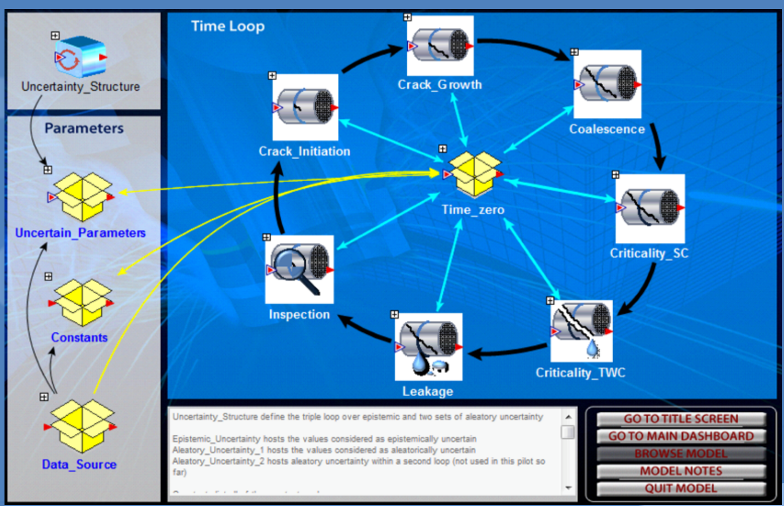
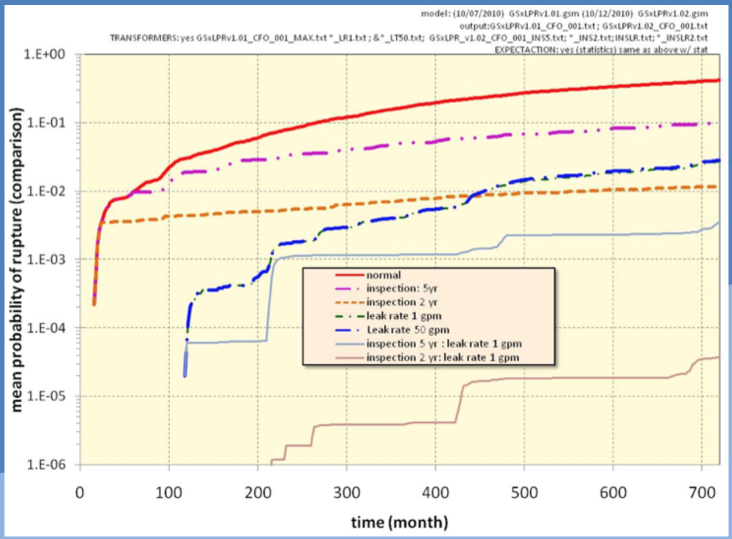
Extremely Low Probability of Rupture (xLPR) Project

