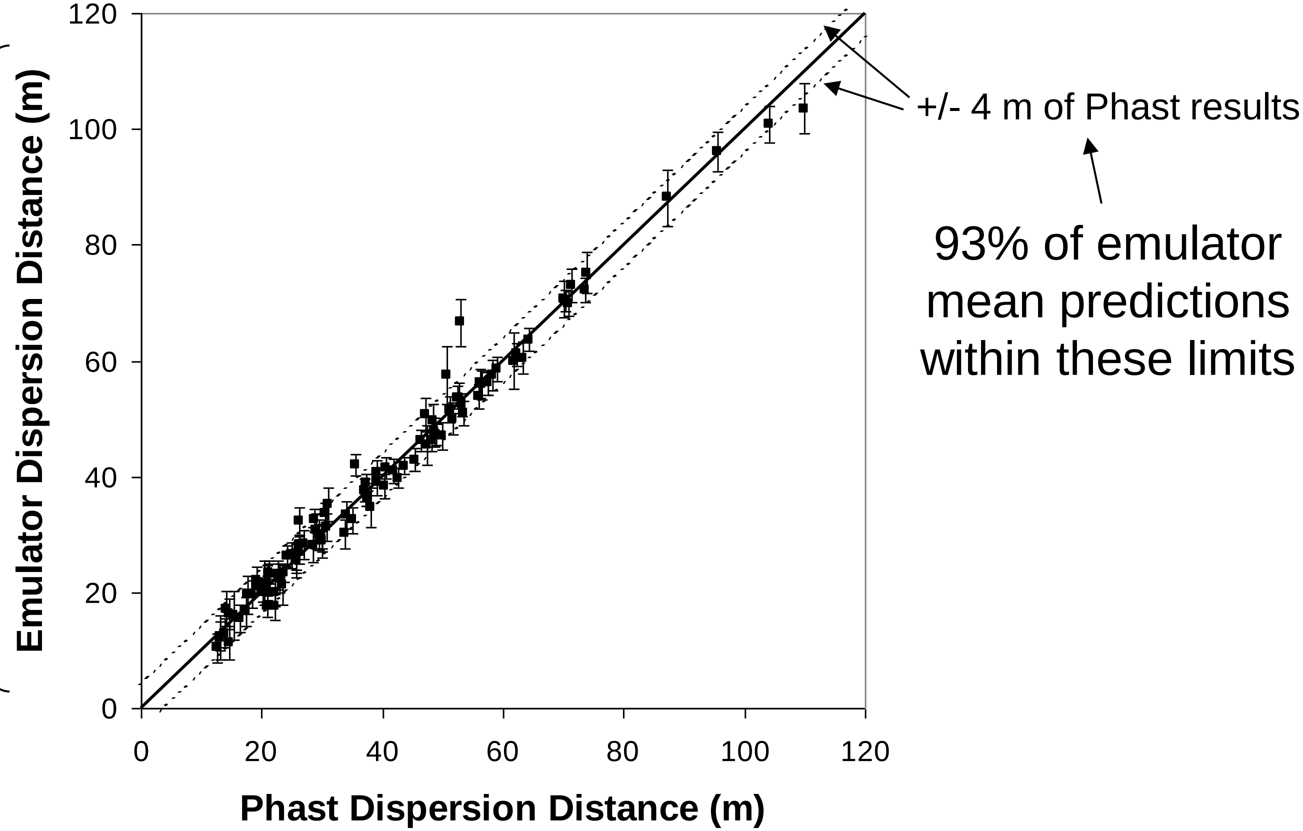


Emulator cross-validation

Emulator predictions of Phast results



- Adequate accuracy for the purposes of identifying model trends
- Analysis repeated with 400 Phast runs gave similar results

Example: LNG pool fires

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- Phoenix large-scale LNG pool fire experiments conducted by Sandia National Laboratories in 2009
- Two tests involved ignited LNG spills on water
  - 21 m diameter LNG pool
  - 83 m diameter LNG pool
- 83 m pool - unexpected results
  - Fire did not extend across LNG pool surface
  - Fire significantly higher than predicted
  - Very little smoke

