Extremely Low Probability of Rupture (xLPR) Project

Framework overview

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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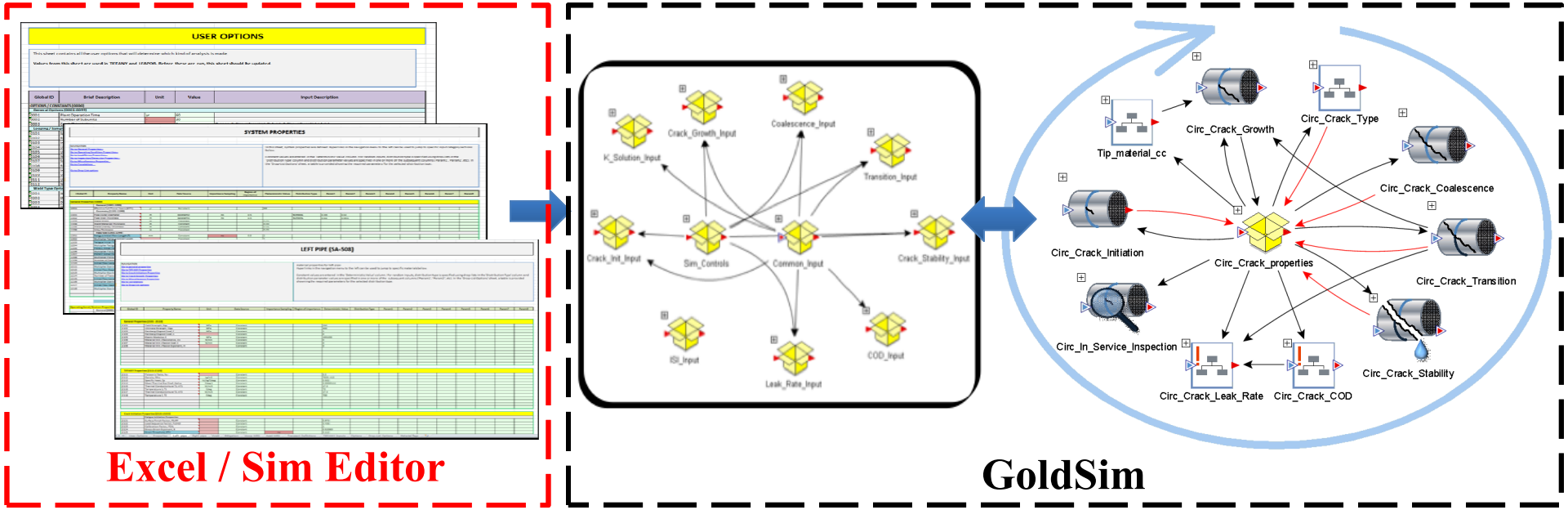
xLPR v2.0 Framework overview

- **GoldSim software:**
  - Dynamic, probabilistic simulation software that serves as the integrating shell linking various modules used in the xLPR model.
- **Input interface (Simulation editor and Excel file):**
  - Interface between user and global structure.
  - Uncertainty distribution associated with each input defined in the Input spreadsheet.
- **Landing platform:**
  - Tie up the Interface, sampling structure and physical (deterministic) models under the same umbrella.
  - List all inputs and user selected options required by the model to run.
- **Physical (deterministic) model:**
  - Linking the sub-models to the Framework (Dynamic Link Libraries).
- **Sampling structure:**
  - Defines the number and order of realization and appropriate values to use based on uncertainty.
  - Outer epistemic loop, and inner aleatory loop.
  - [LHS vs. RS]x[DPD vs. no DPD]x[No importance vs. importance vs. adaptive] for each loop.

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



User interface

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

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GoldSim software

- Dynamic, probabilistic simulation software that serves as the integrating shell linking various modules used in the xLPR model.

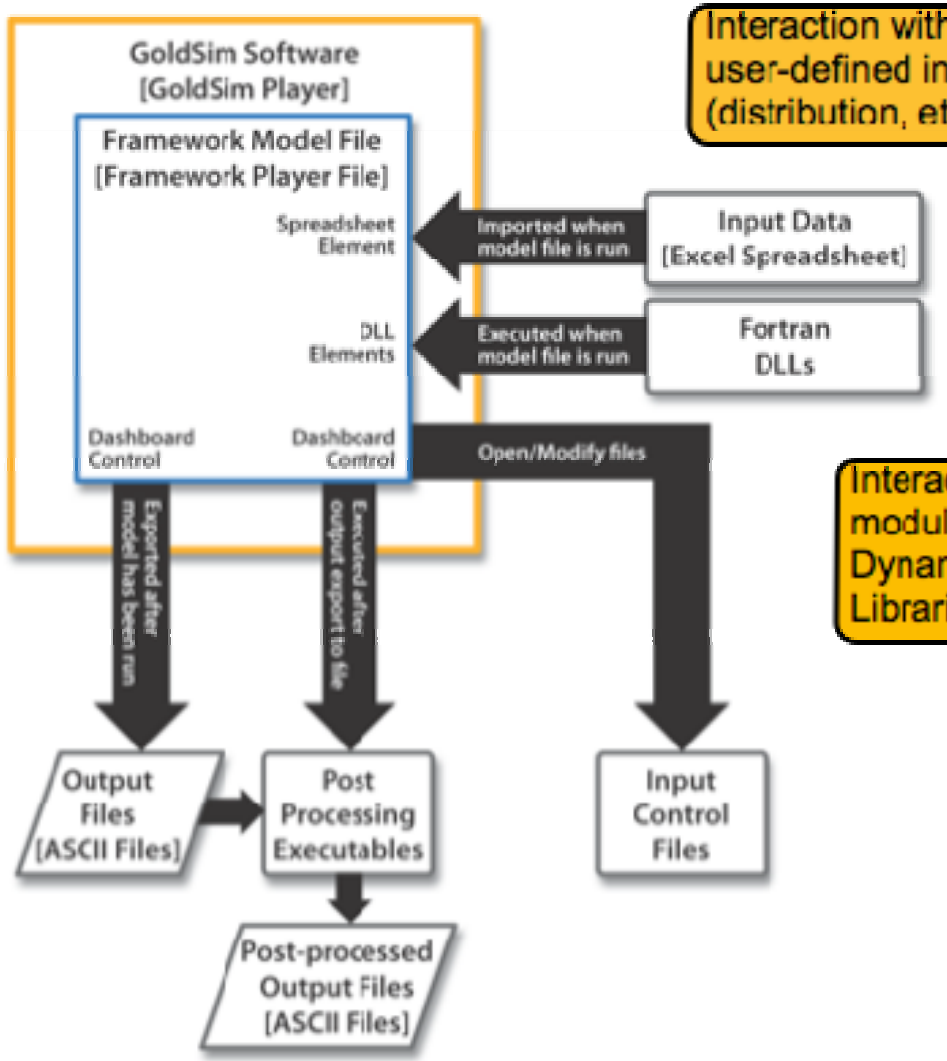
- Full version of the software required for development/change of the Framework.

- All functionalities available to run the code via the free player version of GoldSim.

- User will be able to change modules by creating new DLL (and replacing existing ones).

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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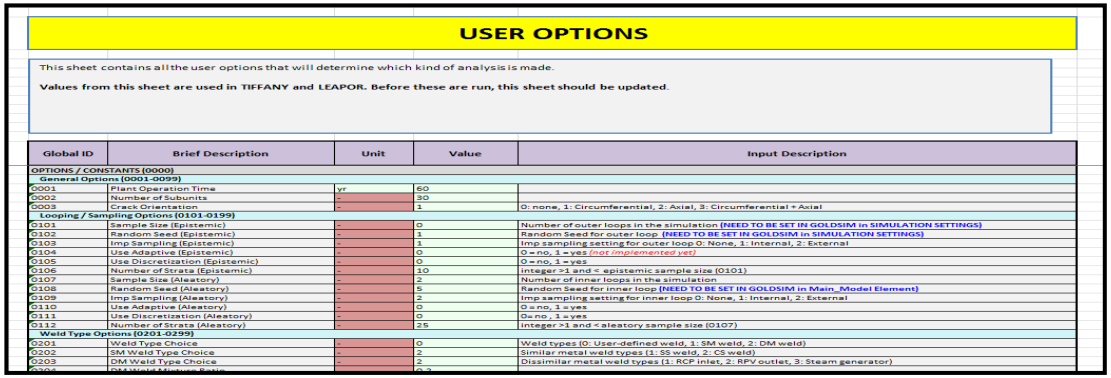
User interface

- Interface between the user and global structure.
- Uncertainty distribution associated with each input defined in the Input Excel spreadsheet.
- Simulation editor (under development) will help the user into creating a reasonable input set.

Input set Excel worksheet: user options



USER OPTIONS

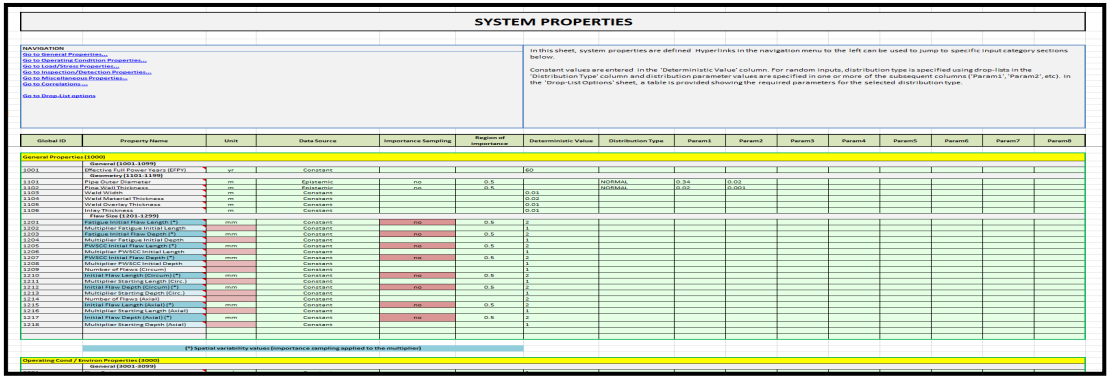
This sheet contains all the user options that will determine which kind of analysis is made.

Values from this sheet are used in TIFFANY and LEAPOR. Before these are run, this sheet should be updated.

Global ID	Brief Description	Unit	Value	Input Description
OPTIONS / CONSTANTS (0000)				
General Options (0001-0099)				
0001	Plant Operation Time	yr	60	
0002	Number of Subunits	-	30	
0003	Crack Orientation	-	1	0: none, 1: Circumferential, 2: Axial, 3: Circumferential + Axial
Looping / Sampling Options (0101-0199)				
0101	Sample Size (Epistemic)	-	0	Number of outer loops in the simulation (NEED TO BE SET IN GOLDSIM in SIMULATION SETTINGS)
0102	Random Seed (Epistemic)	-	1	Random Seed for outer loop (NEED TO BE SET IN GOLDSIM in SIMULATION SETTINGS)
0103	Imp Sampling (Epistemic)	-	1	Imp sampling setting for outer loop 0: None, 1: Internal, 2: External
0104	Use Adaptive (Epistemic)	-	0	0 = no, 1 = yes (not implemented yet)
0105	Use Discretization (Epistemic)	-	0	0 = no, 1 = yes
0106	Number of Strata (Epistemic)	-	10	integer >1 and < epistemic sample size (0101)
0107	Sample Size (Aleatory)	-	2	Number of inner loops in the simulation
0108	Random Seed (Aleatory)	-	5	Random Seed for inner loop (NEED TO BE SET IN GOLDSIM in Main_Model Element)
0109	Imp Sampling (Aleatory)	-	2	Imp sampling setting for inner loop 0: None, 1: Internal, 2: External
0110	Use Adaptive (Aleatory)	-	0	0 = no, 1 = yes
0111	Use Discretization (Aleatory)	-	0	0= no , 1 = yes
0112	Number of Strata (Aleatory)	-	25	integer >1 and < aleatory sample size (0107)
Weld Type Options (0201-0299)				
0201	Weld Type Choice	-	0	Weld types (0: User-defined weld, 1: SM weld, 2: DM weld)
0202	SM Weld Type Choice	-	2	Similar metal weld types (1: SS weld, 2: CS weld)
0203	DM Weld Type Choice	-	2	Dissimilar metal weld types (1: RCP inlet, 2: RPV outlet, 3: Steam generator)

- All user options are read from Excel into GoldSim
- Tabs to define properties, input associated with Left/Right/Weld, mitigation, WRS (hoop/axial), transient, fatigue, option description.
- Exception: epistemic sample size, epistemic random seed, and aleatory random seed are provided and chosen into the GoldSim software.

Input set Excel worksheet: system properties



SYSTEM PROPERTIES

NAVIGATION
Go to General Properties...
Go to Operating Condition Properties...
Go to Load/Stress Properties...
Go to Inspection/Detection Properties...
Go to Miscellaneous Properties...
Go to Correlations ...

Go to Drop-List options

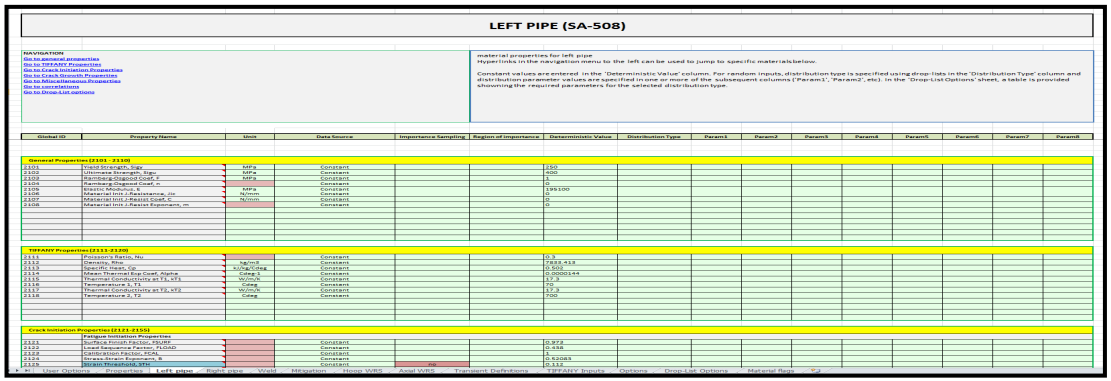
In this sheet, system properties are defined. Hyperlinks in the navigation menu to the left can be used to jump to specific input category sections below.

Constant values are entered in the 'Deterministic Value' column. For random inputs, distribution type is specified using drop-lists in the 'Distribution Type' column and distribution parameter values are specified in one or more of the subsequent columns ('Param1', 'Param2', etc). In the 'Drop-List Options' sheet, a table is provided showing the required parameters for the selected distribution type.