xLPR v2.0: Framework Overview



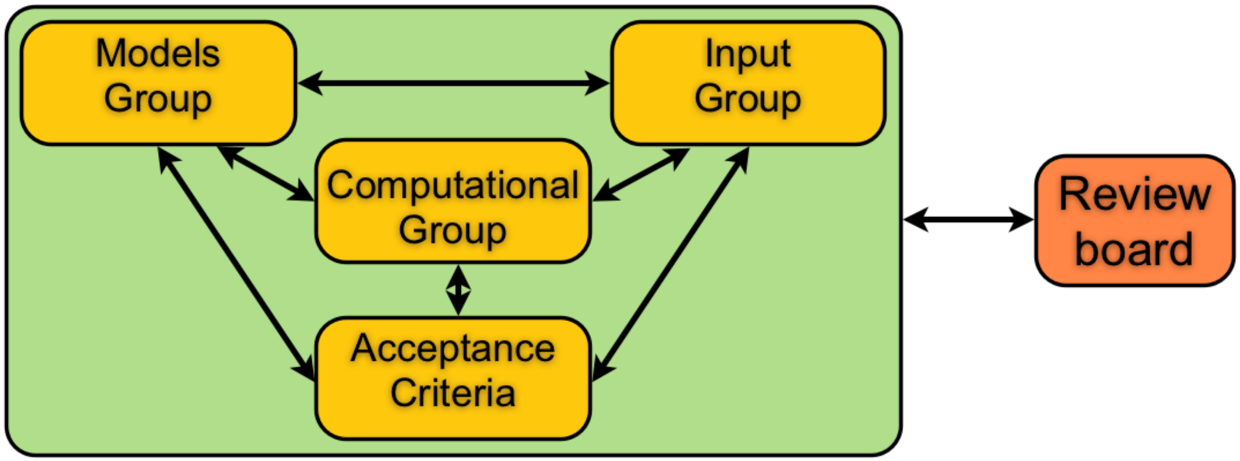


xLPR External Review Board Meeting
February 20, 2013

xLPR v2.0 framework overview: Current status

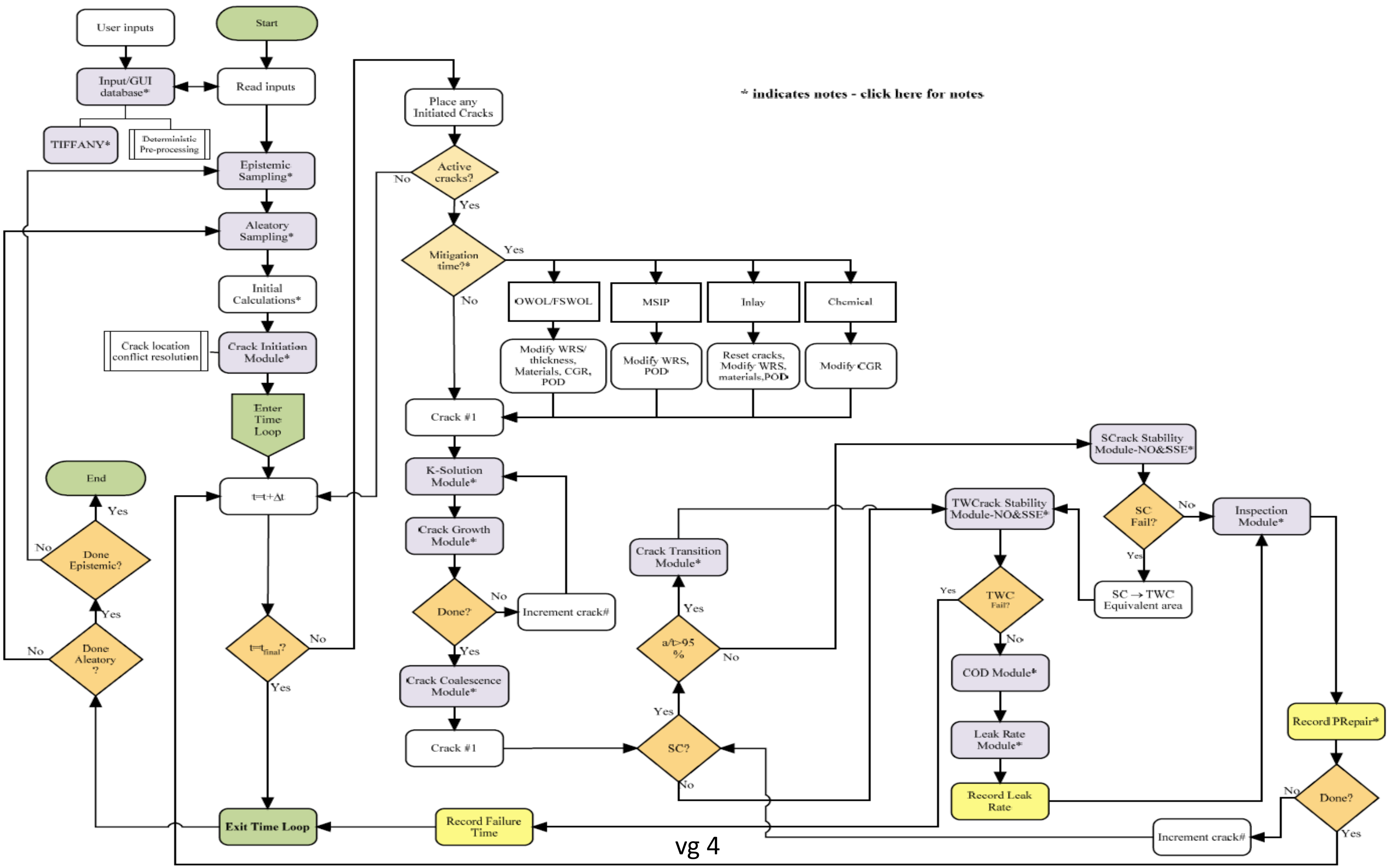
- Integrating role of the computational group.
- Flowchart of xLPR: lessons learned from xLPR v1.0.
- Preprocessing: stress intensity factor and leak rate.
- Goldsim: what is it about?
- Framework development strategy: landing platform, physical models and dashboard.
- Sampling strategy: evolution from xLPR v1.0 consideration of advanced computational methods.

The computational group integrates the various components of xLPR into a robust, tested and verified computational framework



- Develop the overall modular structure including uncertainty and computational methods (sampling and optimization).
- Provide code documentation and training when necessary.
- Cooperative effort between US-NRC/EPRI and industry/national laboratories partners.

This framework is implemented in a modular structure including inputs, loads, materials properties, degradation mechanisms all stochastically based



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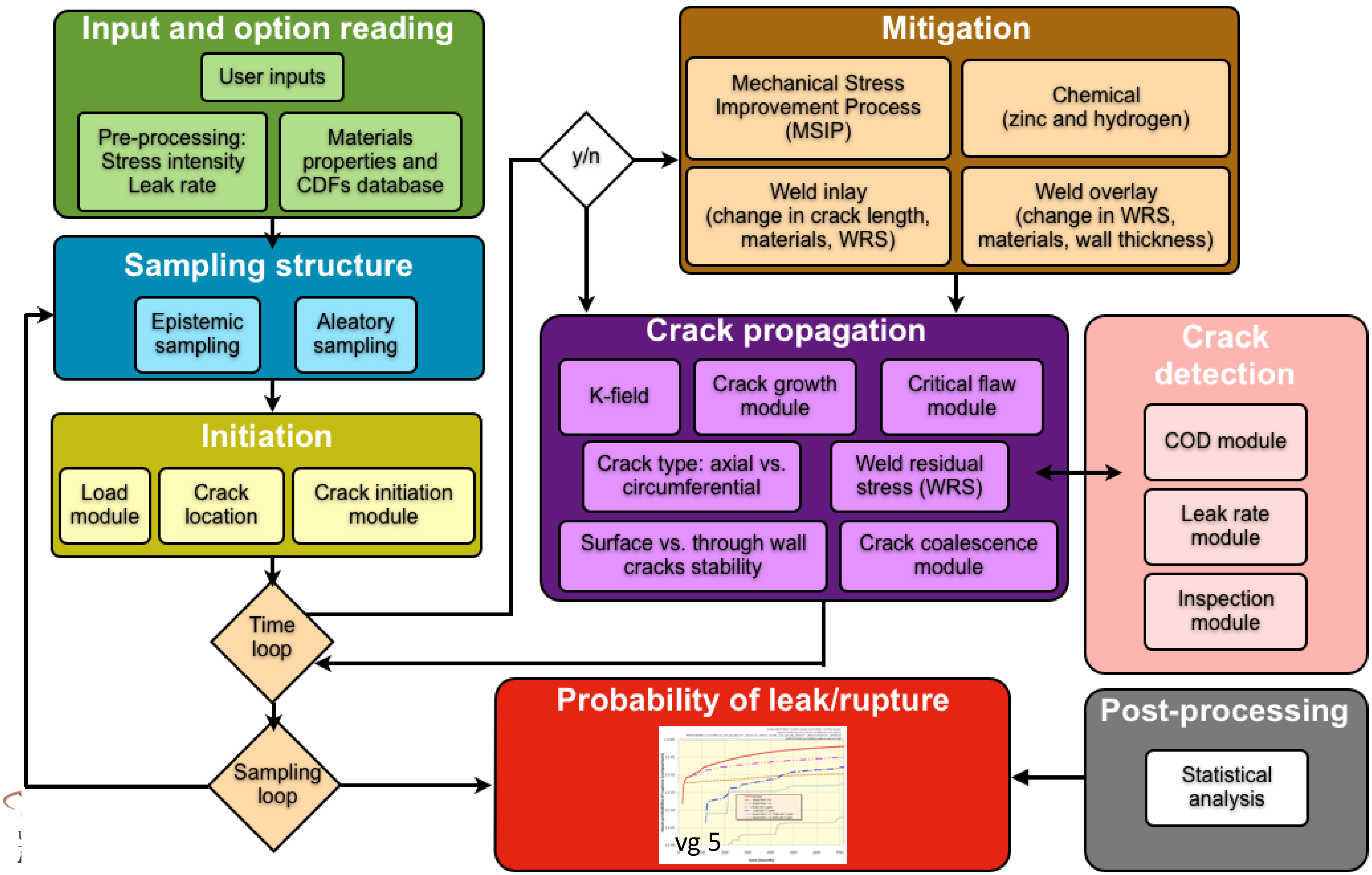

