BWR Probabilistic Risk Analysis using RELAP5-3D and RAVEN

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Introduction

- RAVEN
  - Overview
  - Distributions
  - Samplings
  - Post processing
  - Reliability surfaces

- Demo description

- Results analysis

*This work is part of a more complex and exhaustive analysis supported by the **L**ight **W**ater **R**eactor **S**ustainability Program under the **R**isk **I**nformed **S**afety **M**argin **C**haracterization pathway*

Project Goals

RAVEN was conceived to be an enabling tool for Risk Informed Safety Margin Characterization (RISMC)

RISMC is a methodology to support plant decisions for risk-informed margin management with the aim to improve economics, reliability, and sustain safety of current NPPs

Risk management is enabled by

- **Higher fidelity**
- **Risk Analysis**
- **Uncertainties**
- **Optimization**

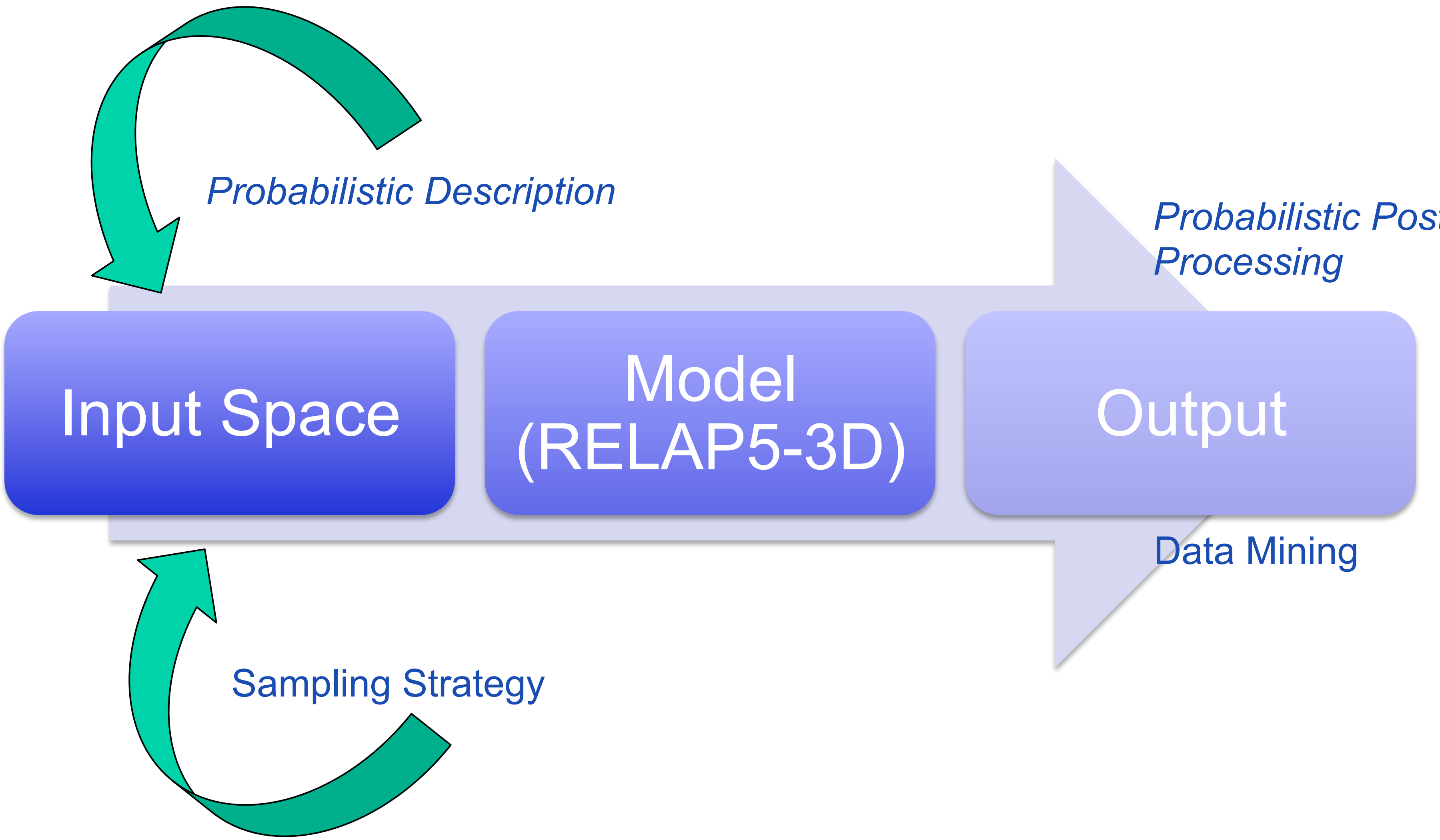
RAVEN: ***RISMC enabling tool***

RAVEN

- RAVEN is package to:
  - Analyze systems that could not be described fully deterministically
  - Perform parametric spaces

- What for?
  - Probabilistic Risk Analysis
  - Risk management
  - Uncertainty Quantification
  - Optimization (partial)
  - Validation (not yet present)