Global ID	Property Name	Unit	Data Source	Importance Sampling	Region of Importance	Deterministic Value	Distribution Type	Param1	Param2	Param3	Param4	Param5	Param6	Param7	Param8
General Properties (1000)															
	General (1001-1099)														
1001	Effective Full Power Years (EFPY)	yr	Constant			60									
	Geometry (1101-1199)														
1101	Pipe Outer Diameter	m	Epistemic	no	0.5		NORMAL	0.34	0.02						
1102	Weld Outer Rideseas	m	Epistemic	no	0.5		NORMAL	0.02	0.001						
1103	Weld Width	m	Constant			0.01									
1104	Weld Material Thickness	m	Constant			0.02									
1105	Weld Overlay Thickness	m	Constant			0.01									
1106	Inlay Thickness	m	Constant			0.01									
	Flaw Size (1201-1299)														
1201	Fatigue Initial Flaw Length (*)	mm	Constant	no	0.5	2									
1202	Multiplier Fatigue Initial Length		Constant			1									
1203	Fatigue Initial Flaw Depth (*)	mm	Constant	no	0.5	2									
1204	Multiplier Fatigue Initial Depth		Constant			1									
1205	PWSCC Initial Flaw Length (*)	mm	Constant	no	0.5	2									
1206	Multiplier PWSCC Initial Length		Constant			1									
1207	PWSCC Initial Flaw Depth (*)	mm	Constant	no	0.5	2									
1208	Multiplier PWSCC Depth		Constant			1									
1209	Number of Flaws (Circum)		Constant			1									
1210	Initial Flaw Length (Circum) (*)	mm	Constant	no	0.5	2									
1211	Multiplier Starting Length (Circ.)		Constant			1									
1212	Initial Flaw Depth (Circum) (*)	mm	Constant	no	0.5	2									
1213	Multiplier Starting Depth (Circ.)		Constant			1									
1214	Number of Flaws (Axial)		Constant			1									
1215	Initial Flaw Length (Axial) (*)	mm	Constant	no	0.5	2									
1216	Multiplier Starting Length (Axial)		Constant			1									
1217	Initial Flaw Depth (Axial) (*)	mm	Constant	no	0.5	2									
1218	Multiplier Starting Depth (Axial)		Constant			1									
	(*) Spatial variability values (importance sampling applied to the multiplier)														
Operating Cond / Environ Properties (2000)															
	General (2001-2099)														

- List all the variables used in the model by category.
- Defines variable units, data source (cst vs. aleatory vs. epistemic).
- List displayed depending on the choice:
  - uncertainty type and associated distribution.
  - deterministic value if constant is selected.

Input set Excel worksheet: mat. properties



LEFT PIPE (SA-508)

NAVIGATION
Go to general properties
Go to TPFARY Properties
Go to Crack Initiation Properties
Go to Crack Growth Properties
Go to Miscellaneous Properties
Go to parameters
Go to Drop-List options

material properties for left pipe
Hyperlinks in the navigation menu to the left can be used to jump to specific materials below.

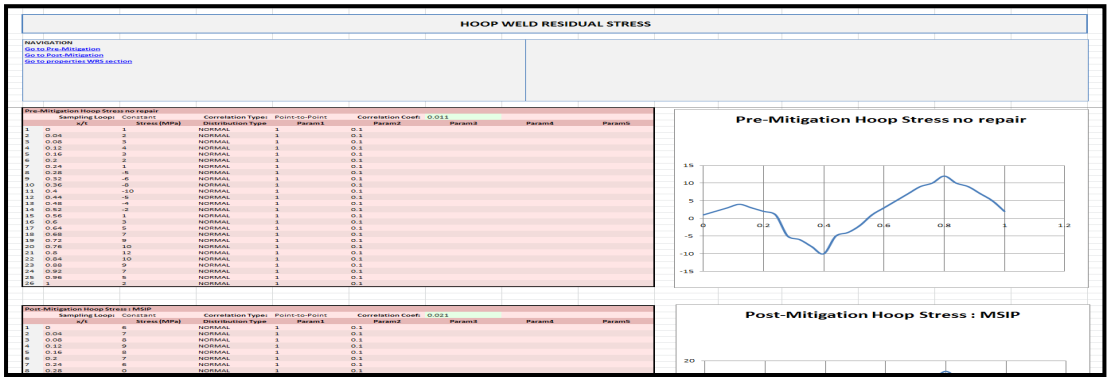
Constant values are entered in the "Deterministic Value" column. For random inputs, distribution type is specified using drop-lists in the "Distribution Type" column and distribution parameter values are specified in one or more of the subsequent columns ("Param1", "Param2", etc). In the "Drop-List Options" sheet, a table is provided showing the required parameters for the selected distribution type.

Global ID	Property Name	Unit	Data Source	Importance Sampling	Region of Importance	Deterministic Value	Distribution Type	Param1	Param2	Param3	Param4	Param5	Param6	Param7	Param8
General Properties (2101 - 2110)															
2101	Yield Strength, Sigy	MPa	Constant			250									
2102	Ultimate Strength, Sigu	MPa	Constant			470									
2103	Ramberg/Osgood Coef, K	MPa	Constant			0									
2104	Ramberg/Osgood Coef, n		Constant			0									
2105	Elastic Modulus, E	MPa	Constant			199100									
2106	Material Init J-Resistance, Jo	N/mm	Constant			0									
2107	Material Init J-Resist Coefficient, C	N/mm	Constant			0									
2108	Material Init J-Resist Exponent, m		Constant			0									
TPFARY Properties (2111-2120)															
2111	Poisson's Ratio, Nu		Constant			0.3									
2112	Density, Rho	kg/m3	Constant			7488.419									
2113	Specific Heat, Cp	kJ/kg/Deg	Constant			0.502									
2114	Mean Thermal Exp Coef, Alpha	Deg-1	Constant			0.0000144									
2115	Thermal Conductivity at T1, kT1	W/m/k	Constant			17.3									
2116	Temperature 1, T1	Deg K	Constant			0									
2117	Thermal Conductivity at T2, kT2	W/m/k	Constant			17.3									
2118	Temperature 2, T2	Deg	Constant			700									
Crack Initiation Properties (2121-2150)															
	Fatigue Initiation Properties														
2121	Surface Finish Factor, FKUM		Constant			0.973									
2122	Load Sequence Factor, FLOAD		Constant			0.638									
2123	Fatigue Strength, Sf		Constant			0									
2124	Strain-Brain Exponent, B		Constant			0.52083									
2125	Strain Threshold, Sfth		Constant		no	0.112									

User Options | Properties | Left pipe | Right pipe | Weld | Mitigation | Hoop WRS | Axial WRS | Transient Definitions | TPFARY Inputs | Options | Drop-List Options | Material flags

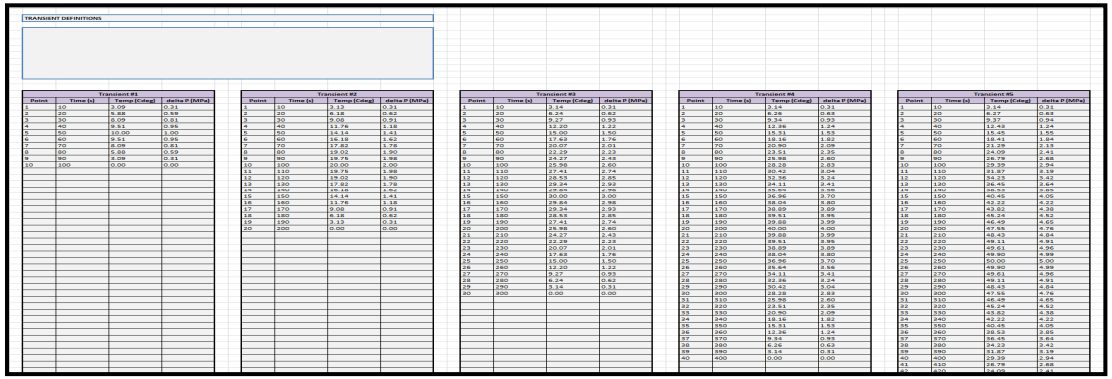
- List all materials properties for selected materials.
- User selects which material is to be used for the left pipe / right pipe / weld / and mitigation (inlay or overlay). Assigned to individual tabs.
- Same characterization as properties for input.

Input set Excel worksheet: WRS



- Universal weight function selected. Up to 26 locations can be used to represent the WRS profile. In the GUI, if distribution selected, the mean is displayed.
- Stress can be entered as a constant or distribution.
- Different distribution can be used for each of the 26 locations.
- Pre- and post- mitigation WRS defined for both Hoop and Axial.
- Weld type , weld properties, and weld repair state (0%, 15%, 50%) can be defined to assign the appropriate geometry and material properties to the problem.

Input set Excel worksheet: transients



TRANSIENT DEFINITIONS

Transient #1			
Point	Time [s]	Temp [Cdeg]	delta P [MPa]
1	10	2.09	0.31
2	20	5.19	0.63
3	30	6.09	0.81
4	40	9.41	0.96
5	50	10.00	1.00
6	60	9.41	0.96
7	70	8.09	0.81
8	80	5.88	0.59
9	90	4.09	0.41
10	100	0.00	0.00

Transient #2			
Point	Time [s]	Temp [Cdeg]	delta P [MPa]
1	10	3.13	0.31
2	20	6.27	0.63
3	30	9.08	0.91
4	40	11.76	1.18
5	50	14.14	1.41
6	60	16.18	1.62
7	70	17.82	1.78
8	80	19.02	1.90
9	90	19.76	1.98
10	100	20.00	2.00
11	110	19.76	1.98
12	120	19.02	1.90
13	130	17.82	1.78
14	140	16.18	1.62
15	150	14.14	1.41
16	160	11.76	1.18
17	170	9.08	0.91
18	180	6.18	0.62
19	190	3.13	0.31
20	200	0.00	0.00

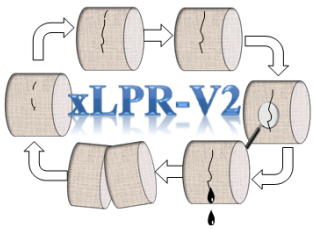
Transient #3			
Point	Time [s]	Temp [Cdeg]	delta P [MPa]
1	10	3.14	0.31
2	20	6.27	0.63
3	30	9.27	0.93
4	40	12.20	1.22
5	50	15.00	1.50
6	60	17.62	1.76
7	70	20.07	2.01
8	80	22.29	2.23
9	90	24.27	2.43
10	100	25.98	2.60
11	110	27.41	2.74
12	120	28.53	2.85
13	130	29.34	2.93
14	140	29.84	2.98
15	150	30.00	3.00
16	160	29.84	2.98
17	170	29.34	2.93
18	180	28.53	2.85
19	190	27.41	2.74
20	200	25.98	2.60
21	210	24.27	2.43
22	220	22.29	2.23
23	230	20.07	2.01
24	240	17.62	1.76
25	250	15.00	1.50
26	260	12.20	1.22
27	270	9.27	0.93
28	280	6.24	0.62
29	290	3.14	0.31
30	300	0.00	0.00

Transient #4			
Point	Time [s]	Temp [Cdeg]	delta P [MPa]
1	10	3.14	0.31
2	20	6.27	0.63
3	30	9.34	0.93
4	40	12.36	1.24
5	50	15.31	1.53
6	60	18.16	1.82
7	70	20.90	2.09
8	80	23.51	2.35
9	90	25.98	2.60
10	100	28.28	2.83
11	110	30.42	3.04
12	120	32.36	3.24
13	130	34.11	3.41
14	140	35.63	3.56
15	150	36.96	3.70
16	160	38.04	3.80
17	170	38.89	3.89
18	180	39.51	3.95
19	190	39.88	3.99
20	200	40.00	4.00
21	210	39.88	3.99
22	220	39.51	3.95
23	230	38.89	3.89
24	240	38.04	3.80
25	250	36.96	3.70
26	260	35.63	3.56
27	270	34.11	3.41
28	280	32.36	3.24
29	290	30.42	3.04
30	300	28.28	2.83
31	310	25.98	2.60
32	320	23.51	2.35
33	330	20.90	2.09
34	340	18.16	1.82
35	350	15.31	1.53
36	360	12.36	1.24
37	370	9.34	0.93
38	380	6.26	0.63
39	390	3.14	0.31
40	400	0.00	0.00

Transient #5			
Point	Time [s]	Temp [Cdeg]	delta P [MPa]
1	10	3.14	0.31
2	20	6.27	0.63
3	30	9.27	0.94
4	40	12.43	1.24
5	50	15.45	1.55
6	60	18.41	1.84
7	70	21.29	2.13
8	80	24.09	2.41
9	90	26.79	2.68
10	100	29.39	2.94
11	110	31.87	3.19
12	120	34.23	3.42
13	130	36.45	3.64
14	140	38.53	3.85
15	150	40.45	4.05
16	160	42.22	4.22
17	170	43.82	4.38
18	180	45.24	4.52
19	190	46.49	4.65
20	200	47.55	4.76
21	210	48.43	4.84
22	220	49.11	4.91
23	230	49.61	4.96
24	240	49.90	4.99
25	250	50.00	5.00
26	260	49.90	4.99
27	270	49.61	4.96
28	280	49.11	4.91
29	290	48.43	4.84
30	300	47.55	4.76
31	310	46.49	4.65
32	320	45.24	4.52
33	330	43.82	4.38
34	340	42.22	4.22
35	350	40.45	4.05
36	360	38.53	3.85
37	370	36.45	3.64
38	380	34.23	3.42
39	390	31.87	3.19
40	400	29.39	2.94
41	410	26.79	2.68
42	420	24.09	2.41

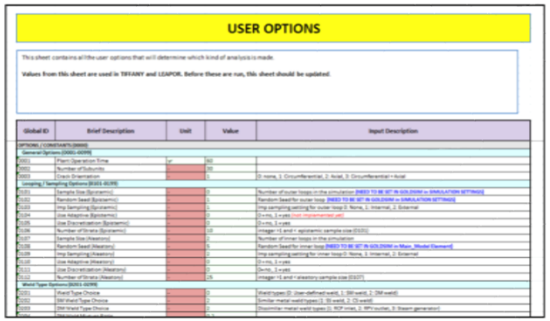
- 20 transients defined.
- Copied in worksheet to be used by TIFFANY add-in.
- User will input transient definitions (up to 20) into one of the three transient types (type I only, type I and II, type III); additional inputs allows the framework to schedule the transients.