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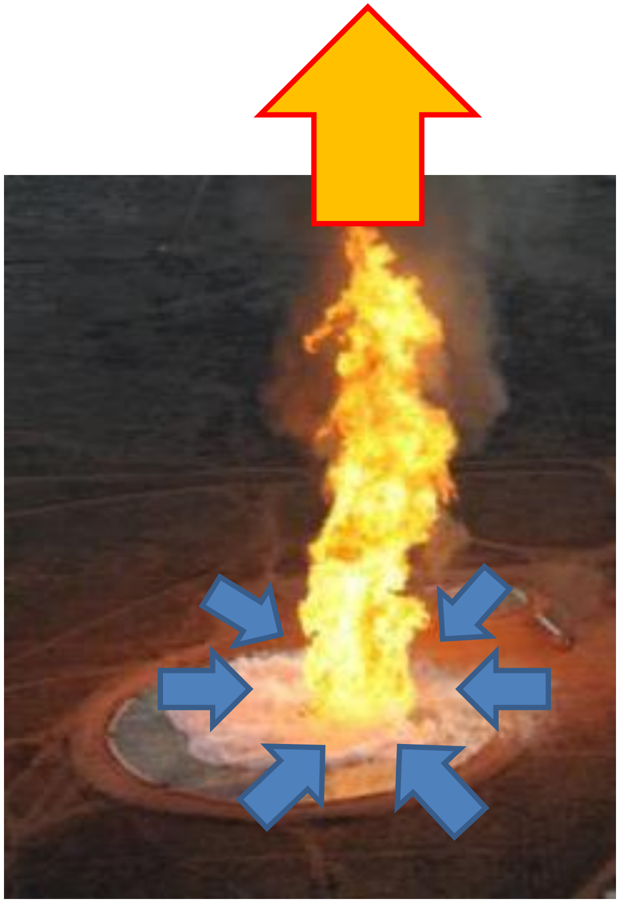
http://prod.sandia.gov/techlib/access-control.cgi/2010/108676.pdf

LNG pool fires: Background

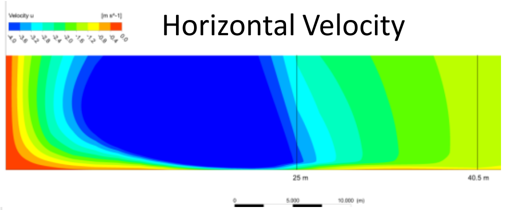
- Hypothesis (proposed by Shell Research Ltd)
  - Strong thermal updraft from large fire
  - High speed inwards flow of air/vapor into the base of the fire
  - Flames unable to spread outwards from central ignition location
- Video analysis
  - 2-3 m/s flow into base of fire
  - Sufficient to arrest flame spread?
- Investigation at HSL funded by Shell Research Ltd
  - CFD modelling
  - Flame spread experiments
- Sensitivity analysis funded by HSE

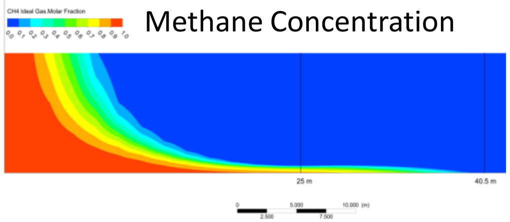


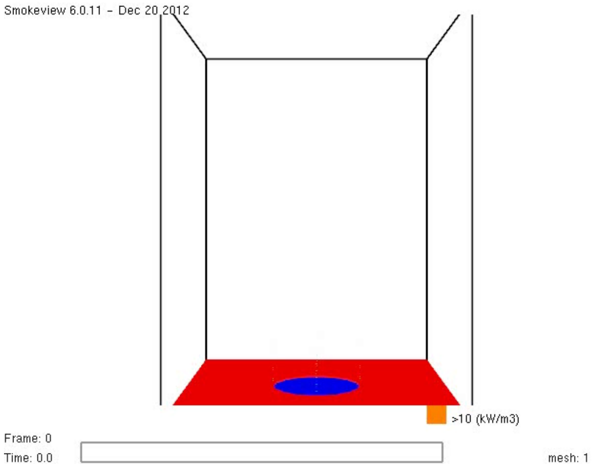
http://prod.sandia.gov/techlib/access-control.cgi/2010/108676.pdf