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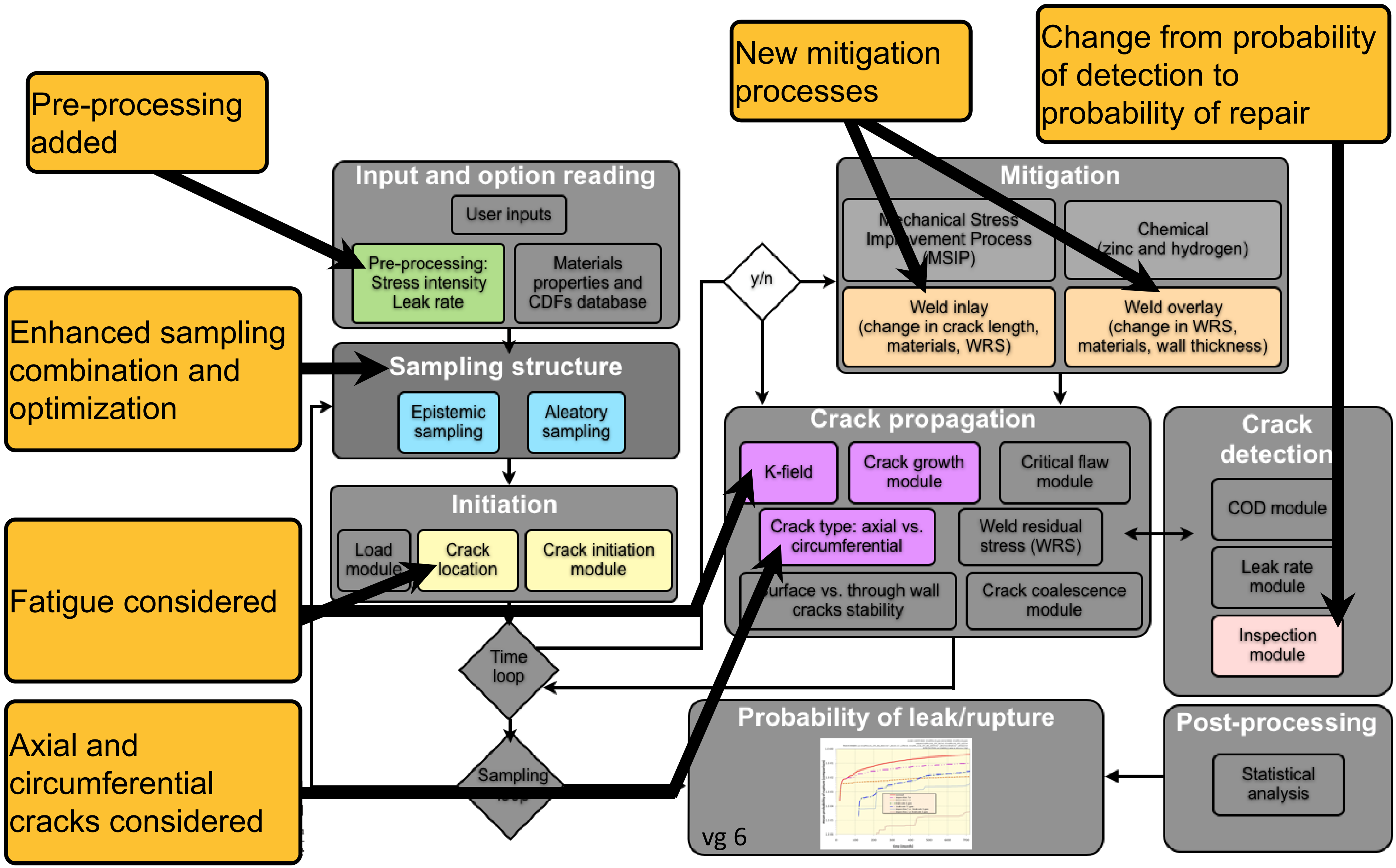
In xLPR v2.0 several modules have been changed and improved based on the lessons learned from xLPR v1.0