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



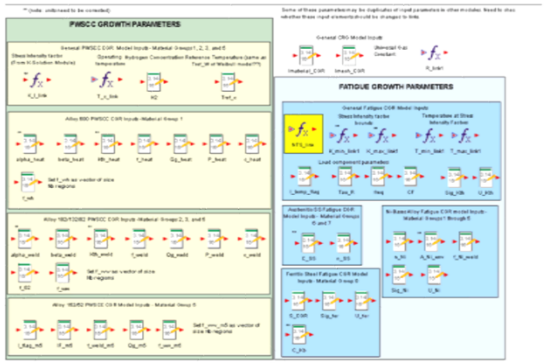
- Data passed through input interface (landing platform) and hands it off to the GoldSim software.

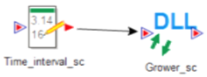
Input distributions
Are defined within the input Excel worksheet. User can also select uncertainty type (aleatory/epistemic).



Uncertain input values are sampled automatically by the code.

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





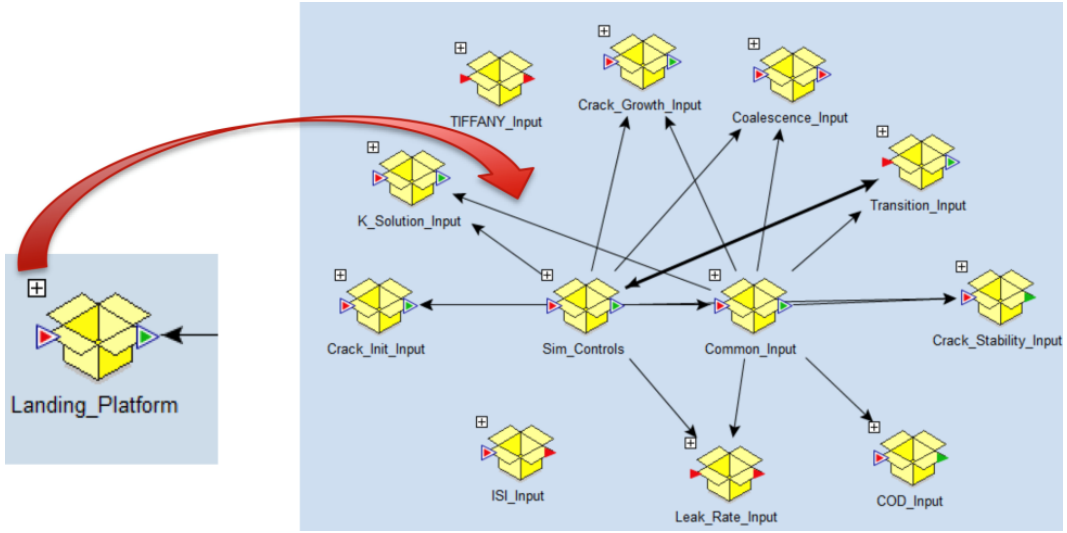
For Detailed Information on the module's features please refer to the Controlled Module Documentation on the xLPR Configuration Management Web Site:
https://websps1.battelle.org/nrcnureg/home/xLPR_CM/Beta%20Model%20Dev/Forms/AllItems.aspx?RootFolder=%2fnrcnureg%2fhome%2fxLPR%5fCM%2fBeta%20Model%20Dev%2fModules%2fGrower%5f%2e1&FolderCTID=&View=%7b8BE040D4%2d490D%2d4B42%2dB1A1%2d238DBE499771%7d

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

Landing platform

- Tie up (hub) the Input (Excel), Sampling Structure (GoldSim) and Physical (deterministic) models (DLLs) under the same umbrella.
- Prepare all inputs and user selected options required by each sub-model for the model to run.

Landing platform: Groups inputs values from Excel input spreadsheet according to their use in sub-models into a common "hub"

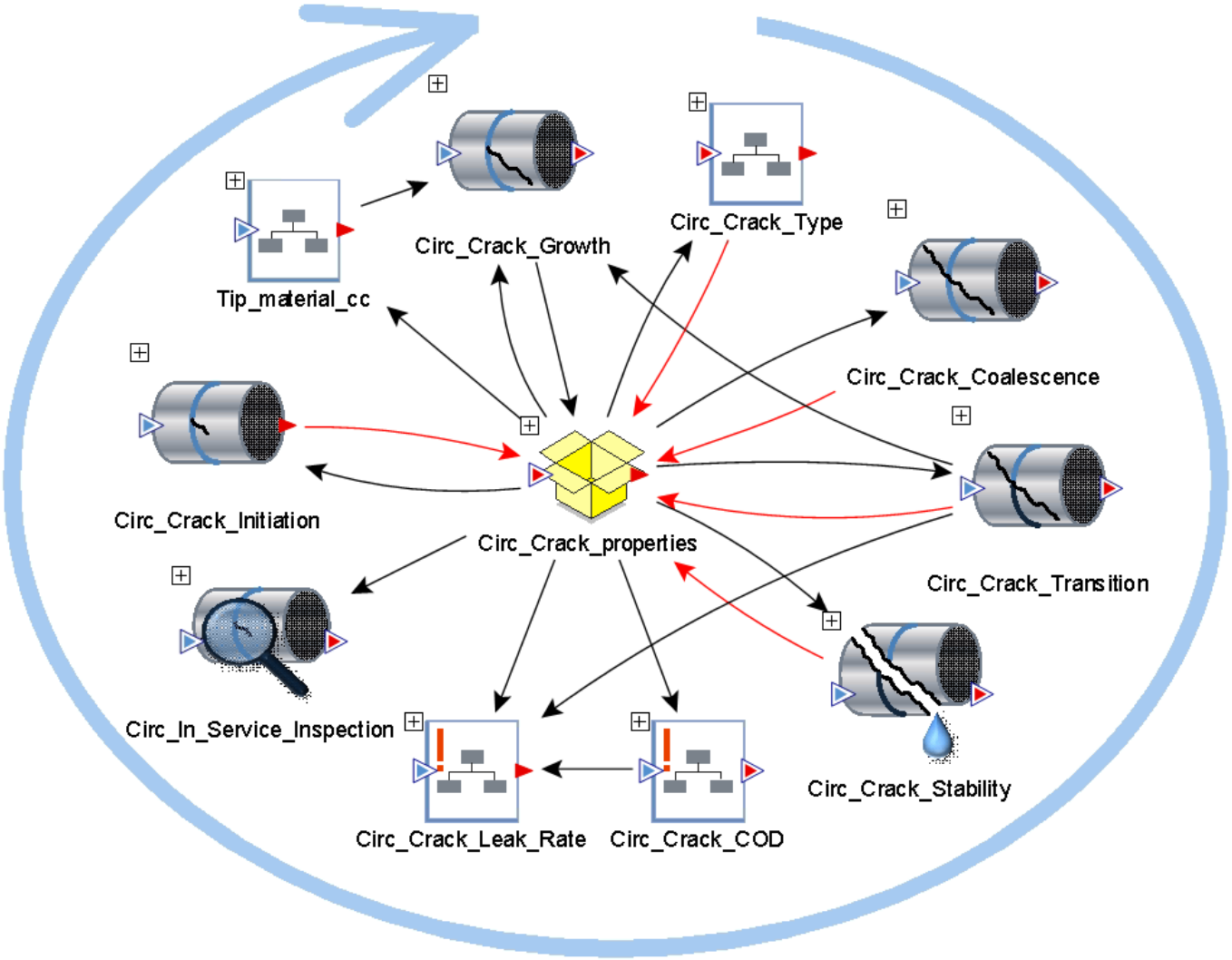


- Each container includes all the information required for the corresponding sub-model to run.
- **Sim controls** have model options (e.g. circ. and/or axial; model choices; fatigue and/or PWSCC.)
- **Common input** regroups inputs and intermediate values that are common to many of the modules.

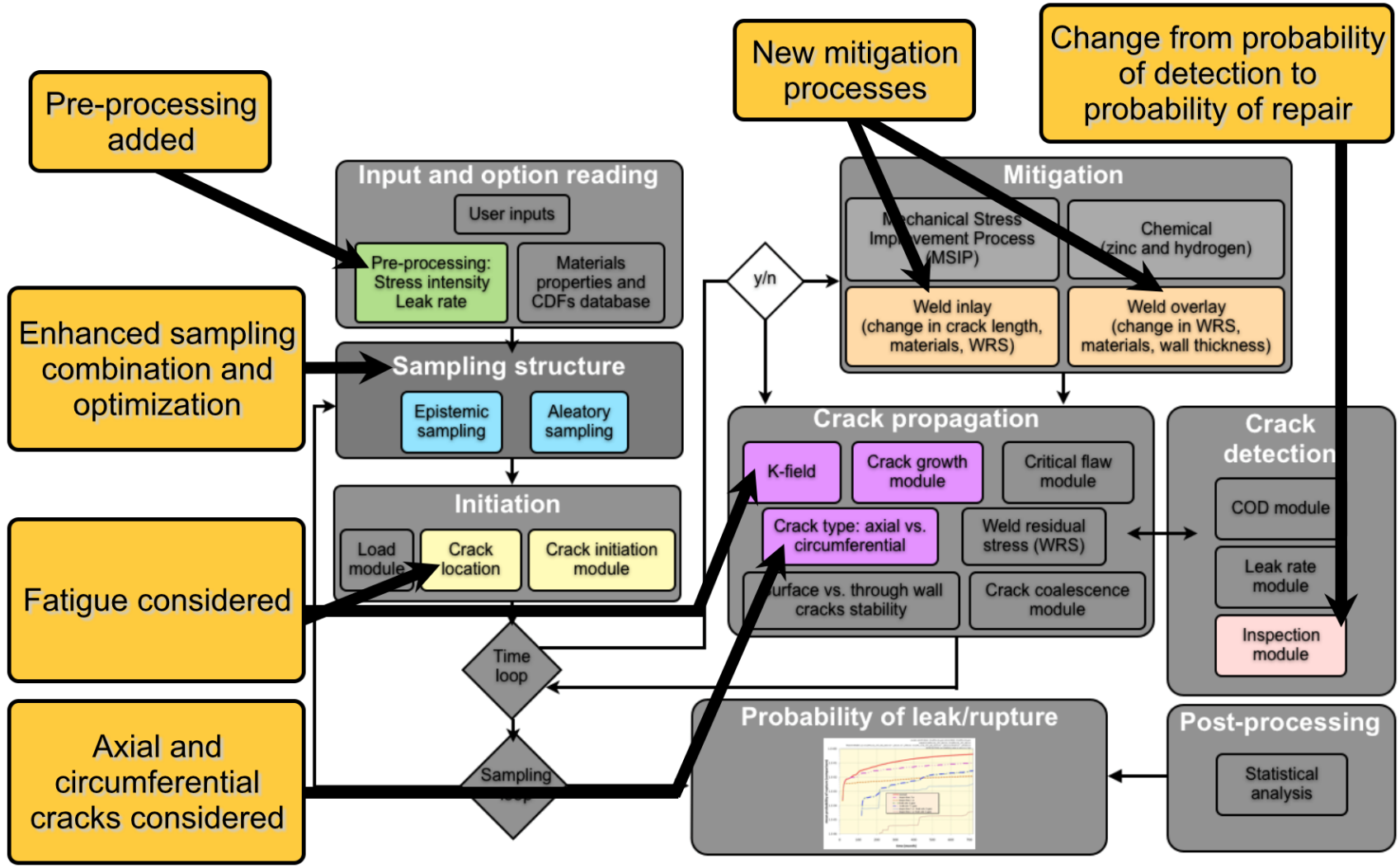
Landing platform: Time interval calculations

- Time is split into discrete time intervals:
  Up to 5 based on operating modes and mitigation times.
- For each time interval (PWSCC), logic script defines: T, pressure, Zn concentration, OD/ID, pipe thickness, normal operating stresses.
- For fatigue, logic script defines time intervals where all the following values constant:
  DO, stresses (min/max), rise time, etc...
- Transient calculation: allows to define how many events (and type) per time step as a function of start/end time, front/back loading, cycles per event, events per year.

Physical (deterministic) model



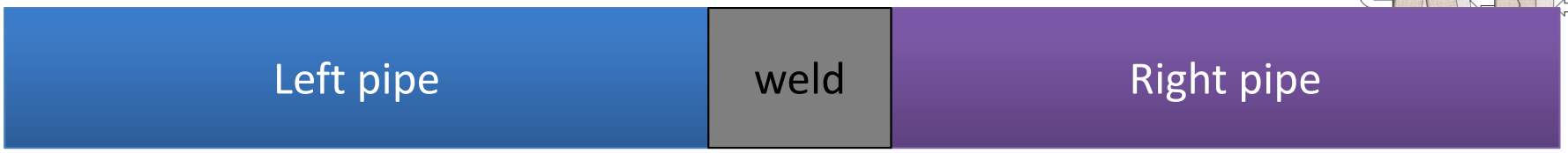
In xLPR v2.0 several modules have been changed and improved based on the lessons learned from xLPR v1.0

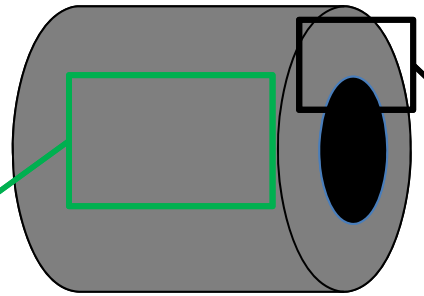


Physical (deterministic) model status

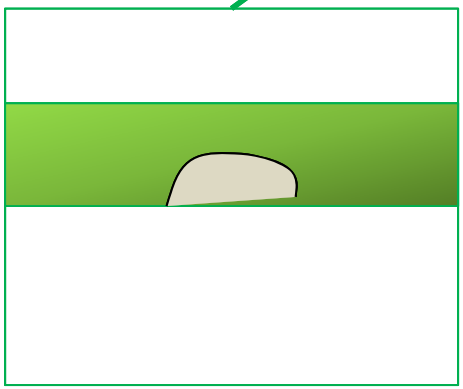
- Circumferential and axial crack evolution have been implemented.
- Both PWSCC and Fatigue mechanisms implemented.
- Currently due to algorithmic restrictions:
  - Time loop starts at coalescence and ends up with crack growth (rate is always applied at end of time loop)
  - New version (under development) will start loop at initiation and end after ISI.
- Features under development :
  - Correlations (WRS implemented)
  - Post-processing
  - Adaptive sampling

Crack modeling (1/2)



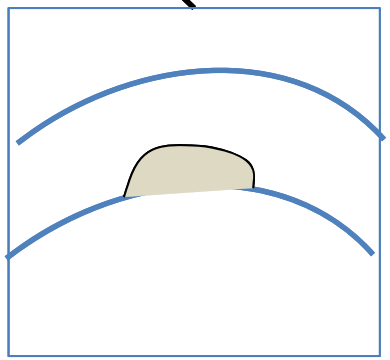


Circumference of pipe divided in N sub-units



Axial cracks

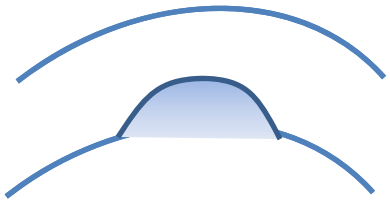
(developed in different planes – do not coalesce)