LNG pool fires: Modelling

- CFD modeling aim
  - To predict the speed of air/vapour entrained into the base of the fire in the Phoenix test
- CFD models tested
  - Ansys-CFX: volumetric heat source
  - FDS: combustion model
- Speed of entrained air/vapour flow
  - Ansys-CFX = 3.7 m/s
  - FDS = 3.2 m/s
- Phoenix test provides only one data point







LNG pool fires: Experiments

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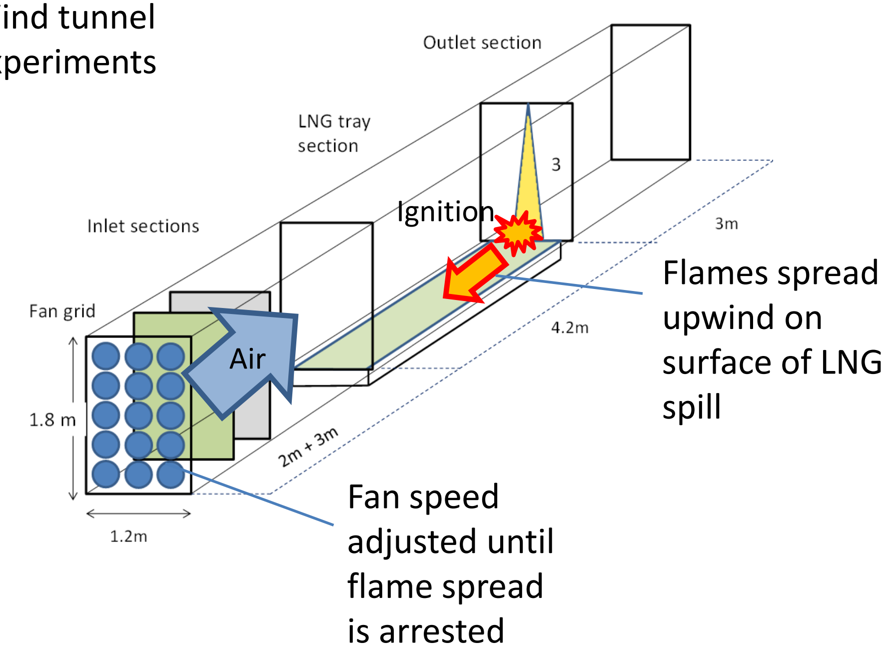
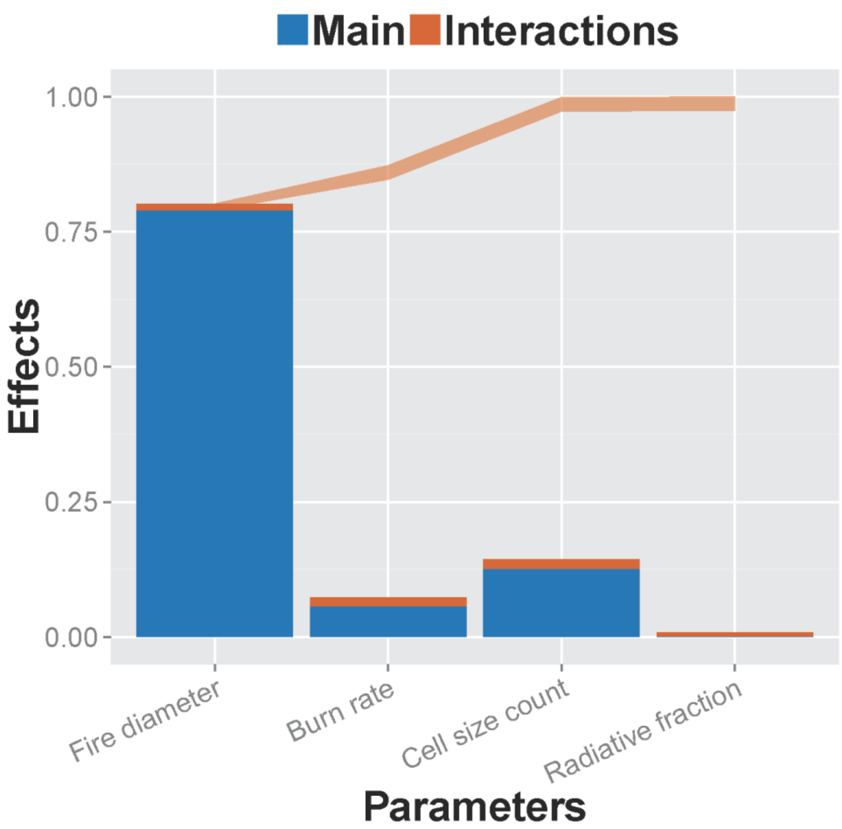
Wind tunnel experiments