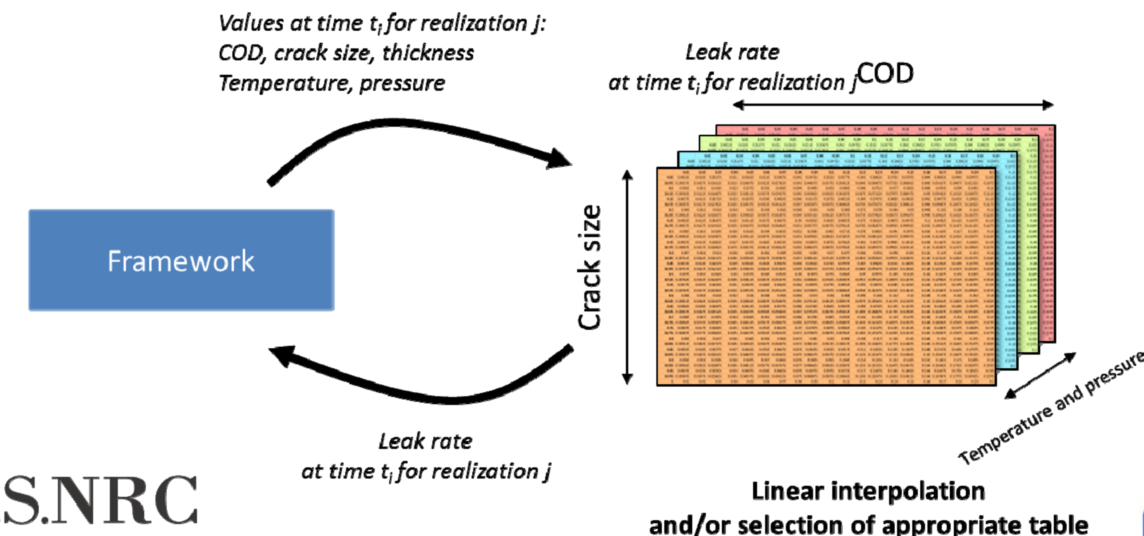


Preprocessing of some factors (stress intensity factor, leak rate) that are not time-dependent or affected by uncertainty is added to reduce computational cost

- **Stress intensity factor (for fatigue crack growth)**
  - **TIFFANY** (**T**hermal stress **I**ntensity **F**actors **F**or **ANY** coolant history) developed by SIA estimates SIF bounds for associated crack sizes
    - Used by Goldsim to linearly interpolate the appropriate estimates for the SIF at a given crack size.
    - Used to estimate fatigue crack growth and could potentially replace SIF module used in xLPR v1.0 for PWSCC crack growth.
- **Leak rate**
  - In xLPR v1.0 SQUIRT consumed most of the calculation time (estimating leak rate code from COD).
  - SQUIRT rewritten (LEAPOR, ORNL) for xLPR v2.0.
  - More computational time saved via "3D" lookup tables according to crack length, minimum COD and each thickness each defined for a given temperature and pressure.
  - Goldsim will linearly interpolate Leak Rate based on these parameters

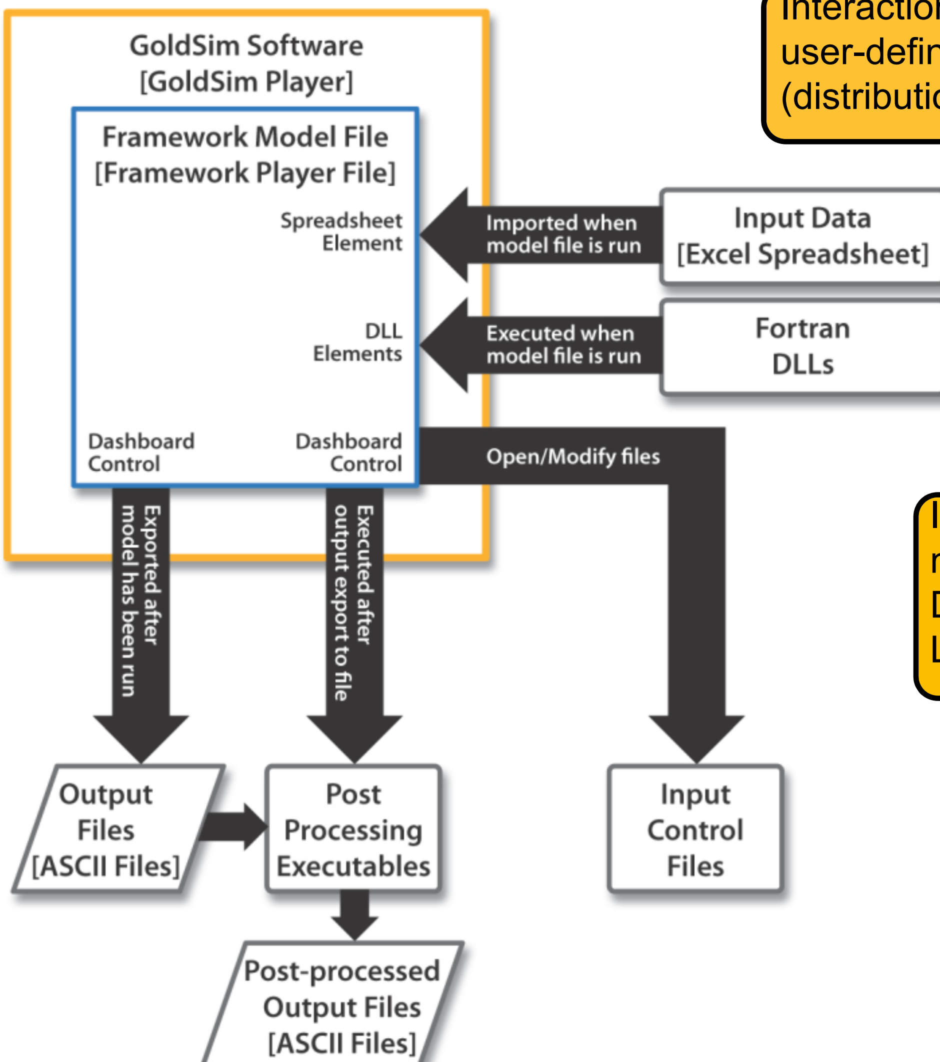
Preprocessing of some factors (stress intensity factor, leak rate) that are not time-dependent or affected by uncertainty is added to reduce computational cost

- **Leak rate**
  - An estimate on module contribution to computational cost have shown that a significant portion of calculation time was due to SQUIRT (estimating leak rate code based on COD).
  - Optimized version of SQUIRT rewritten (LEAPOR, ORNL) for xLPR v2.0.
  - Saving on computational cost by generating “3D” lookup tables according to crack length, minimum COD and each thickness each defined for a given temperature and pressure.