Circumferential cracks

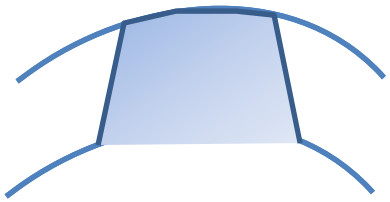
(all in the center of the weld – may coalesce)

Crack modeling (2/2)

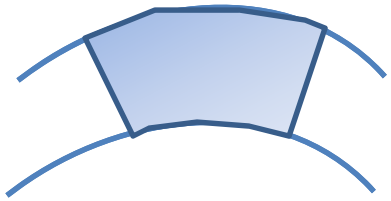


Surface crack (SC)

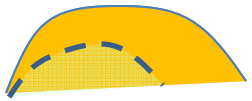
Leaking cracks



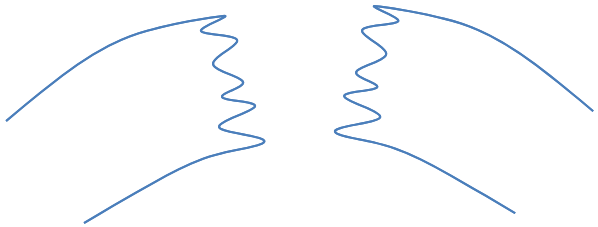
Transitioning crack (TC)



Through wall crack (TWC)

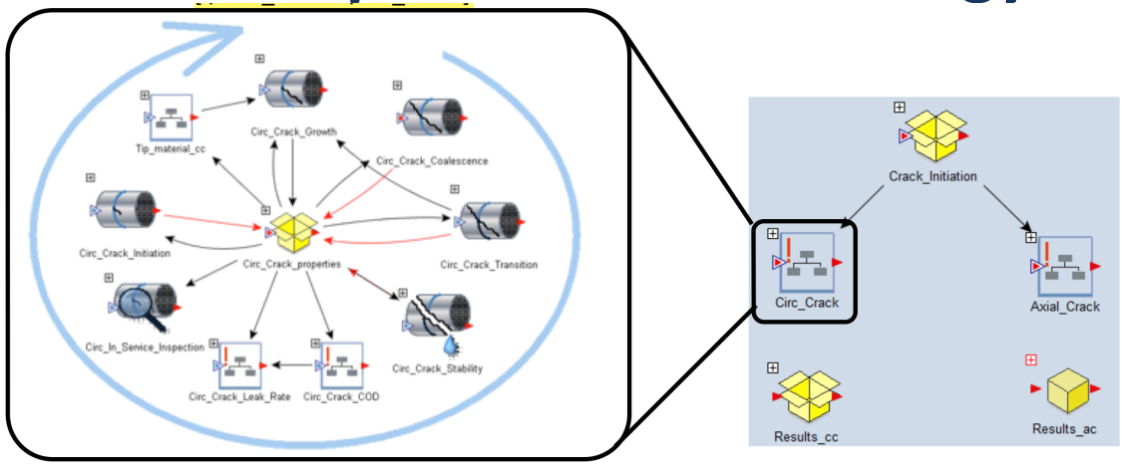


Coalesced crack
(only circ. Crack)



Rupture

Physical (deterministic) model: Purpose and implementation strategy



- **Linking the modules to the Framework (Dynamic Link Libraries).**
- Physical (deterministic) model linked to sampling scheme.
- **Integrator elements** are used to track crack properties (type, position, depth, inner/outer diam., half-length) changing over time.

  Changes in integrator elements are applied as discrete changes (required when several changes may occur within a single time step)
- **Vector structure used to track all sub-units:**
  - Pipe subdivided into N sub-units (i.e. maximum 2N cracks possible for each realization in one simulation).
  - Crack sorted by occurrence time.

Crack definition and tracking (1/3)

- **Crack attributes:**
  - Pipe subdivided into N sub-units
    - Currently N = 30, but can be set up to 100 sub-units.
  - Maximum of 2N cracks possibles (N circumferential, N axial). Axial and circ. cracks can co-exist but do not interact.
  - At each time step, a crack may be defined by 6 properties:
    - Crack type
    - Crack orientation (circ. vs. axial)
    - Crack position (center of segment)
    - Crack depth
    - Crack inner half length
    - Crack outer half length

Crack definition and tracking (2/3)

- **Crack type** provides information about the status of a crack using a relative integer value representing different possible crack aspects:
  - 0: No crack appeared (default and initial at t=0)
  - -1: Surface crack (circ. and axial) Starting status when originating
  - -2: Transitioning crack (circ. and axial) Extending from inner to outer but radial lengths different
  - -3: (idealized) through wall crack (circ. and axial) Inner length and outer lengths are similar

- Furthermore positive numbers are used to track specific evolution
  - i Crack has coalesced with crack #i (circ. only) (from i=1 to nb cracks)
  - 200: Pipe rupture (end of calculation)

- **Crack position and history** ([radians] for circ.; [m] for axial) used to track center of crack.
  - Position of an axial crack center always starts at the center of the weld segment and does not change regardless of different pipe material on left and right of weld; No asymmetrical growth.

Crack definition and tracking (3/3)

- **Crack depth** represents the depth of the crack from the inside of the pipe toward the outside.
  - Used for both circ. and axial cracks (only for surface cracks)
  - Dimensionless and expressed as a fraction of pipe wall thickness

- **ID half-length** represents the crack along pipe inner-radius.
  - Used for both circ. and axial cracks whether surface, transitioning or through-wall.
  - Normalized to dimensionless number:
    - Axial: normalized by L (length of the weld)
    - Circ.: Normalized by π (expressed as radian initially)

- **OD half-length** represents the crack along pipe outer radius.
  - Used for both circ. and axial cracks when they are transitioning or becoming through-wall.
  - Normalized to dimensionless number the same way as ID half-length

Pre-processing

- Generate look-up tables for changes in stresses and K values for fatigue crack initiation and fatigue crack growth during transients.

- Generate look-up tables for leak rate.

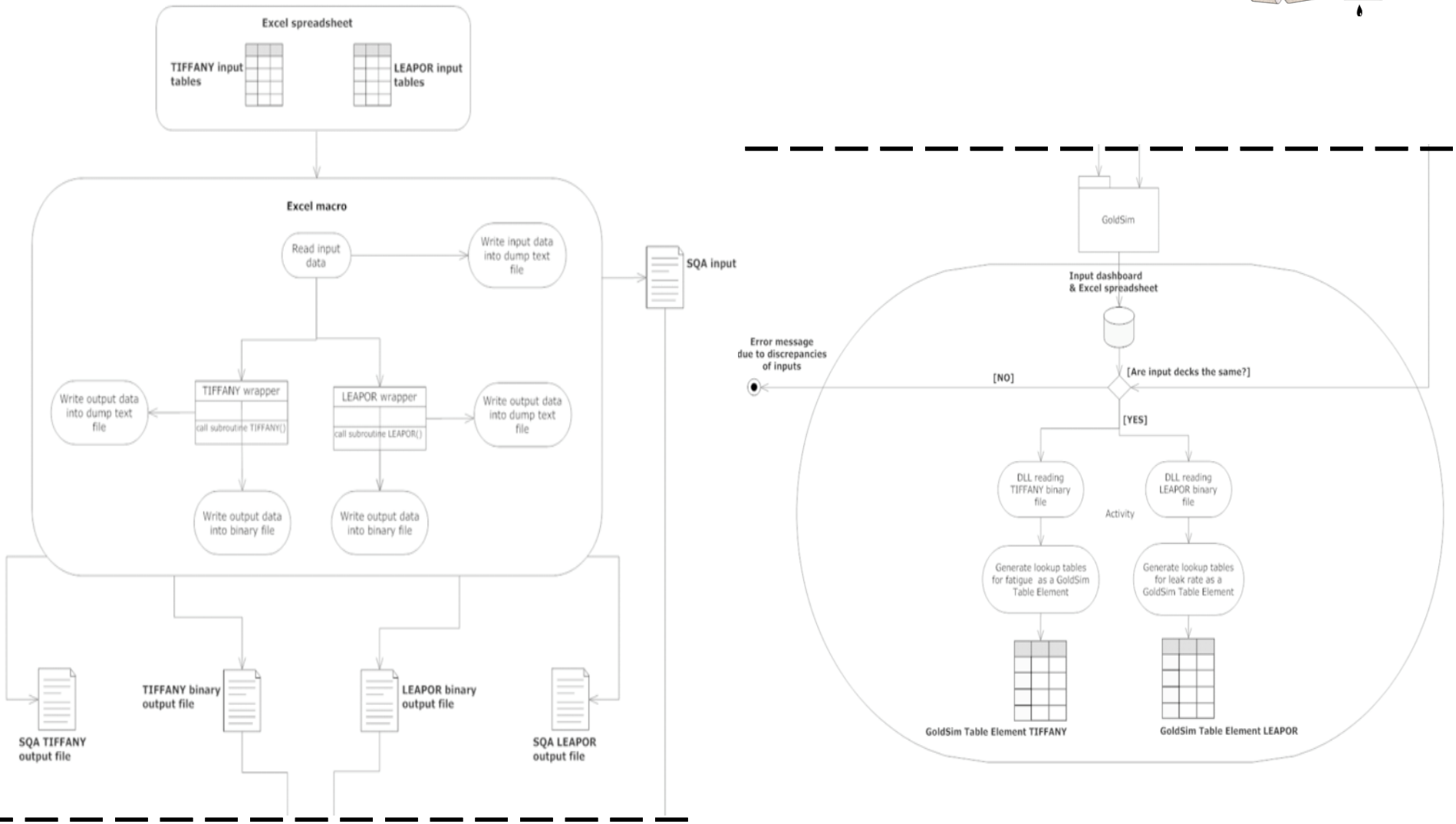
- Look-up tables to be interpolated by the Framework.

TIFFANY and LEAPOR functionalities

- **TIFFANY** estimates SIF bounds for associated temperatures which are subsequently used by GoldSim to linearly interpolate the appropriate estimates for the SIF at a given temperature.
- Used to estimate fatigue crack growth and could potentially replace SIF module used in xLPR v1.0 for PWSCC crack growth.

- **LEAPOR (LE**ak **A**nalysis of **P**iping **O**ak **R**idge) is used to calculate leakage rates through tight cracks.
- 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.

Preprocessing flowchart



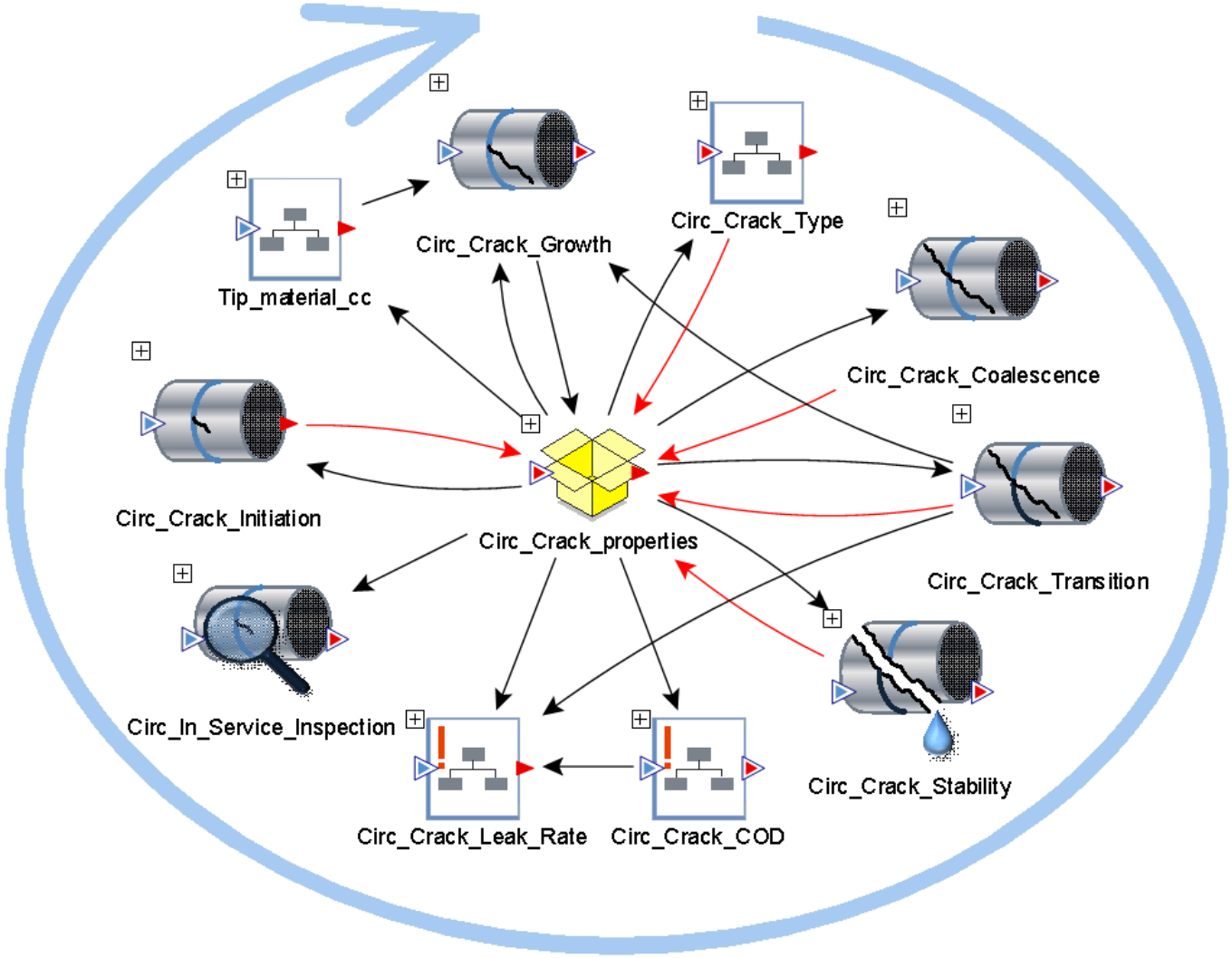
TIFFANY and LEAPOR execution

- TIFFANY and LEAPOR embedded as a DLL subroutine and an Excel add-in to link the xLPR 2.0 inputs Excel worksheet and TIFFANY / LEAPOR.
- Output generated by TIFFANY and LEAPOR transmitted as a binary file to the GoldSim software.
- Additional files containing all the input data used for the runs. Two text files containing calculated results from TIFFANY and LEAPOR (not used by the code – only QA purpose)
- **TIFFANY:**
  - Developed execution logic to use weld material properties and operating data as specified in input worksheets.
  - For each execution, TIFFANY produces 34 look-up tables for each transient, each operating period and each transient type.
  - Implemented logic for pre- and post-mitigation runs.
- **LEAPOR:**
  - Developed data gathering logic (similar to TIFFANY).
  - Pipe outer diameter and wall thickness used to establish discretization of COD , crack length, and wall thickness.
  - For each execution, LEAPOR produces 16 lookup tables.