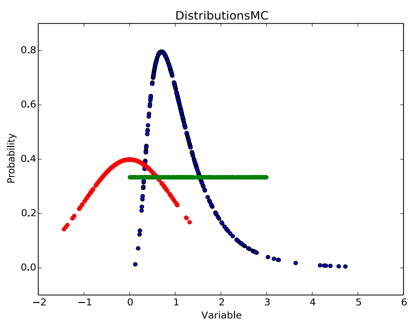
How: Input-Model-Output

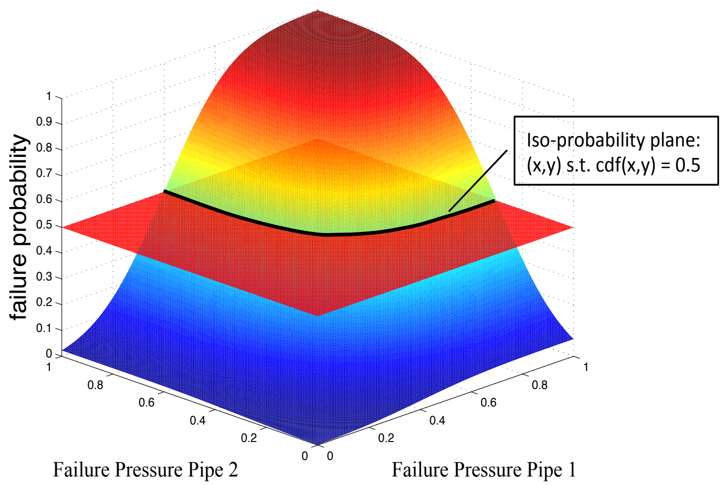


Distribution Coverage

- Most common used 1D distributions

- Custom N-Dimensional distributions

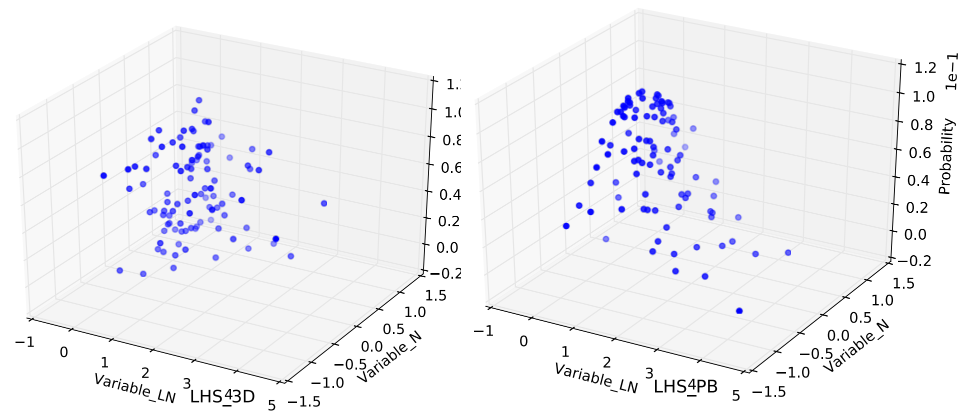




Probability Distribution Function	Truncated Form Available	Probability Distribution Function	Truncated Form Available
Bernoulli	No	Poisson	No
Binomial	No	Triangular	Yes
Exponential	Yes	Uniform	Yes
Logistic	Yes	Weibull	Yes
Lognormal	Yes	Gamma	Yes
Normal	Yes	Beta	Yes

One Point Samplers

- To explore the input space we need sampling strategies:
  - Monte Carlo
  - Grid
  - Stratified Samplers



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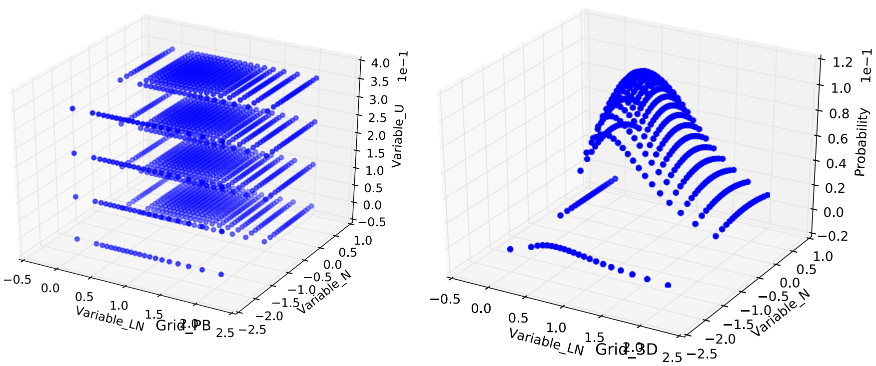
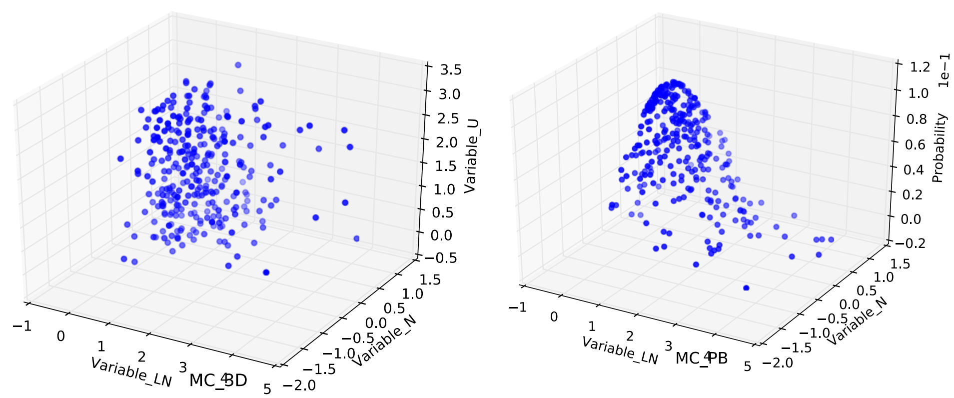