Goldsim was chosen as the probabilistic framework to integrate the various components of this effort and to perform probabilistic analysis in a QA manner

Object oriented to allow development of algorithms via graphical elements with specific properties (dashboard).



Interaction with Excel to read user-defined information (distribution, etc.).

Interaction of any module defined as Dynamically Linked Libraries (DLL).

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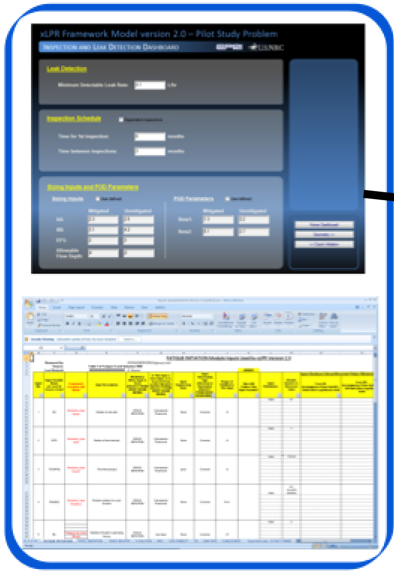
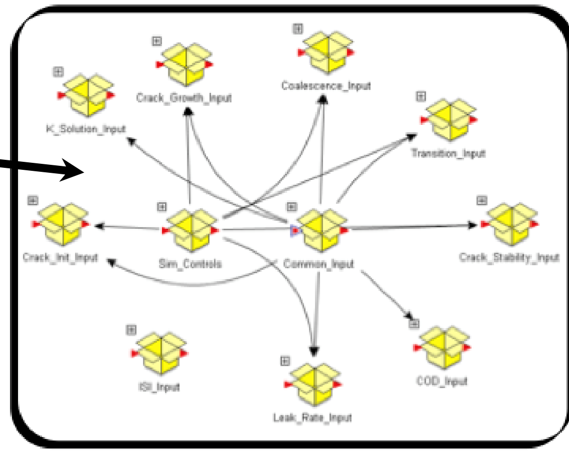
The framework is constructed using a landing platform to allow a parallel development of the physical models, the user-friendly interface and sampling methodologies

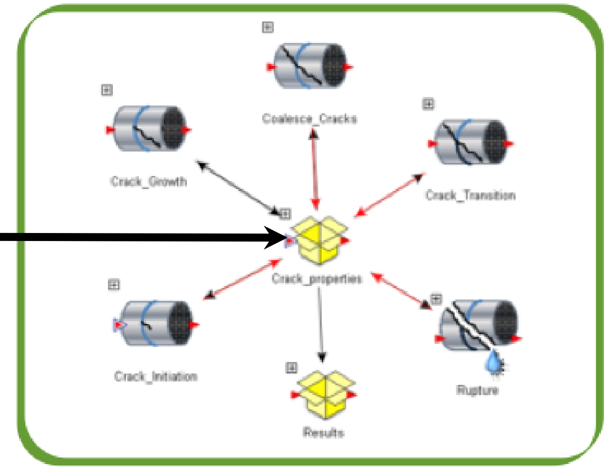


User interface
Dashboard implemented within Goldsim defined by the **input group** and Excel spreadsheets hosting distributions for input parameters.



Landing platform
Definition of all input variables as well as simulation controls

In collaboration with the **input group** (simulation settings) and the **model group** (input/output of each model).



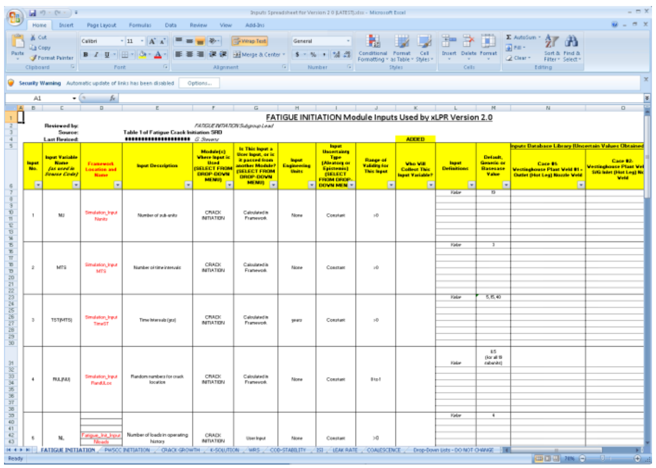
Physical (deterministic) models
Definition of all input variables as well as simulation controls.

Each module developed by the **model group** and compiled as a DLL.