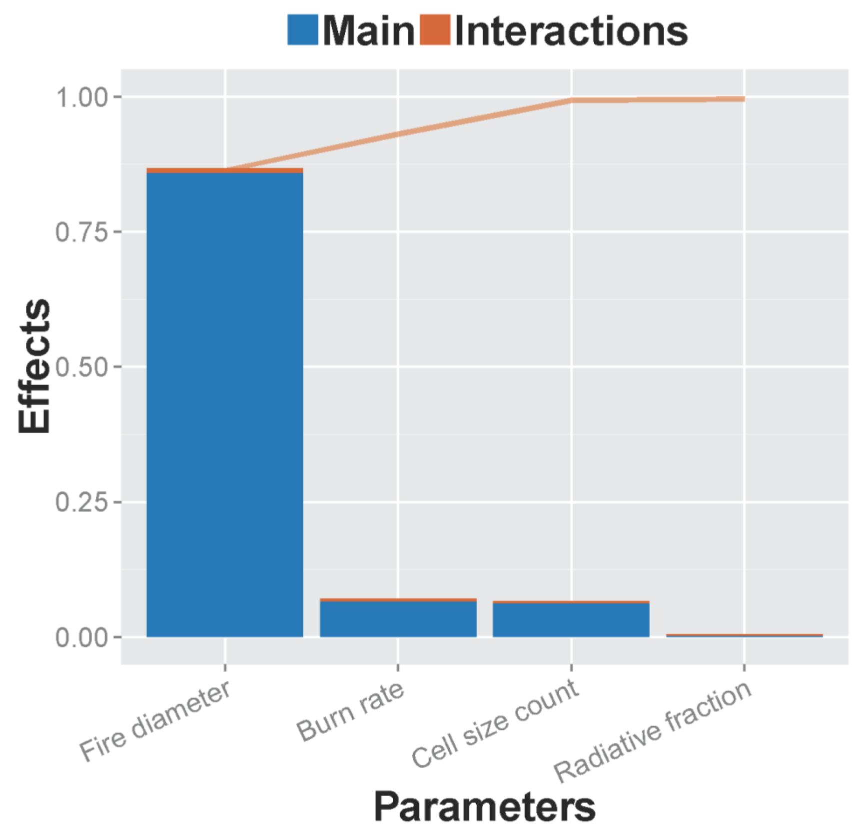


- Main findings
  - Flame stabilised when air flows were 2.8 and 3.2 m/s
  - Flame progressed further along low speed areas adjacent to walls
  - Stabilised conditions equated to turbulent flame speed of 2 m/s