Grid (1764 points)



Monte Carlo (300 points)

Statistical Post Processing

The following post processing capabilities are part of the standard analysis

For each single input and/or output

- Mean
- Sigma
- Skewness (asymmetry)
- Kurtosis (more/less peaked than a standard normal)

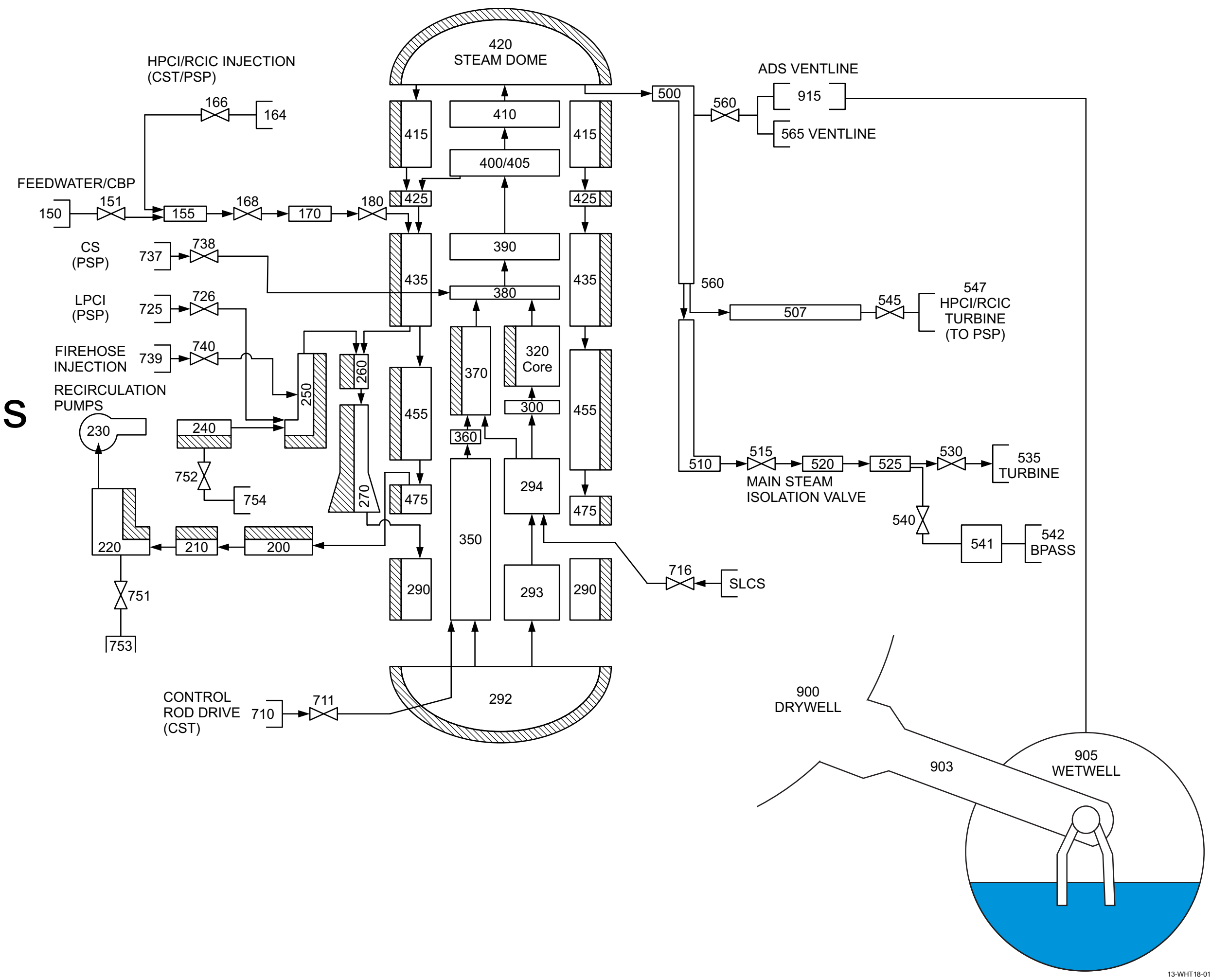
To examine the input/output relationship