- **This strategy allows for multi-entities to share and work on the framework development in an efficient and parallel manner.**

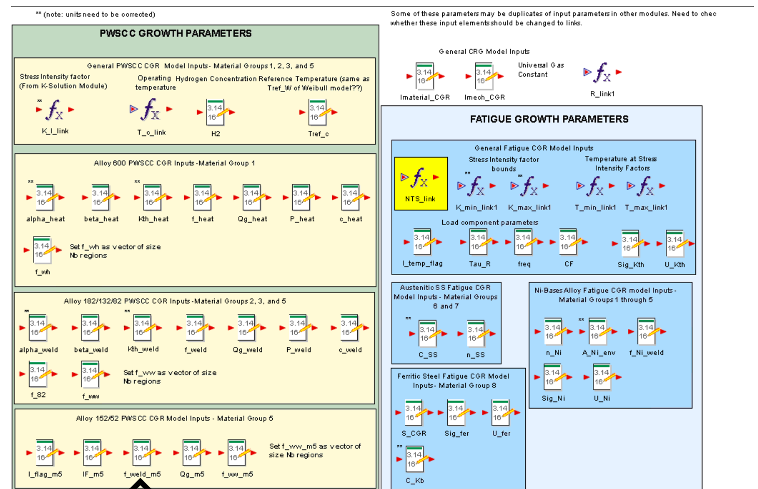
The framework collects the user-defined probability distributions (input), samples and allocates them accordingly to each physical module

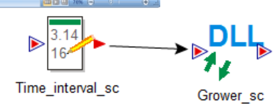
Input distributions
Are pre-defined (but can be changed) within the Excel spreadsheet. User can also change uncertainty type (aleatory/epistemic).



Uncertain input values are sampled automatically by the code.

Sampled model inputs
Are associated with appropriate unit in the landing platform.





Sample input are sent to the module compiled as a DLL.

For Detailed Information on the module's features please refer to the Controlled Module Documentation on the xLPR Configuration Management Web Site:
https://websps1.battelle.org/nrcnureg/home/xLPR_CM/Beta%20Model%20Dev/Forms/AllItems.aspx?RootFolder=%2fnrcnureg%2fhome%2fxLPR%5fCM%2fBeta%20Model%20Dev%2fModules%2fGrower%5f2%2e1&FolderCTID=&View=%7b8BE040D4%2d490D%2d4B42%2dB1A1%2d238DBE400771%7d

Run only when Crack_Type = -1 (SC)

Using stress intensity estimate in previous submodel, as well as time interval and crack location, Grower estimate the updated crack depth and half crack length.

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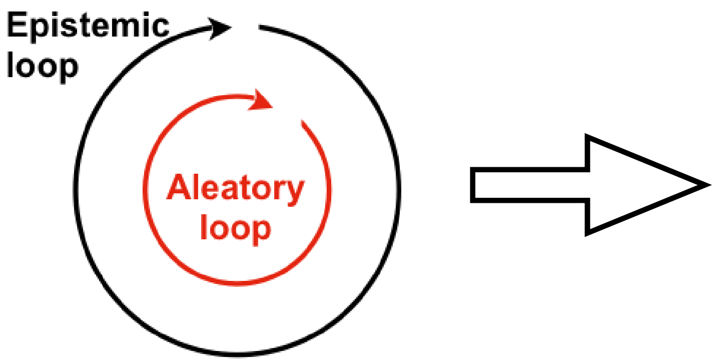
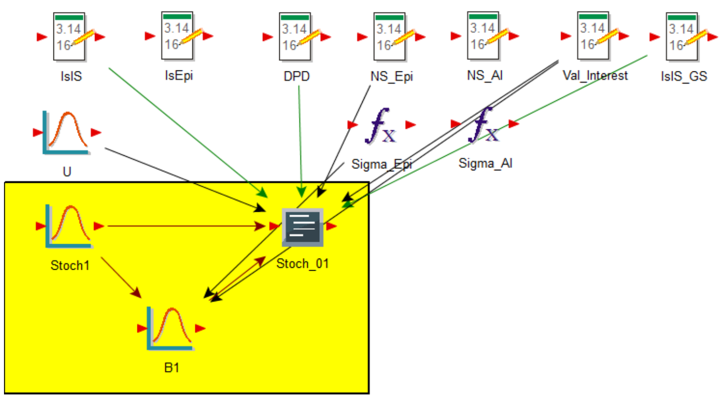
In xLPR v2.0, the sampling strategy is optimized and dissociated from the uncertainty characterization giving the user flexibility on the sampling method to be used