LNG pool fires: Entrainment velocity sensitivity analysis

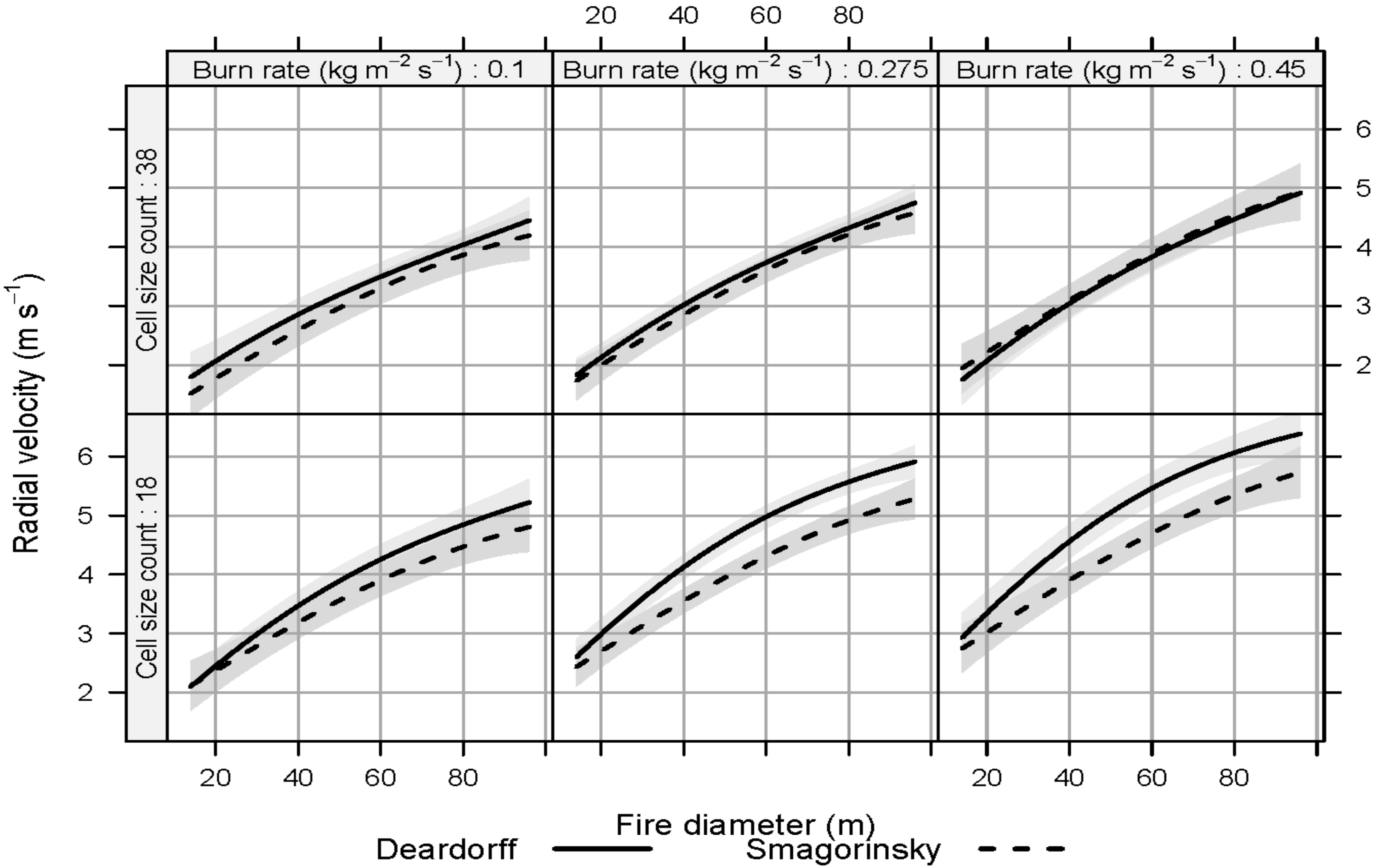


Deardorff turbulence model



Smagorinsky turbulence model

LNG pool fires: Entrainment velocity model behaviour



LNG pool fires: Sensitivity analysis

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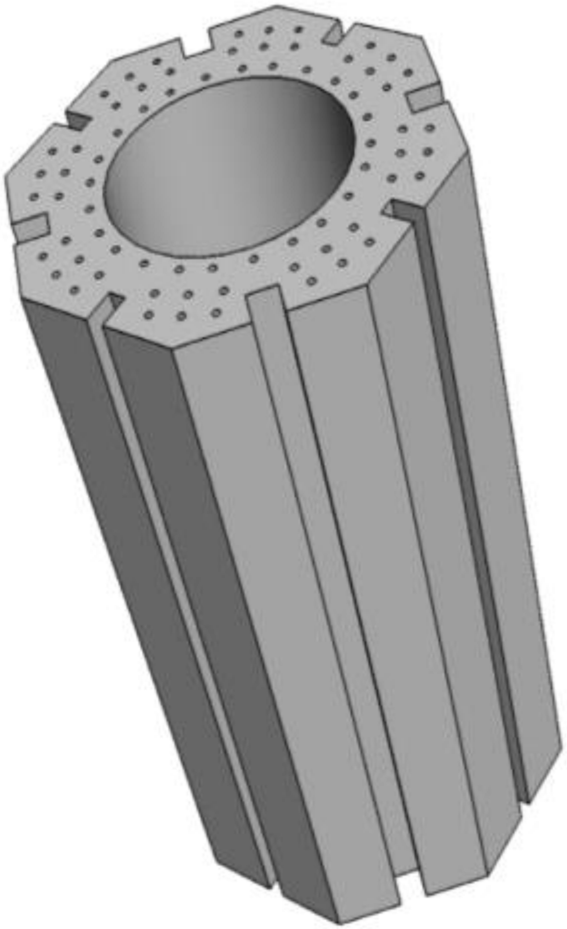
- Pool diameter had greatest influence on entrainment velocity
- Burn rate had only minor effect on entrainment
- Turbulence model predictions converged on finer mesh
- Inwards flow of air/vapour exceeds 2 m/s when pool diameter > 20 m

AGR graphite bricks