- Correlation matrix
- Covariance matrix
- Sensitivity matrix (multidimensional linear regression)
- Normalized sensitivity matrix (% change of the response / % change in the answer)

DEMO

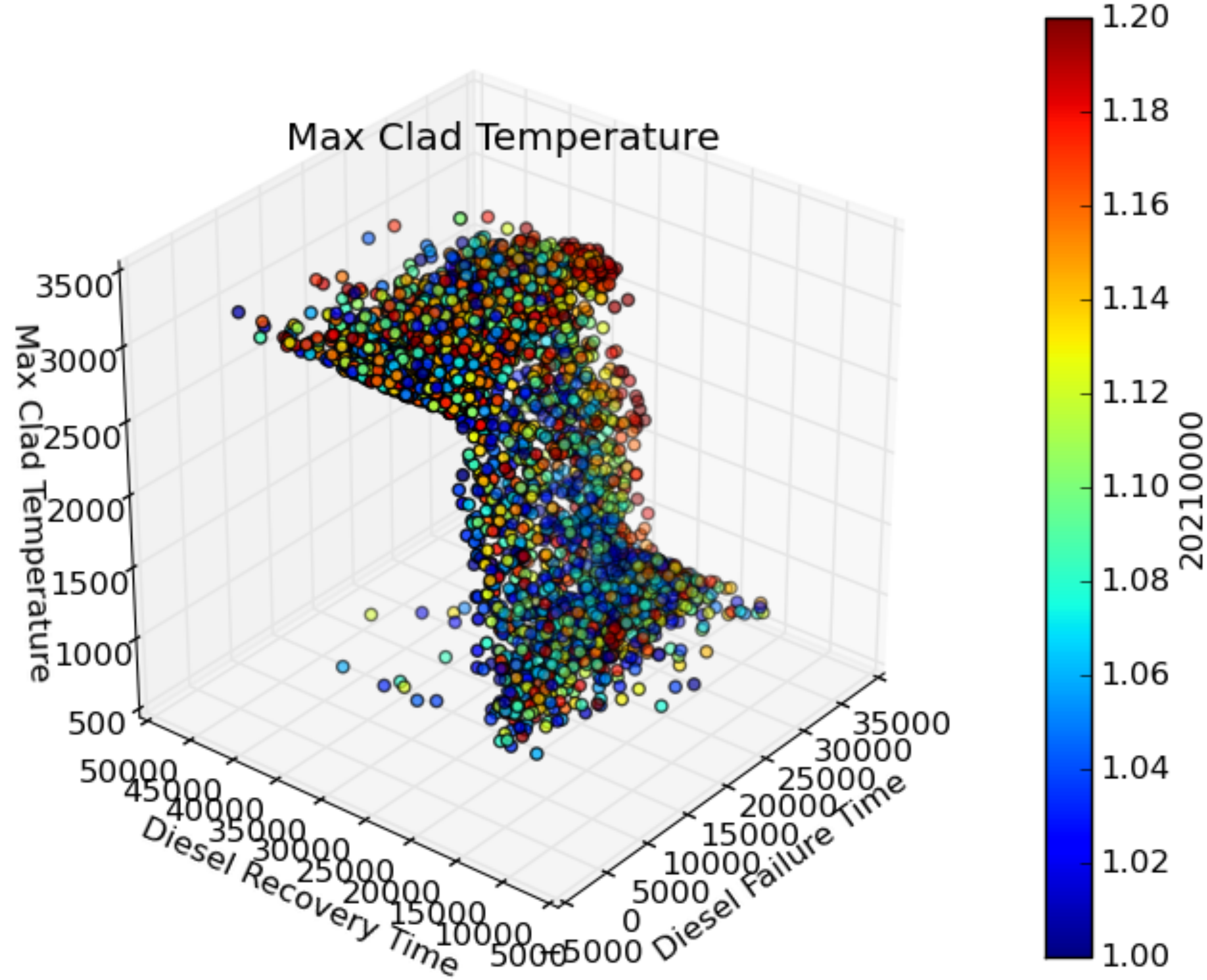
Sampled variables:

- Elapsed time before DG loos
  - Distribution: exponential
  - Lambda: 2.5E-6
  - Upper bound: 28800 s
- Diesel Down time:
  - Distribution: normal
  - Mean: 26460 s
  - Sigma: 5400 s
- Power Level
  - Distribution: uniform
  - Lower bound: 1.0
  - Upper bound: 1.2