Modules

- **Contain the physical models describing:**
  Crack initiation, crack growth, crack coalescence, crack transition and crack stability.

- **Information is passed from one module to the other through the landing platform.**


Tip_material_cc
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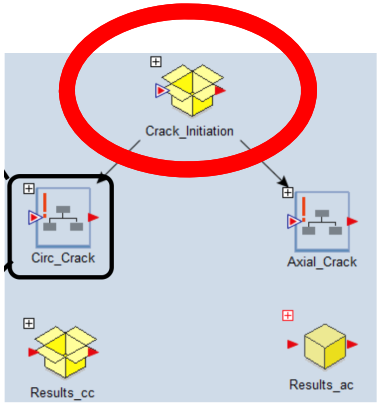
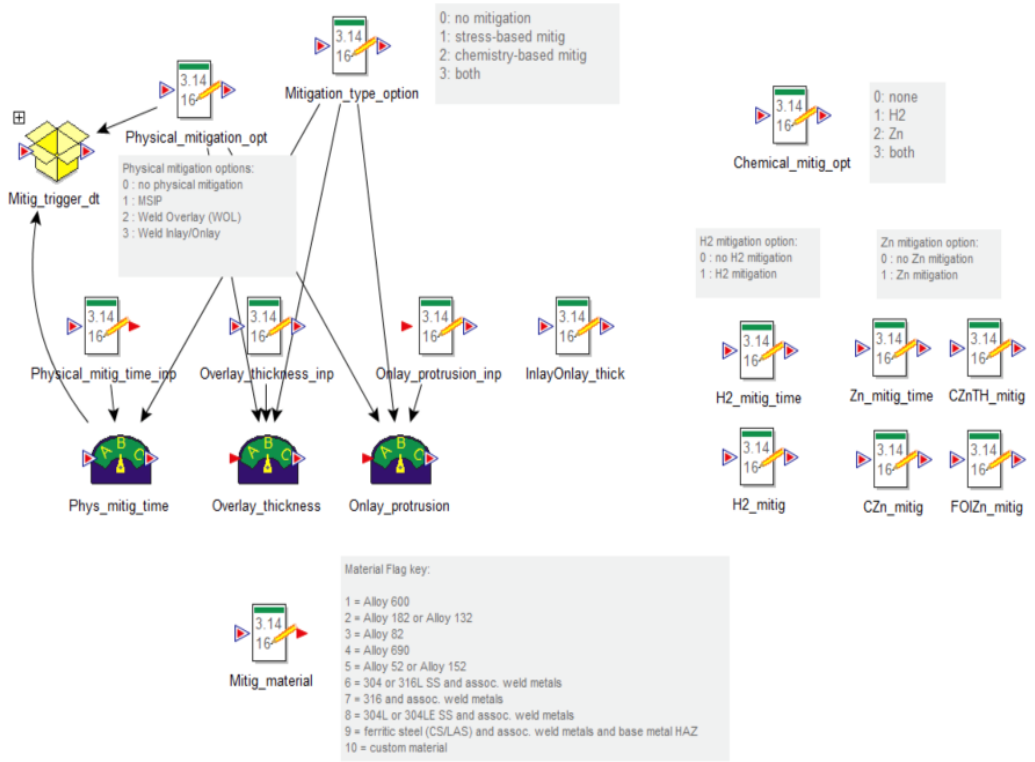
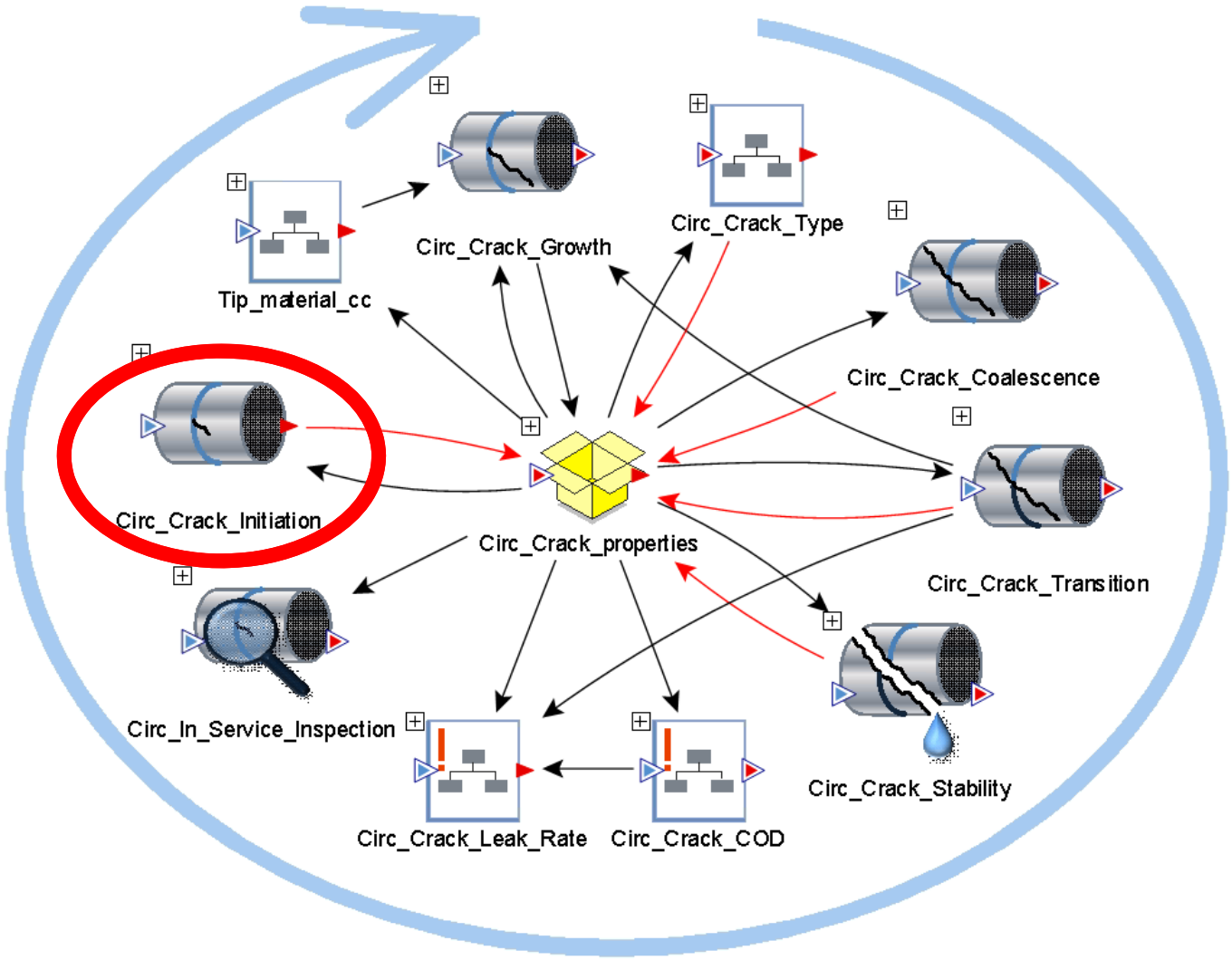
Circ_Crack_Type
Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
Circ_Crack_Transition
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD


Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Mitigation: Framework implementation



- Performed before the simulation starts.
- Logic implemented to identify appropriate mitigation time step.
- Depending on the type of mitigation various internal state variables are redefined (e.g. stresses [MSIP], WRS, geometry, crack location [inlay/onlay]).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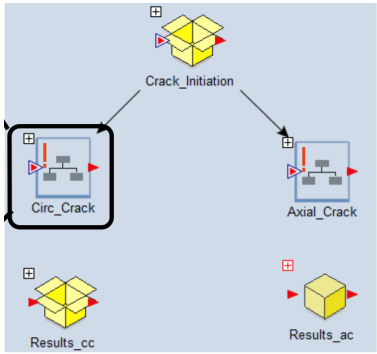
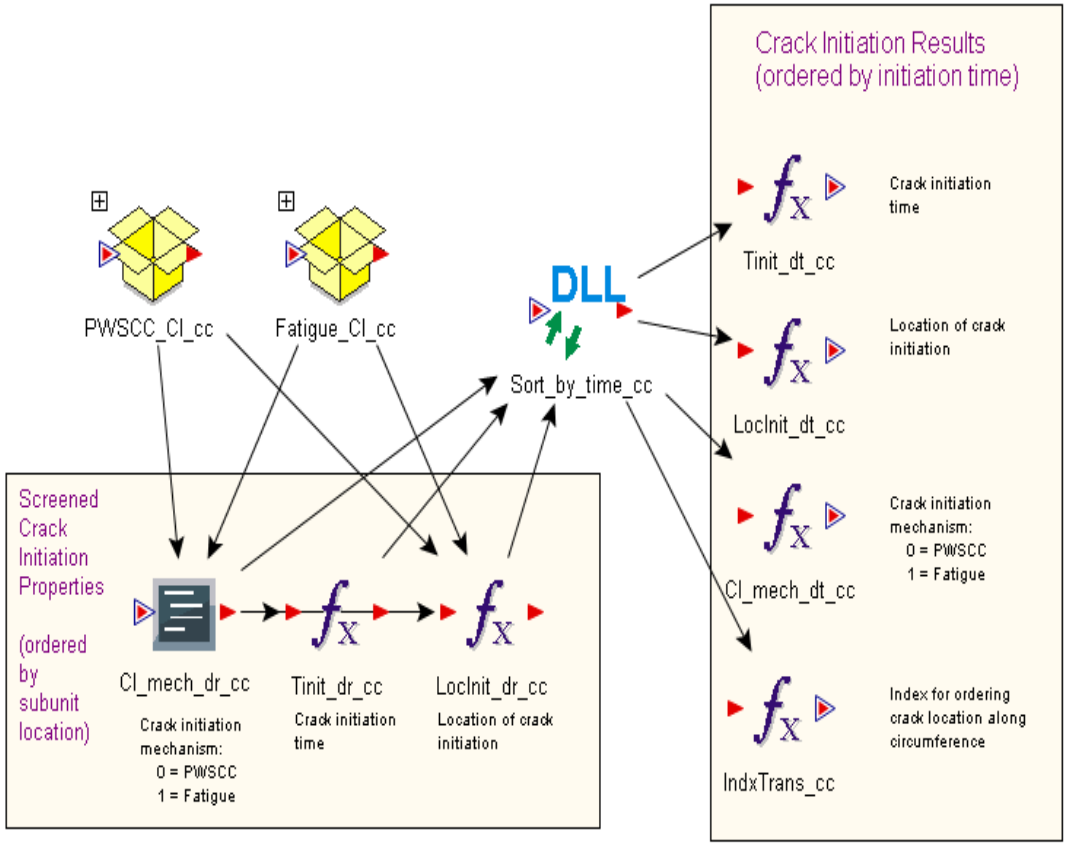
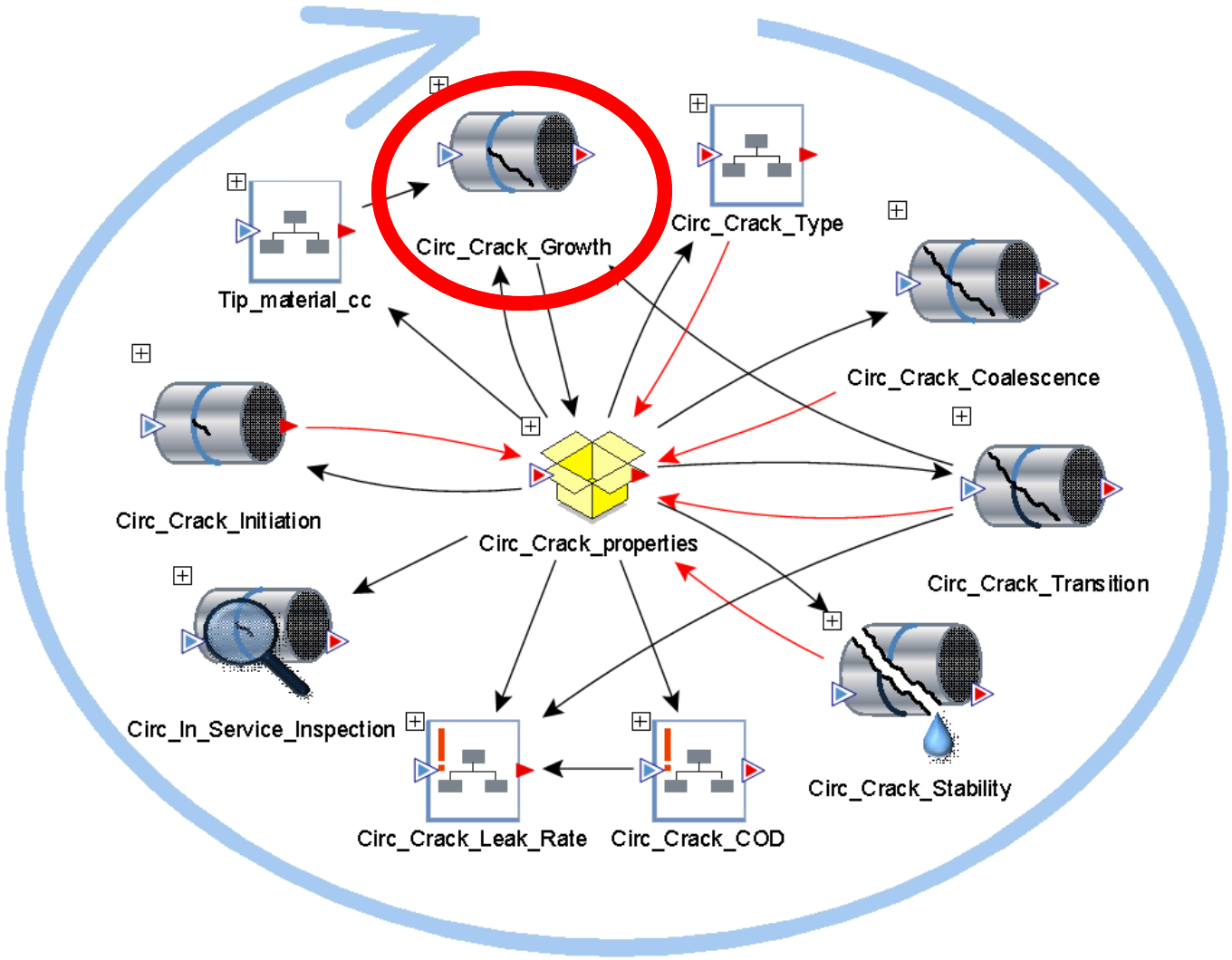
Tip_material_cc
Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
Circ_Crack_Transition
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD


Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Crack Initiation: Framework implementation

- Logic implemented to define crack initiation time intervals.
- Logic implemented to ensure that multiple cracks initiated within time step will all be triggered.
- For inlay/onlay: call crack initiation with inlay properties and adjust crack initiation times after inlay mitigation is applied.