- Graphite properties change due to radiation
- Limited data available, collected during shutdowns
  - Inspection
  - Sampling
- Finite element modelling of graphite bricks
- Emulator used to perform Global Sensitivity Analysis of FE model

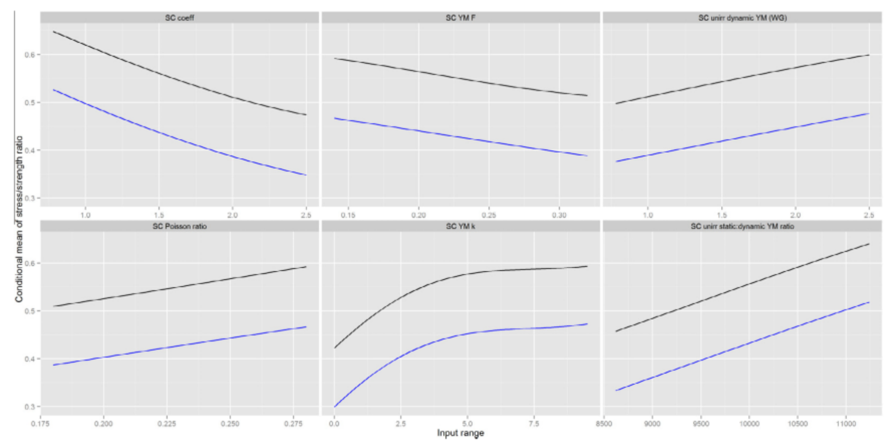


AGR graphite bricks

- 20 uncertain parameters, 100 simulations 6 influential parameters
- Main effects of 6 influential parameters

Main and total effect sensitivity indices for the 20 input parameters in the experiment. Results are based on an analysis of outputs at 10fpy for the at power and shutdown conditions.