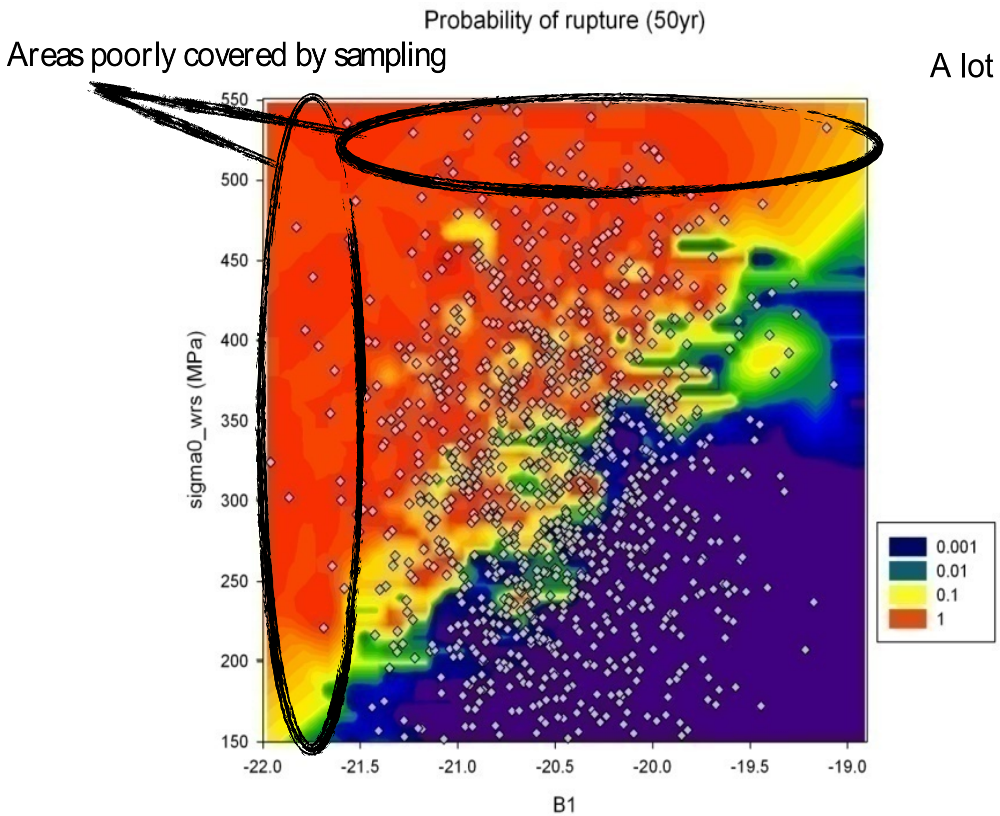




- **Two loops considered (one can be ignored by setting the sampling size to 1). For each loop, the user can select from the following options:**
  - Simple random sampling (SRS) or Latin Hypercube sampling (LHS).
  - Discretization Probability Distribution (DPD).
  - Importance sampling applied to selected values.
  - Use of optimization instead of importance sampling for selected values (in dev)
- **Possibility of creating 12 sampling combination: [LHS vs. SRS]x[DPD vs. no DPD]x[No importance vs. importance vs. adaptive] for each loop (totaling 12^2 combinations)**
- **2 importance techniques (gamma-clustering (Emc^2) and importance sampling (Goldsim) and one adaptive method (DPD adaptive (Emc^2)) are considered for xLPR v2.0**

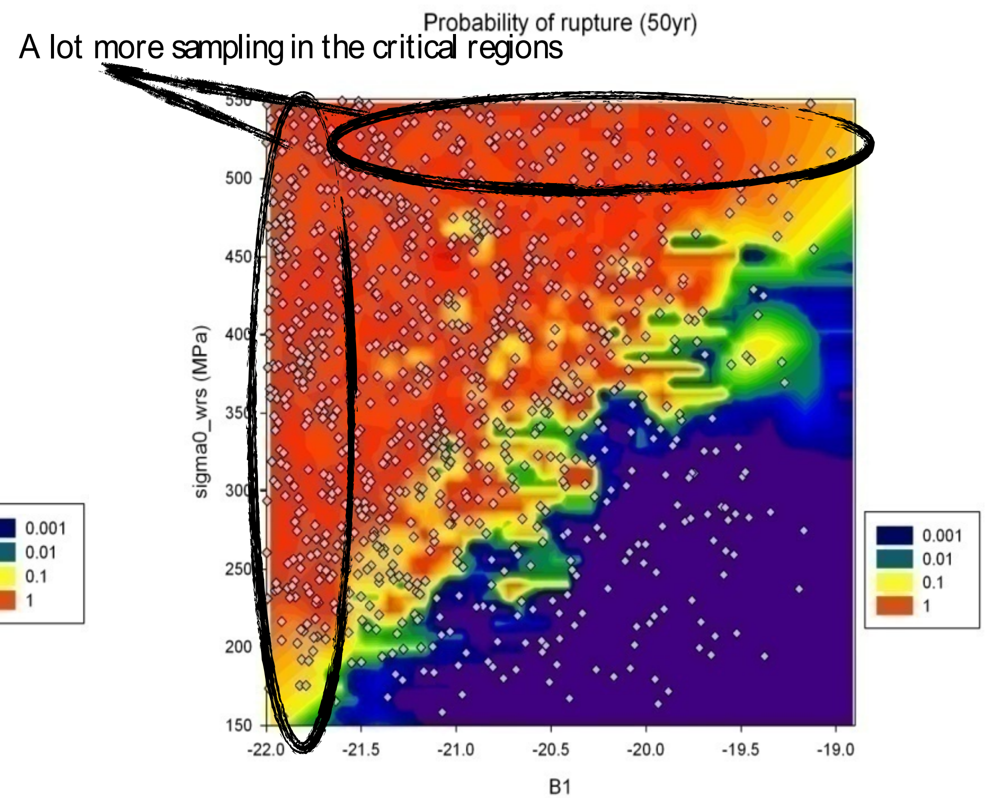
xLPR v1.0 and the pilot study underlined the importance of focusing sampling on regions of interest to accurately estimate extremely low rupture probabilities

Rupture probability as a function of crack initiation and weld residual stress using regular *vs*. importance sampling highlights the shortcomings of regular sampling



Regular sampling

More than half of the points sampled outside of the region of interest

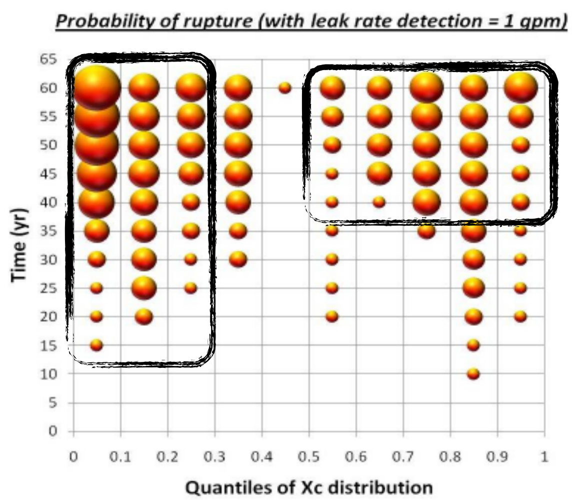


Importance sampling

Most of the points sampled in the region of interest

This resulted in the inclusion of sampling enhanced capabilities in xLPR v2.0 to insure that regions of interest are found and correctly sampled