Graphical Output Monte Carlo

- 4000 Monte Carlo runs, 1000 job in parallel



Max Clad Temperature Statistical Figures

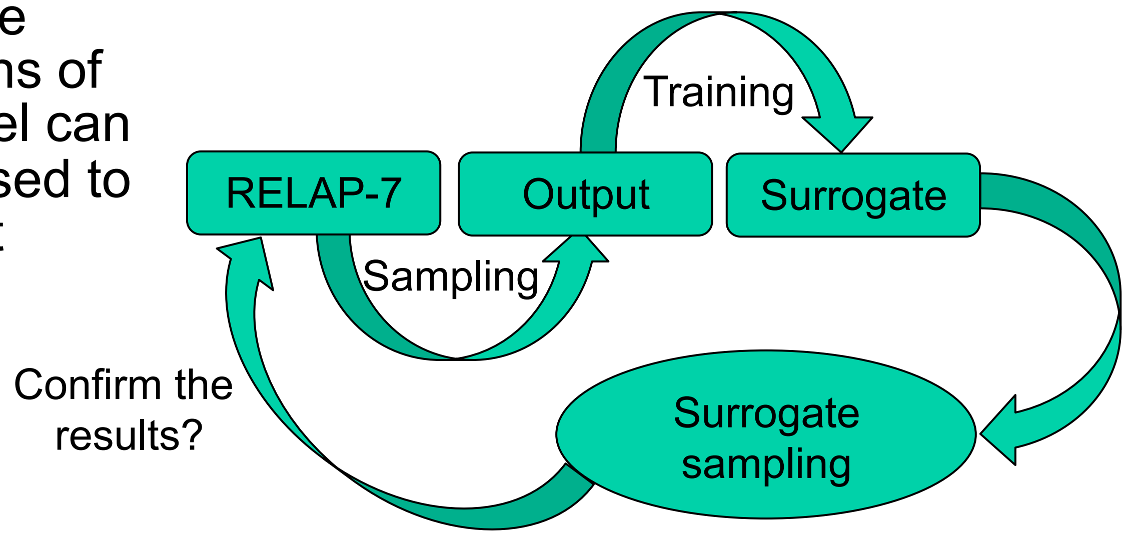
- A RELAP5-3D edit to monitor the time evolution of the max clad temperature has been built
- RAVEN will extract the max clad temperature over time
- Statistical figures for max clad temperature achieved:
  - Mean: 2.329E+03
  - Sigma: 9.0557E+02
  - Kurtosis: -1.547E+00
  - Median: 3.092E+03
  - Skewness: -5.256E-01
- Failure Probability 60.99%

Sensitivity/Ranking: Pearson

	Power	Max Clad Temperature	Diesel Failure Time	Diesel Recovery Time
Power	1	2.1193E-01	-2.1194E-02	4.0291E-03
Max Clad Temperature	2.1193E-01	1	-4.5497E-01	6.3735E-01
Diesel Failure Time	-2.1194E-02	-4.5497E-01	1	1.30376E-02
Diesel Recovery Time	4.0291E-03	6.3735E-01	1.30376E-02	1

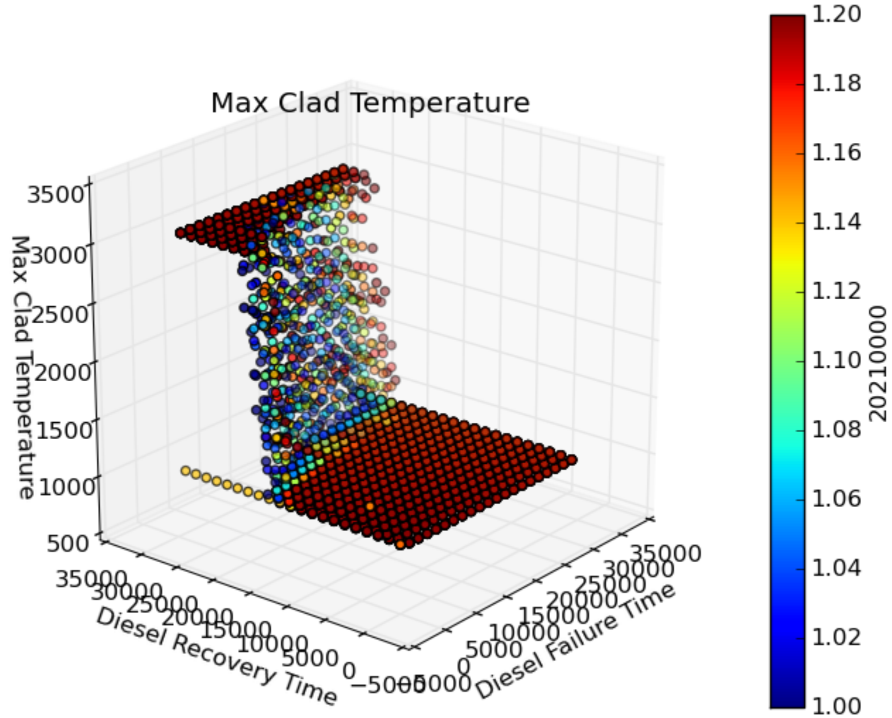
Surrogate Models

- Surrogate models is a general name to describe:
  - A set of equations of faster solution with respect the original set
  - The parameters of the surrogate model set of equations could be *trained* to approximate the original system
  - Most of the time the number of equations of the surrogate model can be arbitrary increased to achieve the sought accuracy