Circ_Crack_Growth
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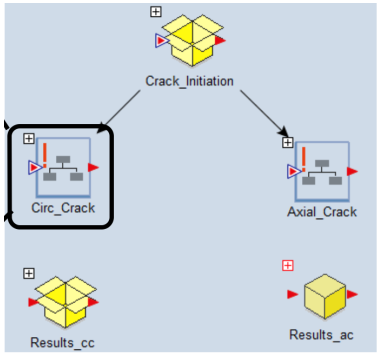
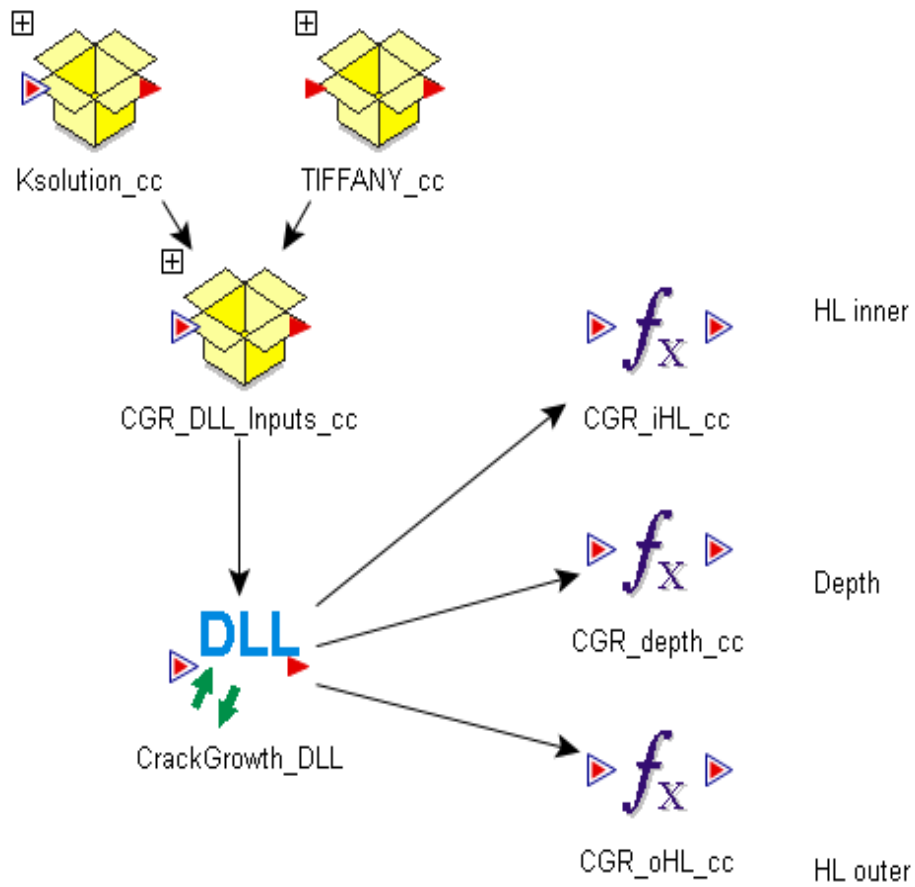
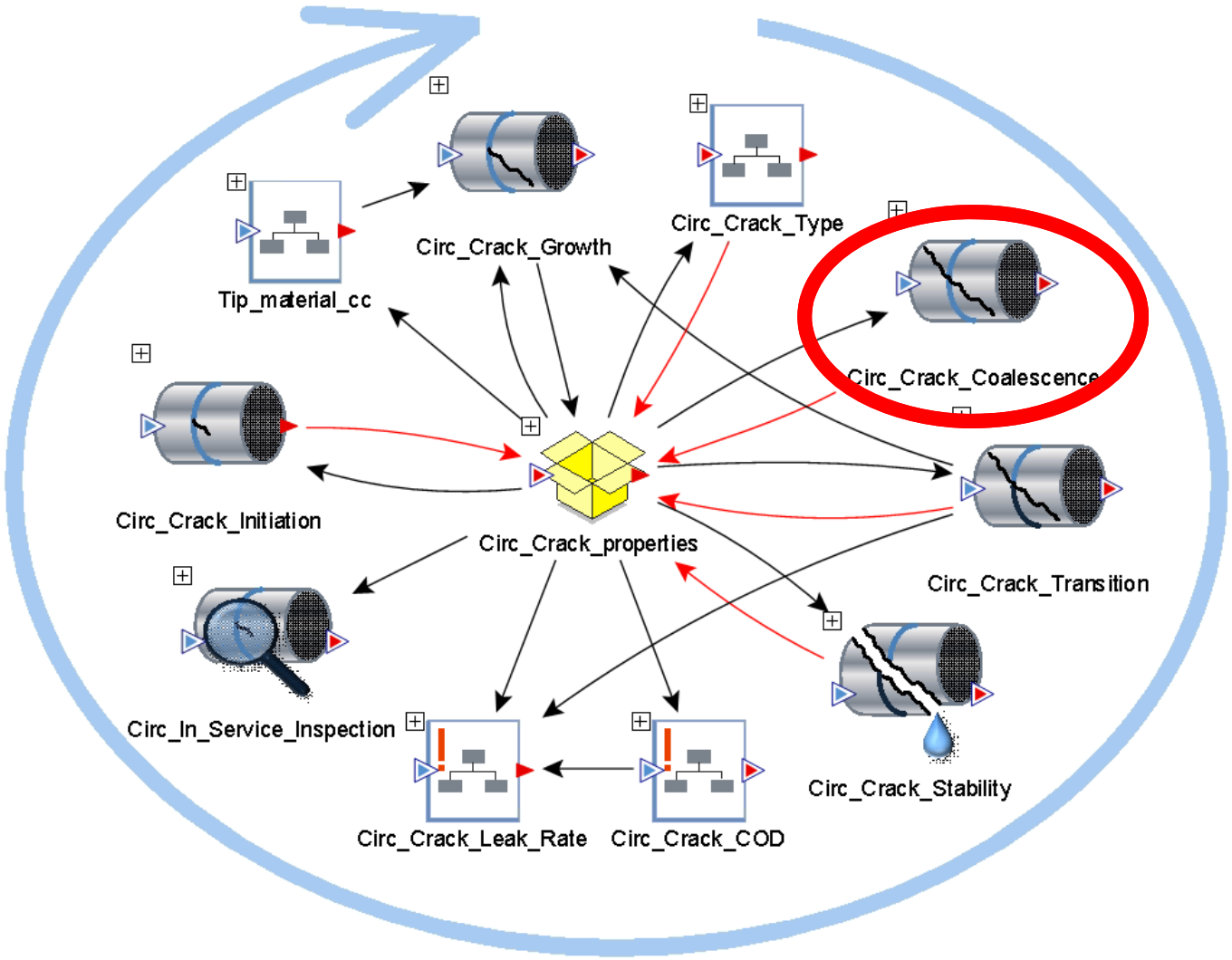
Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
Circ_Crack_Transition
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD


Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Crack growth/K-sol: Framework implementation

- Two crack growth mechanisms are considered:
  - PWSCC
  - Fatigue
- Script to identify materials where each crack tip is located as a function of time, inlay/onlay/overlay, and crack depth to define correct materials properties for crack growth.
- Fatigue K-solution is read from look-up table created by TIFFANY.
- Stress intensity factor vectorized by crack tip.

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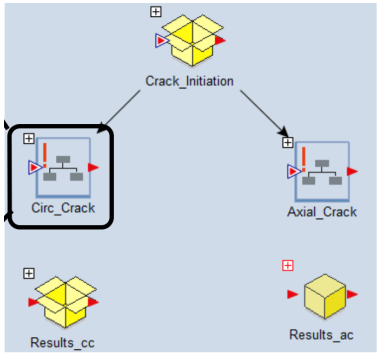
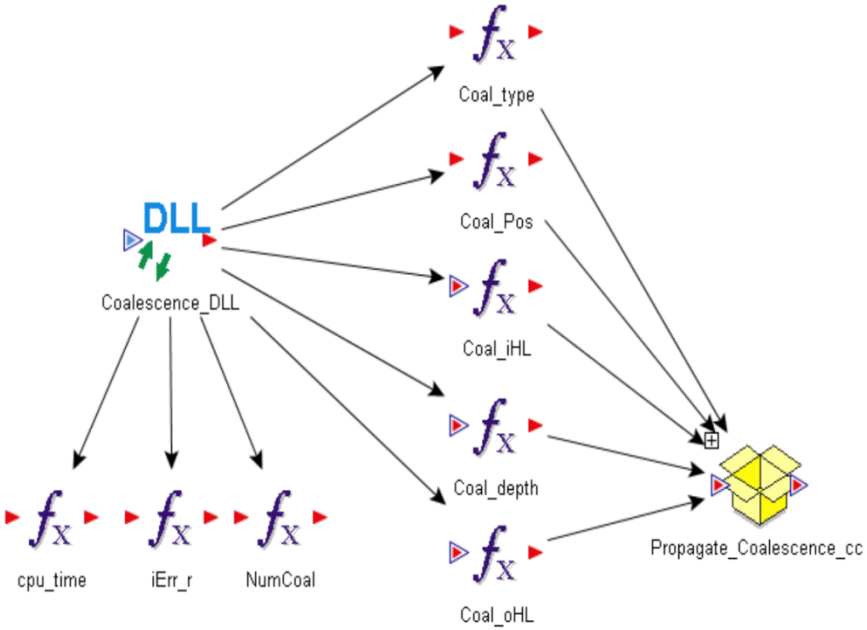
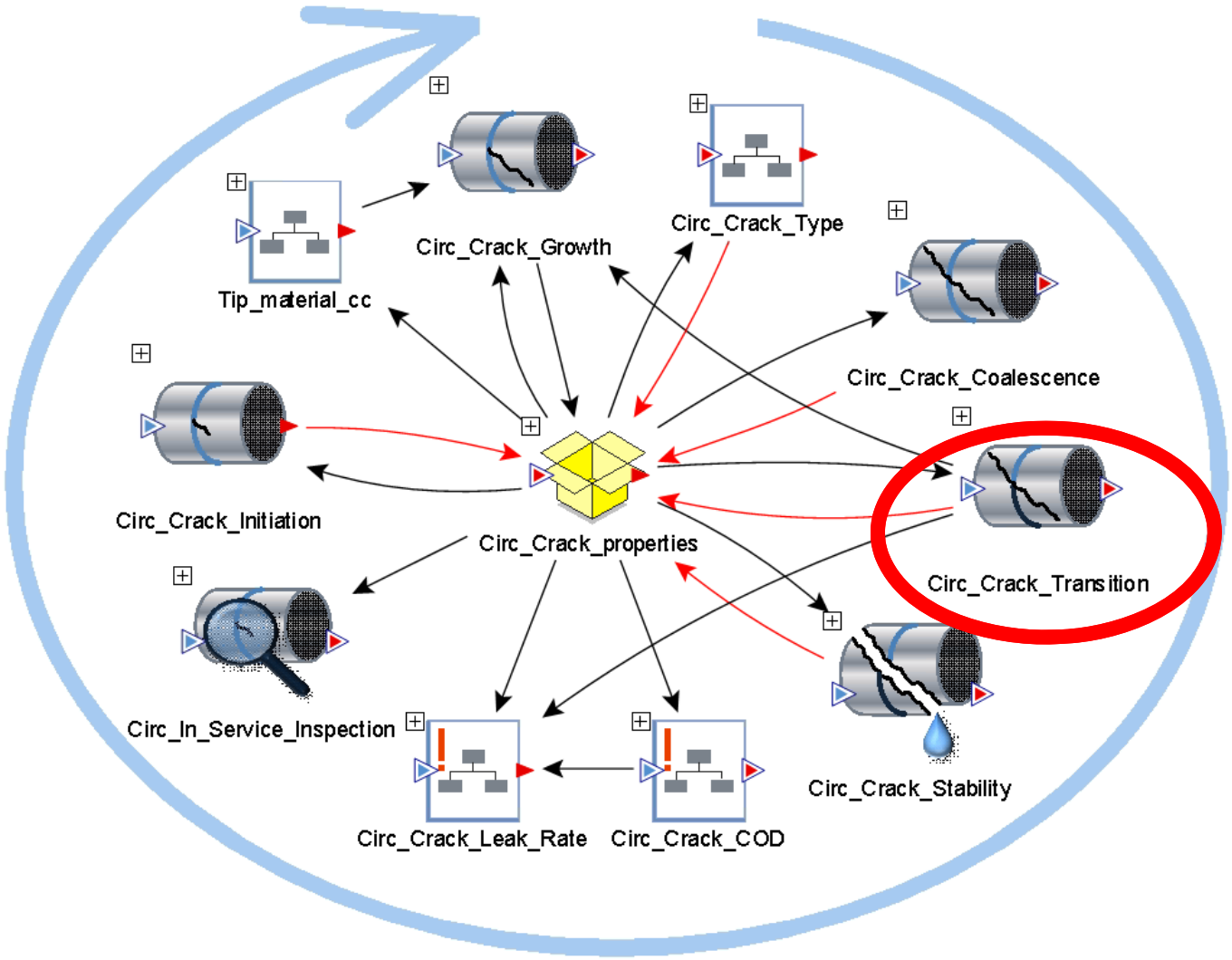
Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
Circ_Crack_Transition
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD


Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Crack coalescence: Framework implementation

- The purpose of this module is to perform the function of simulating crack coalescence of circumferential (no axial) cracks at a given time step.
- For each time step after an active crack has been found the coalescence module is invoked by the coalescence DLL wrapper via the Framework.
- Attribute modified:
  - Crack type, depth, location, ID/OD half length, # of coalescence events
- Crack keeping the information is the one that is the closest to the top dead center reference (coalescer vs. coalescee).