Parameter	Power (10 fpy)		Shutdown (10 fpy)	
	Main effect	Total effect	Main effect	Total effect
Primary creep coefficient	0.0001	0.0005	0.0001	0.0005
Primary creep Poisson's ratio	0.0000	0.0000	0.0000	0.0000
Primary creep Young's modulus weight loss fitting constant F_i	0.0019	0.0093	0.0018	0.0092
Primary creep Young's modulus weight loss fitting constant k_i	0.0057	0.0136	0.0058	0.0137
Primary creep Unirradiated dynamic Young's modulus (WG)	0.0011	0.0016	0.0011	0.0016
Primary creep Unirradiated dynamic Young's modulus (AG)	0.0000	0.0000	0.0000	0.0000
Primary creep Unirradiated static to dynamic Young's modulus ratio	0.0002	0.0023	0.0002	0.0023
Primary creep Irradiated dynamic Young's modulus amplitude term *a*	0.0000	0.0000	0.0000	0.0000
Primary creep Irradiated dynamic Young's modulus location term *b*	0.0000	0.0001	0.0000	0.0000
Primary creep Unirradiated Shear modulus	0.0000	0.0000	0.0000	0.0000
Secondary creep coefficient	0.2310	0.2474	0.2319	0.2489
Secondary creep Poisson's ratio	0.0535	0.0628	0.0537	0.0629
Secondary creep Young's modulus weight loss fitting constant F_i	0.0421	0.0857	0.0418	0.0852
Secondary creep Young's modulus weight loss fitting constant k_i	0.2094	0.2763	0.209	0.276
Secondary creep Unirradiated dynamic Young's modulus (WG)	0.0739	0.0808	0.0735	0.0804
Secondary creep Unirradiated dynamic Young's modulus (AG)	0.0000	0.0000	0.0000	0.0000
Secondary creep Unirradiated static to dynamic Young's modulus ratio	0.2825	0.3011	0.2823	0.3009
Secondary creep Irradiated dynamic Young's modulus amplitude term *a*	0.0003	0.0017	0.0003	0.0017
Secondary creep Irradiated dynamic Young's modulus location term *b*	0.0056	0.0175	0.0056	0.0175
Secondary creep Unirradiated Shear modulus	0.0008	0.0058	0.0008	0.0058



http://dx.doi.org/10.1016/j.nucengdes.2016.09.007

Conclusions

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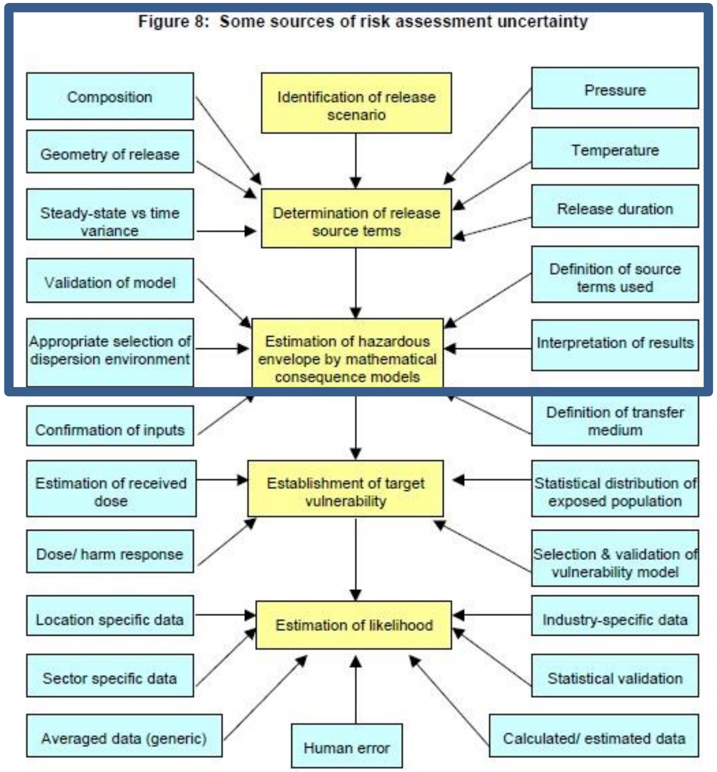
- Global sensitivity analysis can identify important parameters and provide useful understanding of model behaviour
- Emulator-based approach can be used for practical engineering calculations at low cost
  - Phast CO_2 dispersion simulations and analysis took less than 30 minutes on a laptop
- In principle, these methods are applicable to other models and types of inputs, e.g. QRA

Future work

- Joint industry project on sensitivity and uncertainty analysis for QRA
  - Consequence modelling
  - Probabilistic modelling



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Acknowledgements

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