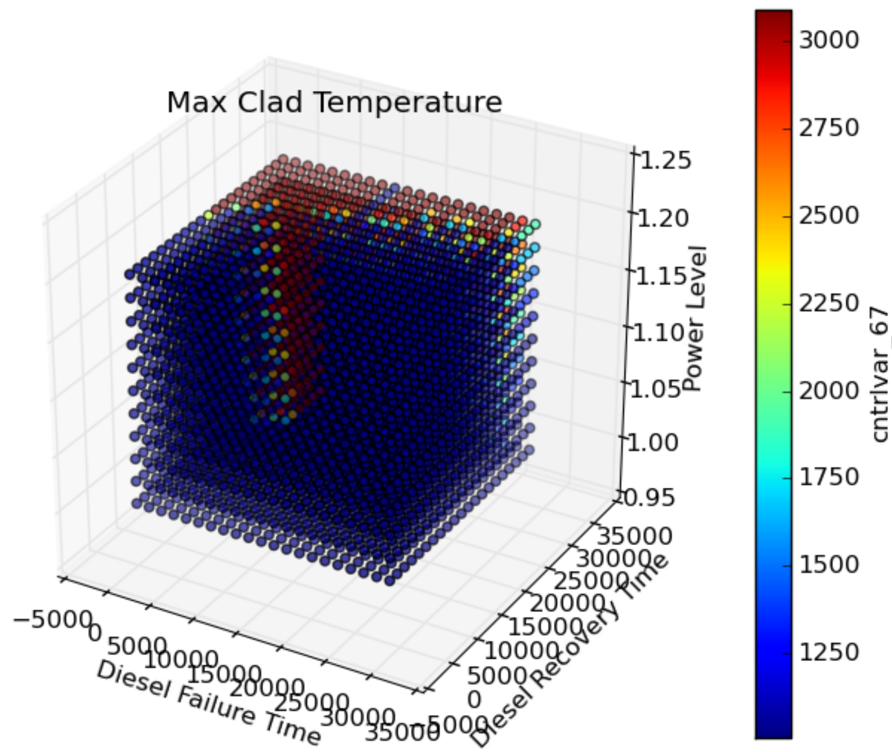


The surrogate is sampled to determine the input space leading to the sought outcome

Grid Sampling



- 20 x 20 x 20 grid on the sampled variables
- 8000 runs in parallel on 1000 processors



Monte Carlo on the Surrogate Model

- Statistical figures for max clad temperature achieved:

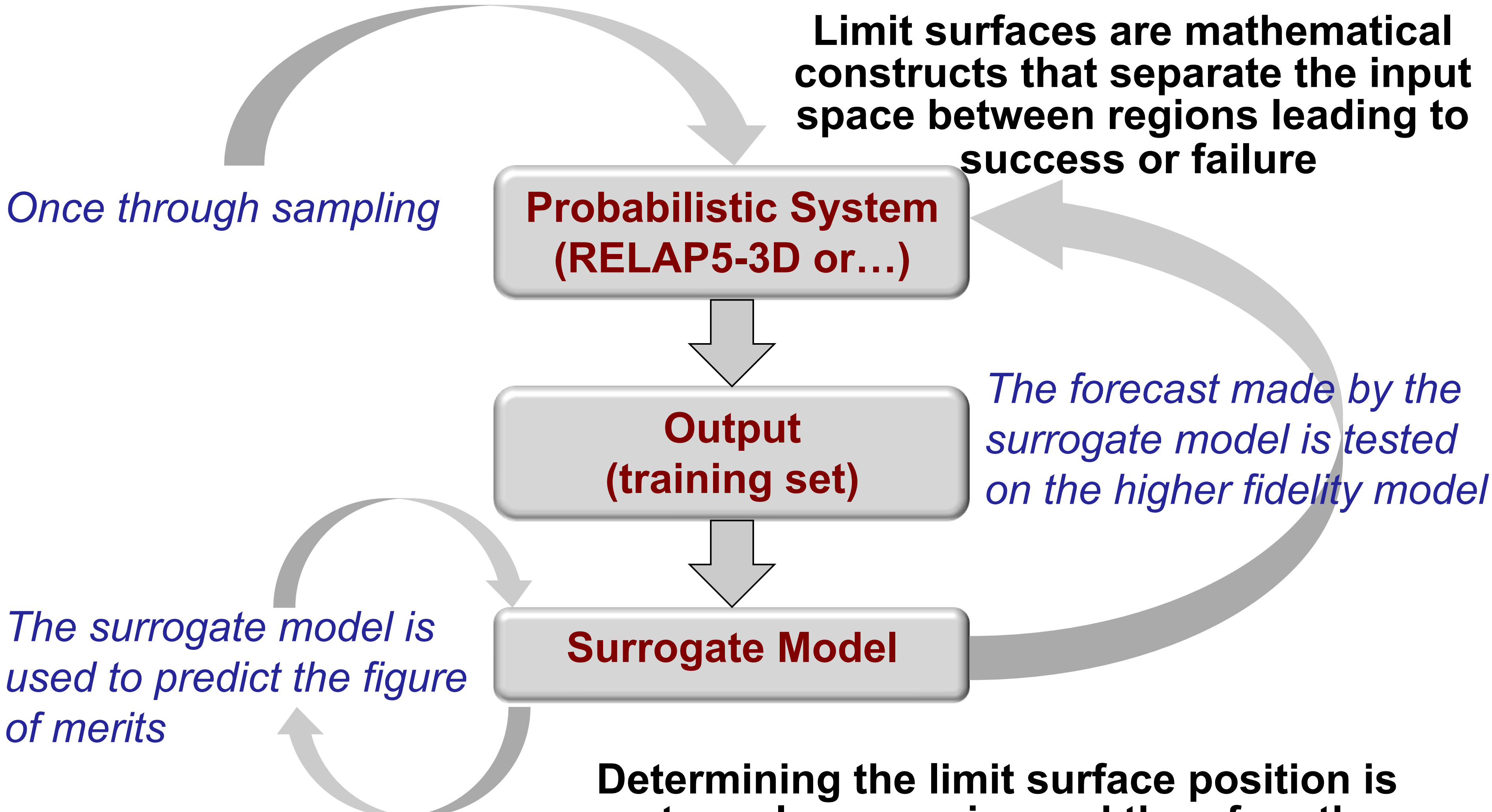
Entry	Original	Surrogate
Mean:	2.3296E+03	2.3103E+03
Sigma:	9.0559E+02	8.4599E+02
Kurtosis:	-1.547E+00	-1.4497E+00
Median:	3.092E+03	2.683E+03
Skewness:	-5.256E-01	-5.0662E-01
Failure Pb	60.99%	60.82%