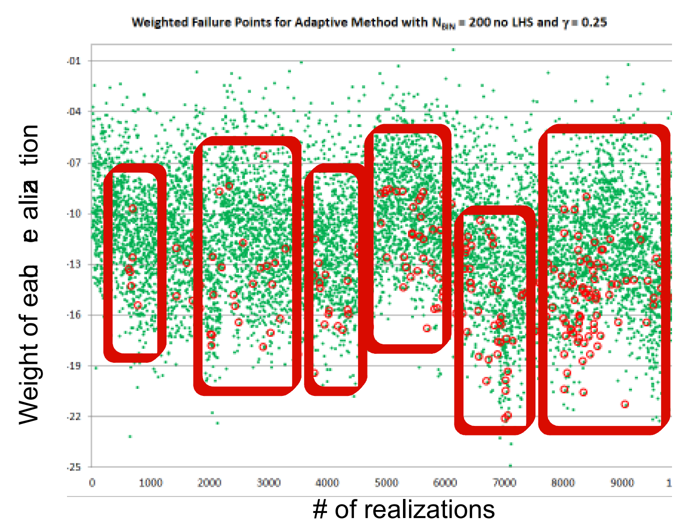
- **In xLPR v2.0, the sampling strategy is not uniquely based on the user knowledge**
- **Adaptive and optimized strategies are adopted to cover relevant regions of the input space.**



(Xc = Distance from ID weld residual stress crosses zero)

Regions of interest can be disjoint and a simple importance sampling may not be sufficient (i.e where to apply importance sampling)

Adaptive techniques cover different regions in the input space so that no region of interest that could affect the probability is missed

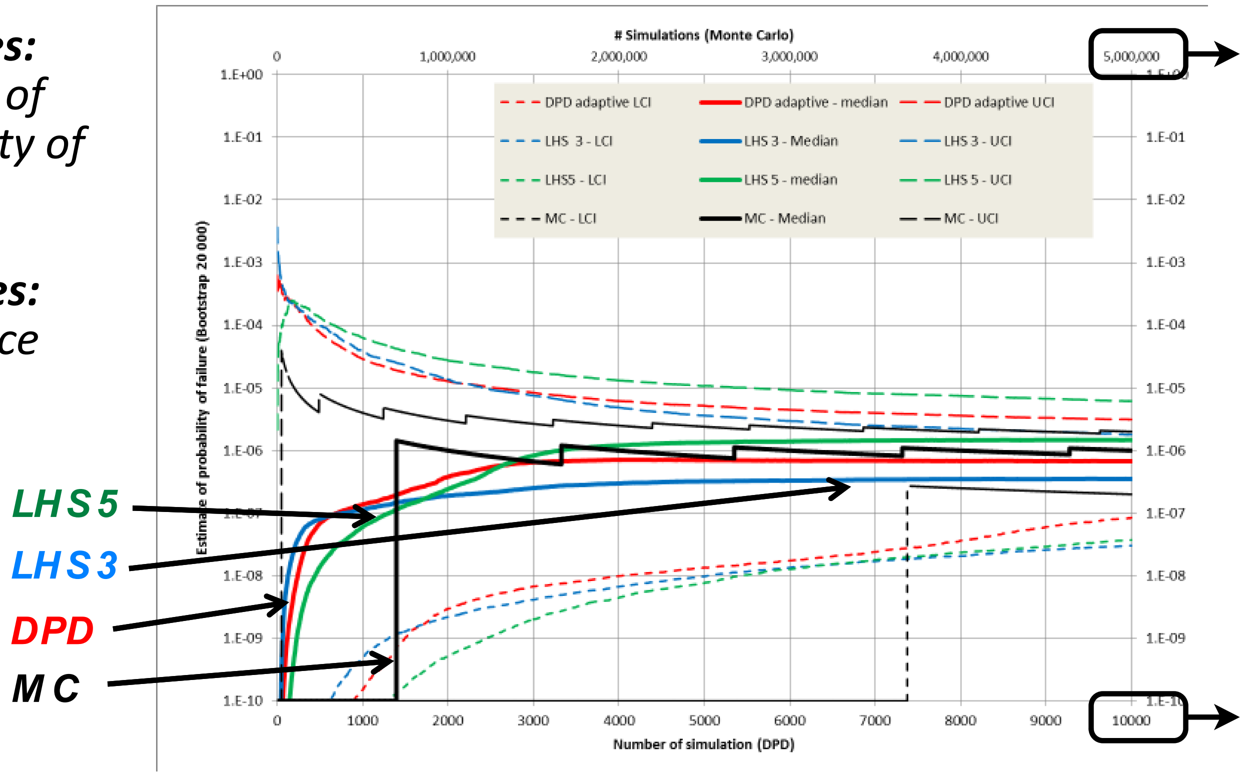


This resulted in the inclusion of sampling enhanced capabilities in xLPR v2.0 to insure that regions of interest are found and correctly sampled

Not only can adaptive sampling can cover disparate regions in the input space, it also reduces the number of samples needed to confidently estimate low rupture probability (~10^{-6}).

Solid lines: *Estimate of probability of rupture*

Dash lines: *Confidence interval*



Regular MC require 5 million runs for stable estimate

Adaptive DPD requires ≈100 less samples than MC

Adaptive DPD gives stable estimate with 10,000 runs

xLPR v2.0 framework: a robust, modular, tested and verified probabilistic computational framework for calculating the probability of leak-before-break

- Use of Goldsim software as the probabilistic framework
  - Landing platform as the central hub to integrate the various components.
  - Dashboard interface to facilitate usability and option selection.
  - Importance sampling applied to selected values.
- Modular structure implemented and improved based on pilot study and previous version
  - Pre-processing stage added for SIF and leak-rate to reduce computational cost.
  - Additional degradation mechanisms and mitigation processes implemented in v2.0.
  - Consideration of circumferential and axial cracks.
- Sampling strategy improved to include advanced computational method
  - [LHS vs. SRS.] x [DPD vs. no DPD] x [No importance vs. importance vs. adaptive].
  - Versatility in the sampling method to use.
  - The modular structure of the framework enables the inclusion of additional optimization techniques in the future.
- Alpha framework should be delivered end of February
  - Computational team will be ready to incorporate new modules at this time.
  - Beta version available by the end of summer 2013.