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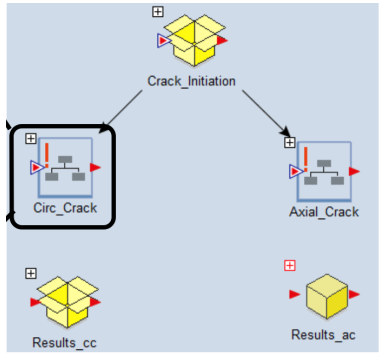
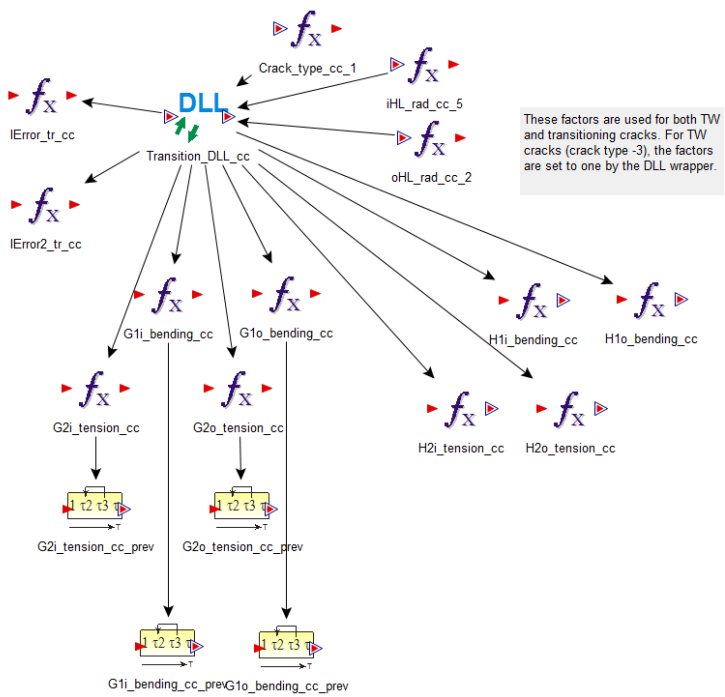
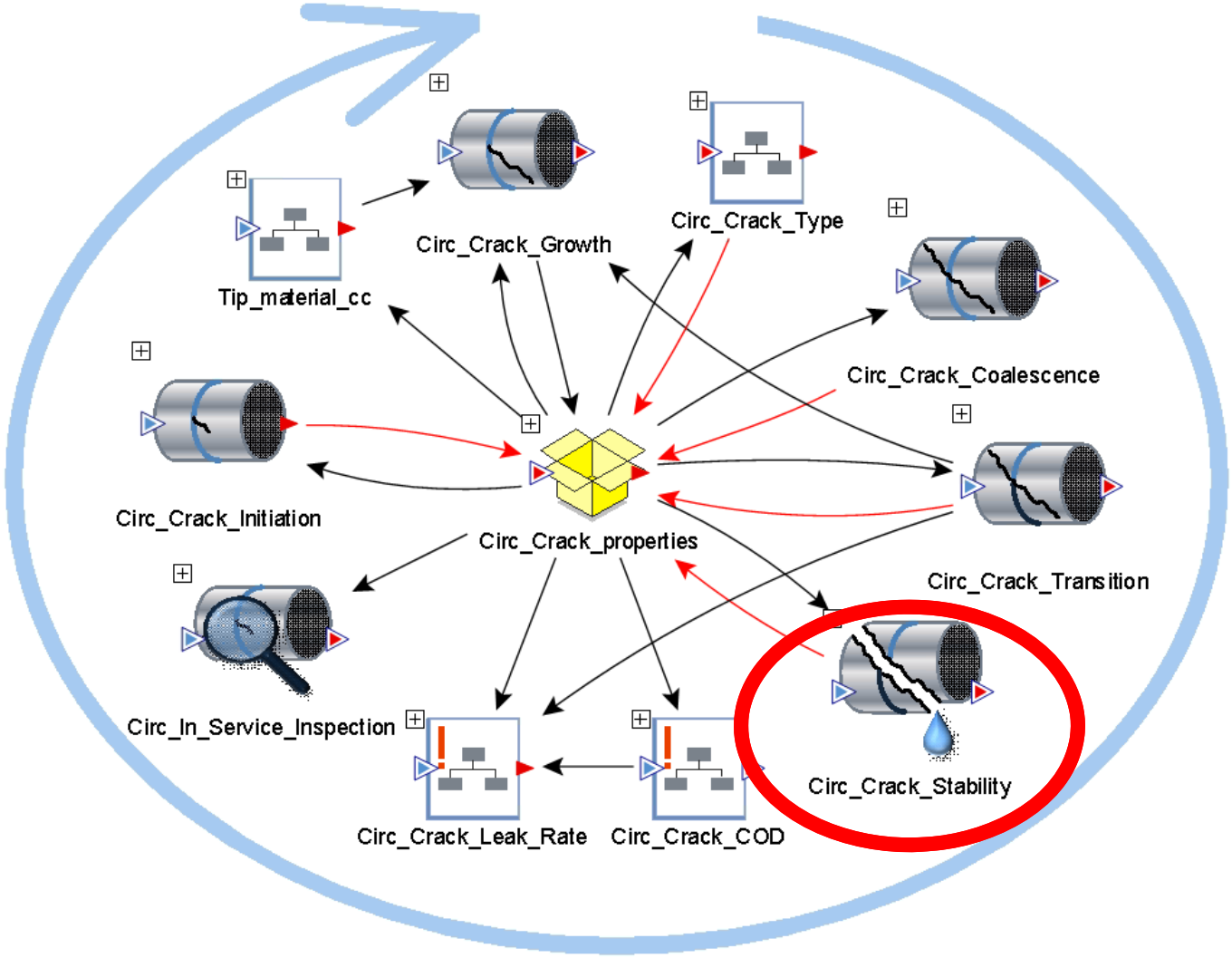
Circ_Crack_Type
Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
Circ_Crack_Transition
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD


Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Crack transition: Framework implementation

- Transition updates crack type from SC to TRC and TRC to TWC based on ratio of inner and outer half-lengths (crack type change).
- Calculates initial OD half-length (crack type change).
- Logic implemented to set non-dimensional depth to 1 (crack type change).
- Calculates correction factors (K and COD) for transitioning cracks (crack transition).

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Circ_Crack_Type
Circ_Crack_Coalescence
Circ_Crack_Initiation
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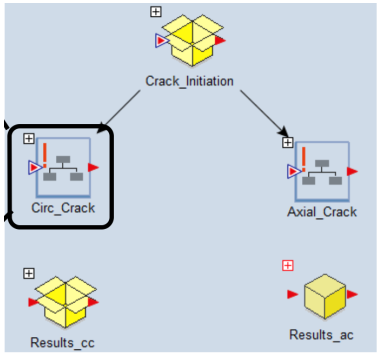
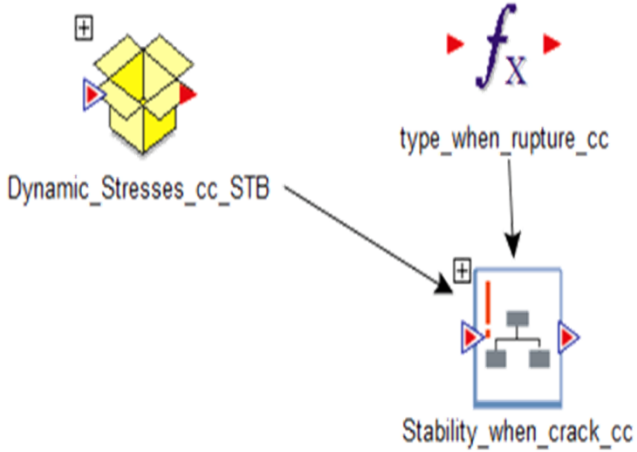
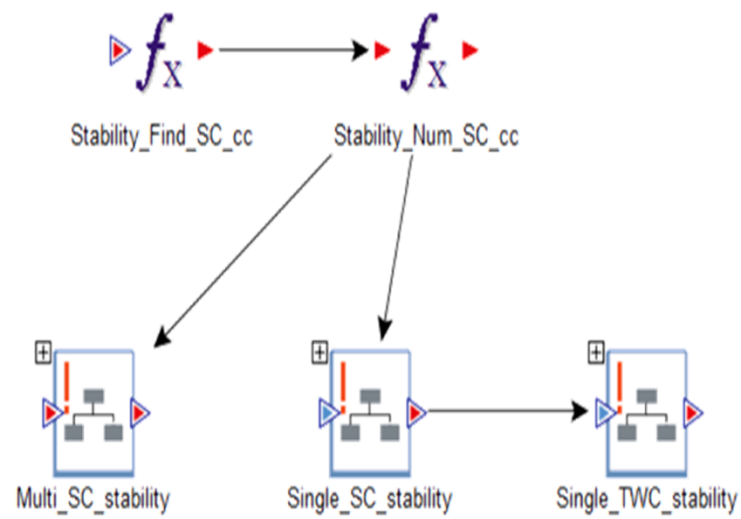
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD

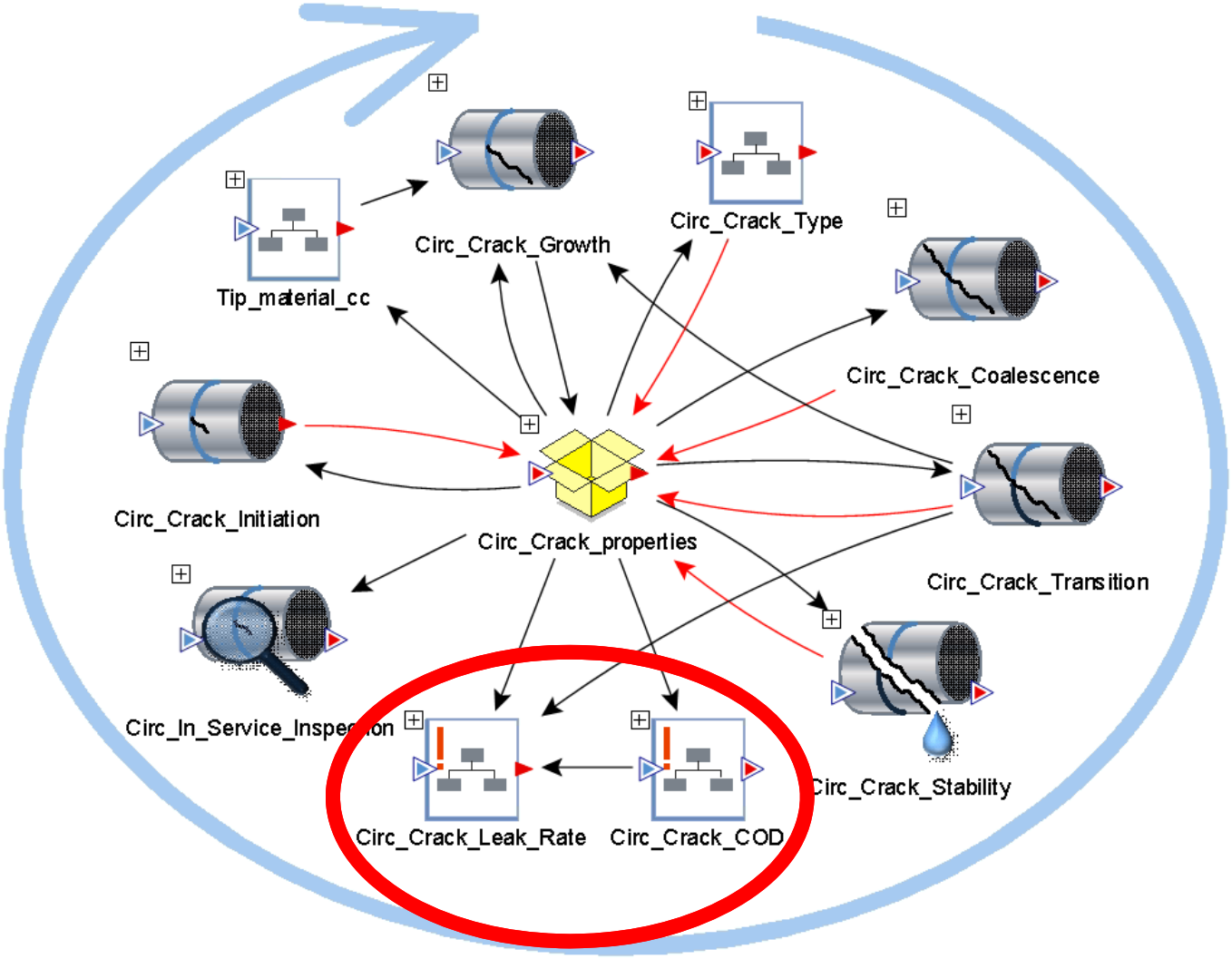

Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Crack stability: Framework implementation

- For each time step (+ predicted time steps) after an active crack has been found the stability module is invoked by the stability DLL wrapper via the Framework.
- Logic implemented to determine if a surface crack becomes a TWC or if we have rupture.
- If only SC, multiple NSC model used (rupture).
- If at least one TWC: Single SC fail (SC to TWC) and single TWC fail model (rupture).
- Seismic consequences tracked:
  - If multiple SC or single TWC gives rupture, track time and continue with nominal.
  - If single SC gives rupture (NSC), check resulting TWC for rupture.