- The matching of the results between the Monte Carlo Sampling on the RELAP5-3D code and the build surrogate confirm the good training set

- New input distributions could be tested without re-running the sampling

Limit Surface

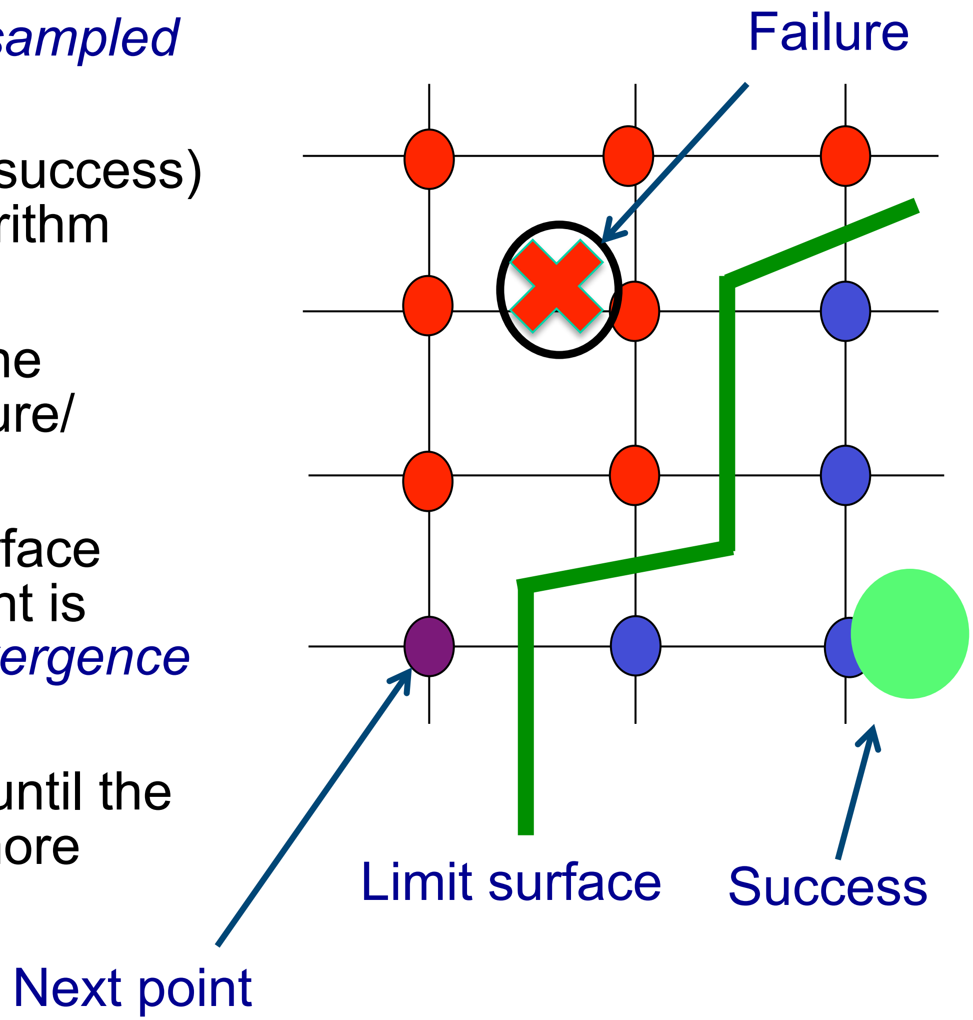
Limit surfaces are mathematical constructs that separate the input space between regions leading to success or failure



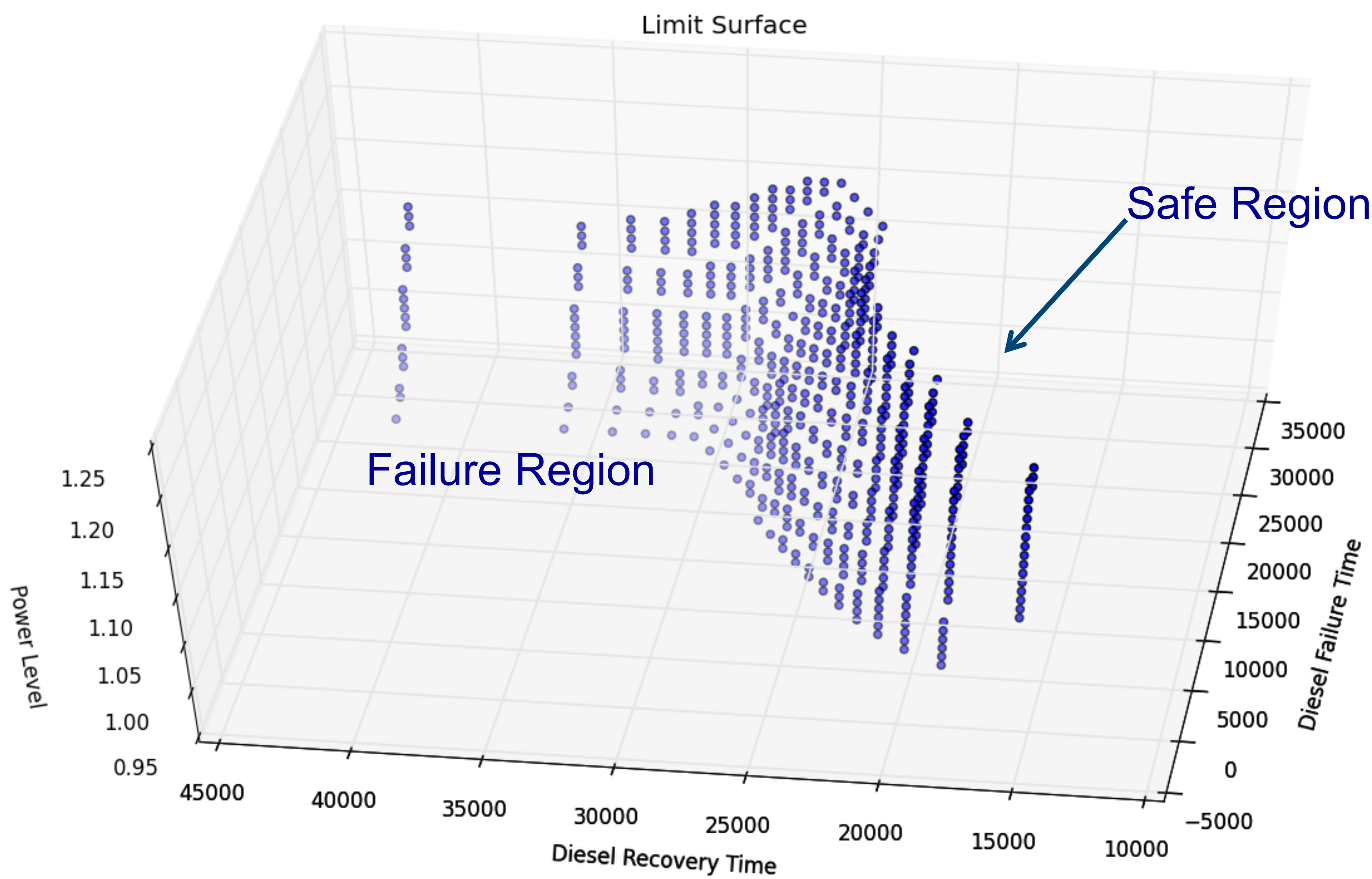
Determining the limit surface position is extremely expensive and therefore the acceleration methodologies are used

The Limit Surface: Simulation Flow

1. Training on initial *low number of sampled points*
2. A fine grid is classified (failure or success) based on a closest neighbor algorithm (*sampling of the surrogate*)
3. The limit surface is identified by the location of transition between failure/ success
4. The most far point on the limit surface from any other already tested point is choose to test the classifier (*convergence test*)
5. Process starts back from point 2 until the limit surface does not move anymore



The Limit Surface



Conclusion

- RAVEN add powerful tools like surrogate models and limit surface analysis to the engineers toolbox in a flexible environment
- Classical PRA and uncertainty quantification is already part of RAVEN capabilities
- Dynamic event tree is currently under testing for RELAP5-3D
- Several university are currently becoming partners of the RAVEN development (Oregon State University, Ohio State University, Politecnico Milan, University Rome)
- Several other code are coupled to RAVEN like any generic MOOSE based application, RELAP-7, HYDRA