Tip_material_cc
Circ_Crack_Growth
Circ_Crack_Type
Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
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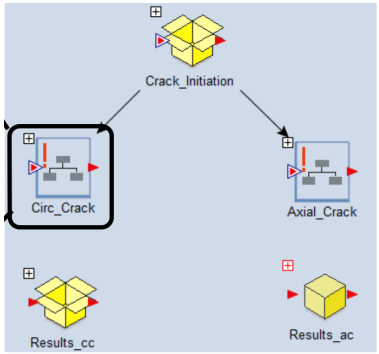
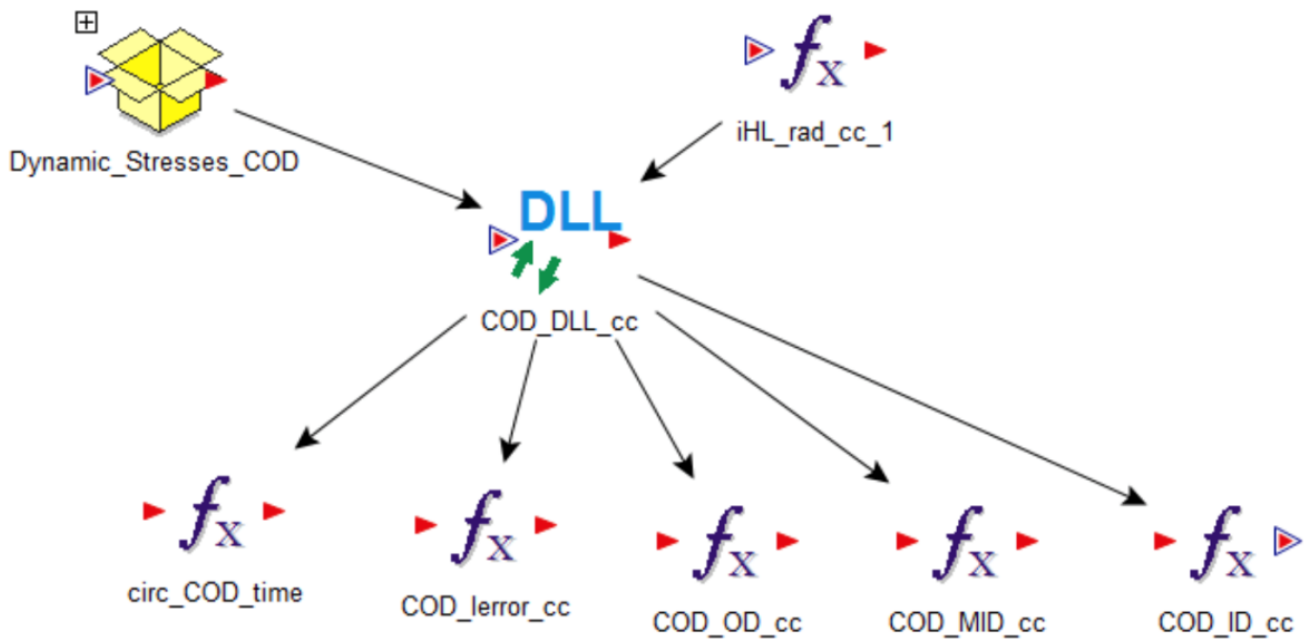
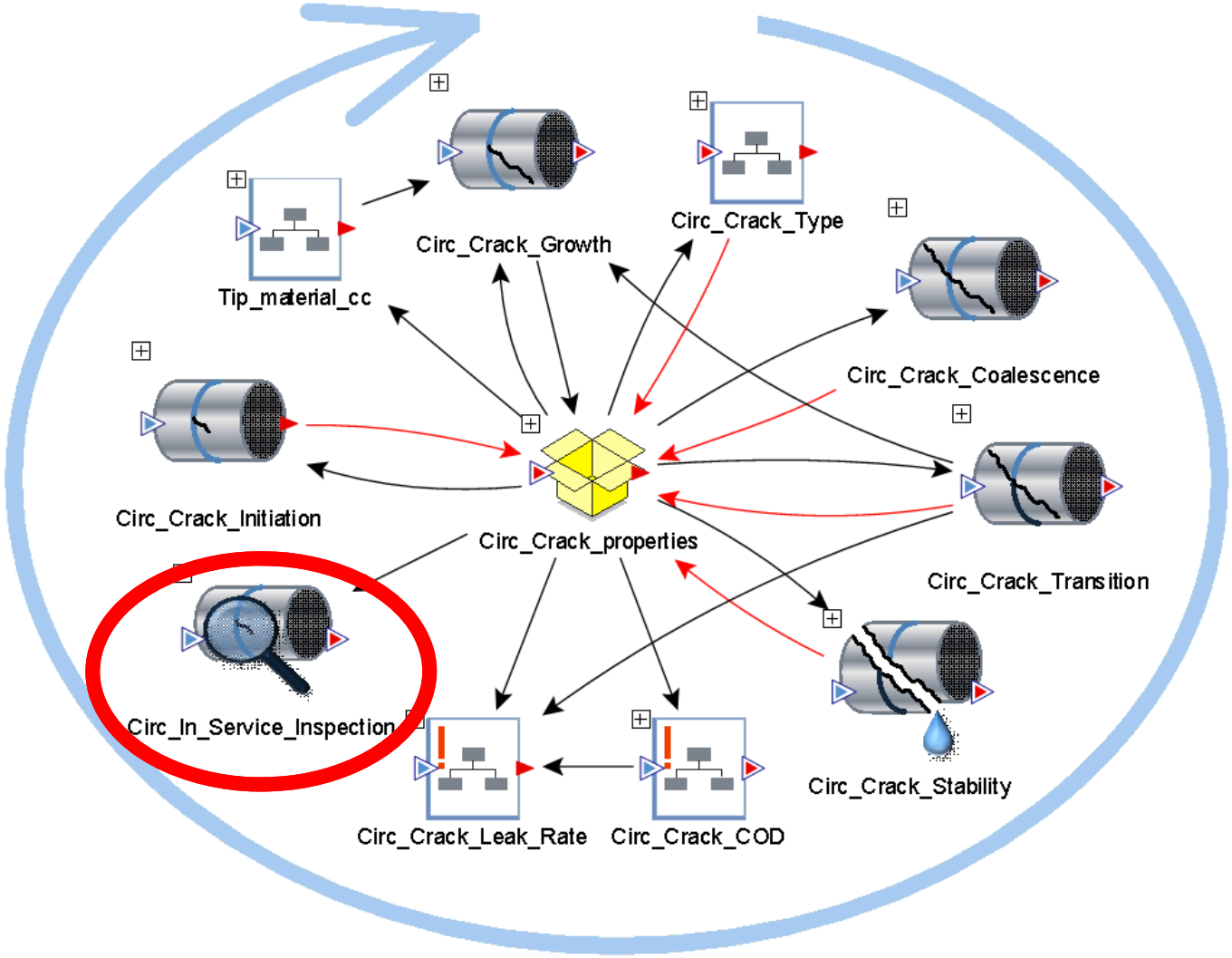
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD


Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

Leak rate calculation: Framework implementation

- COD estimated using module
- Leak rate estimated via lookup tables calculated as pre-processor (LEAPOR)

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Circ_Crack_Coalescence
Circ_Crack_Initiation
Circ_Crack_properties
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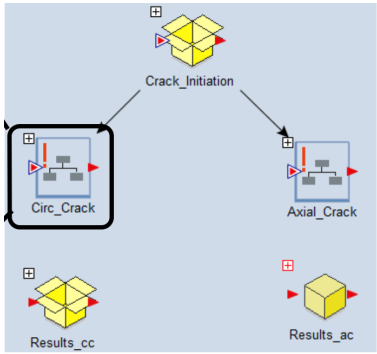
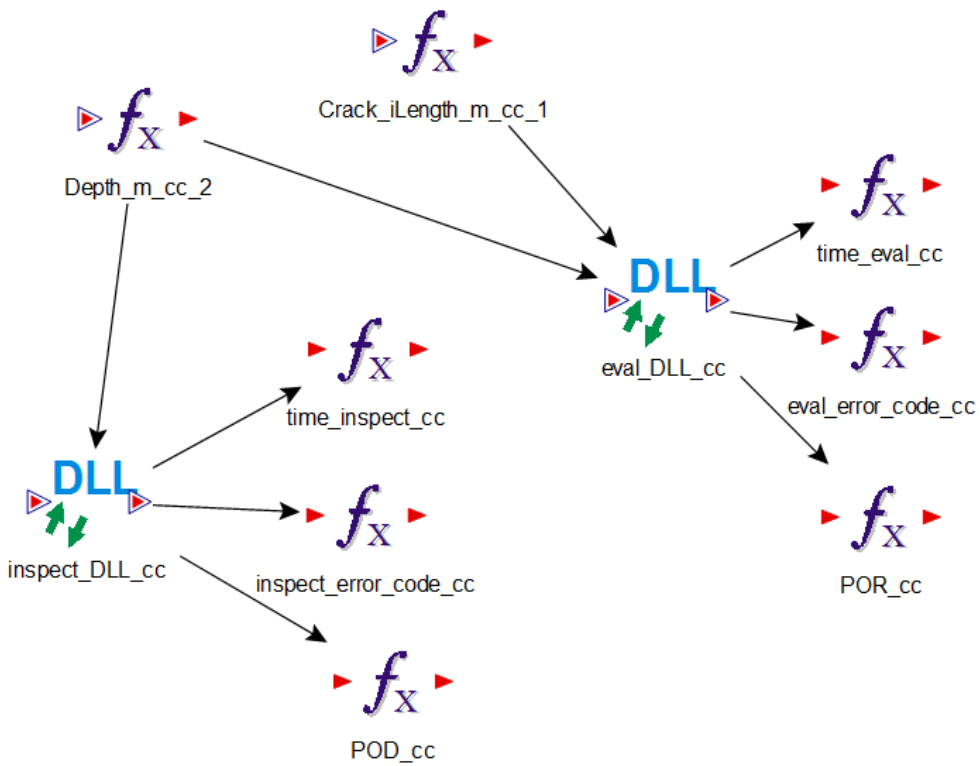
Circ_In_Service_Inspection
Circ_Crack_Stability
Circ_Crack_Leak_Rate
Circ_Crack_COD

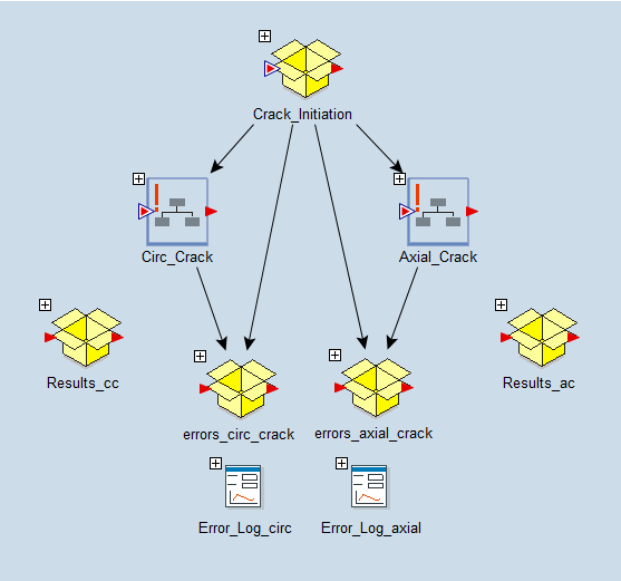

Crack_Initiation
Circ_Crack
Axial_Crack
Results_cc
Results_ac

ISI: Framework implementation

- Calculates the probability of detection AND probability of repair for each crack (two different routines from the same DLL).

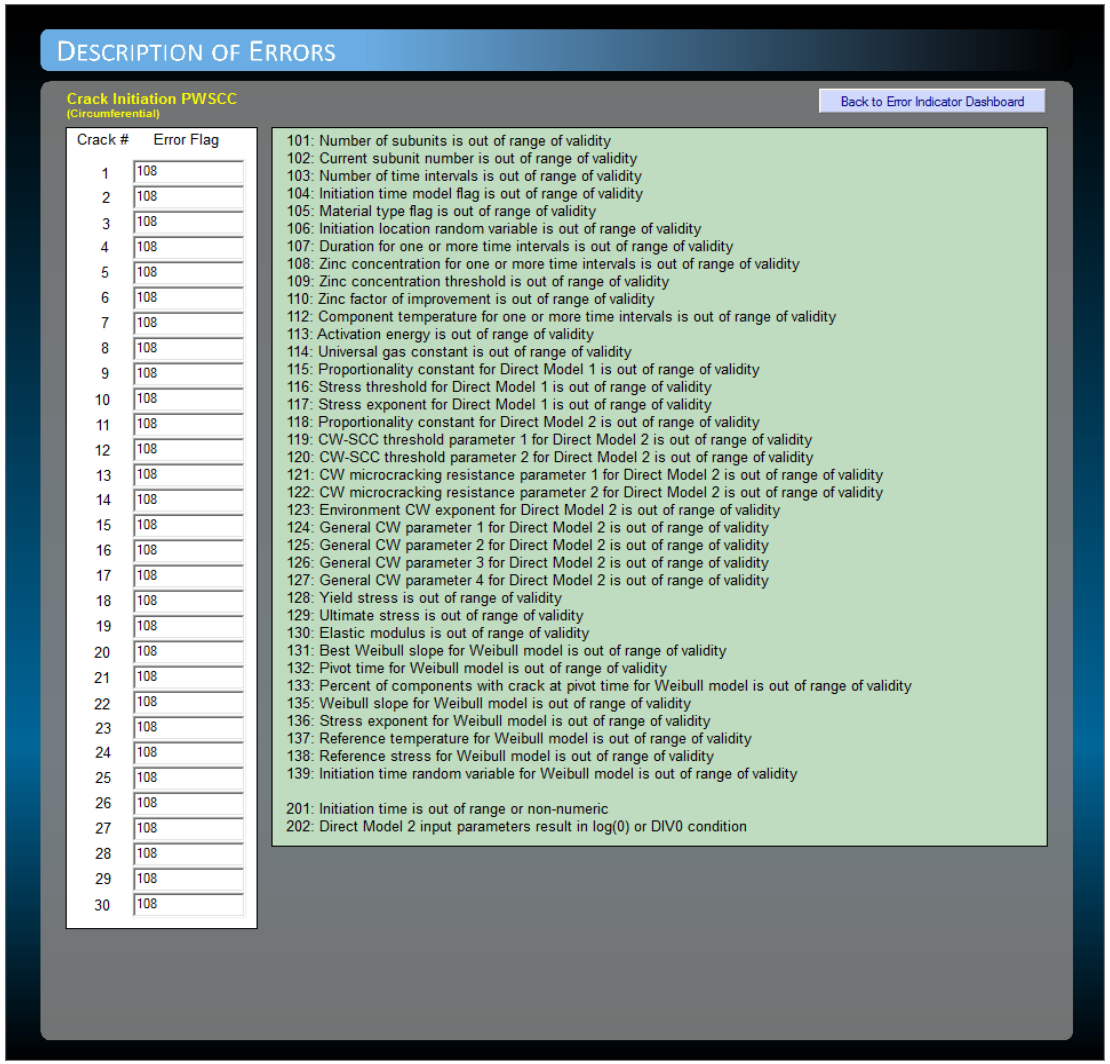


Error dashboard



- Individual error tracking dashboards for circumferential and axial cracks
- Diagnostic tool

Error dashboard



- Error elements tracked per module per sub-unit
- List of error code meanings provided for each module
- Time history results available for each error element
- Additional development and debugging continuing with testing

Output

- Office of Nuclear Reactor Regulation (NRR) leading effort to develop xLPR Acceptance criteria. Align output with acceptance criteria.

- Time history of any internal variable can be saved within the GoldSim software.

- Cumulative probability of initiation, leakage, rupture, rate of change of leak rate (tied up to small/medium/large LOCA).

Sampling structure

- Defines the number and order of realization and appropriate values to use based on uncertainty.
- Outer epistemic loop, and inner aleatory loop.
- [LHS vs. RS]x[DPD vs. no DPD]x[No importance vs. importance vs. adaptive] for each loop.

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 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 development).
- **Possibility of creating 12 sampling combinations: [LHS vs. RS]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)).**

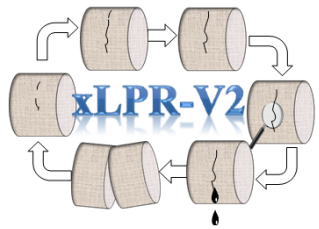
Extremely Low Probability of Rupture (xLPR) Project

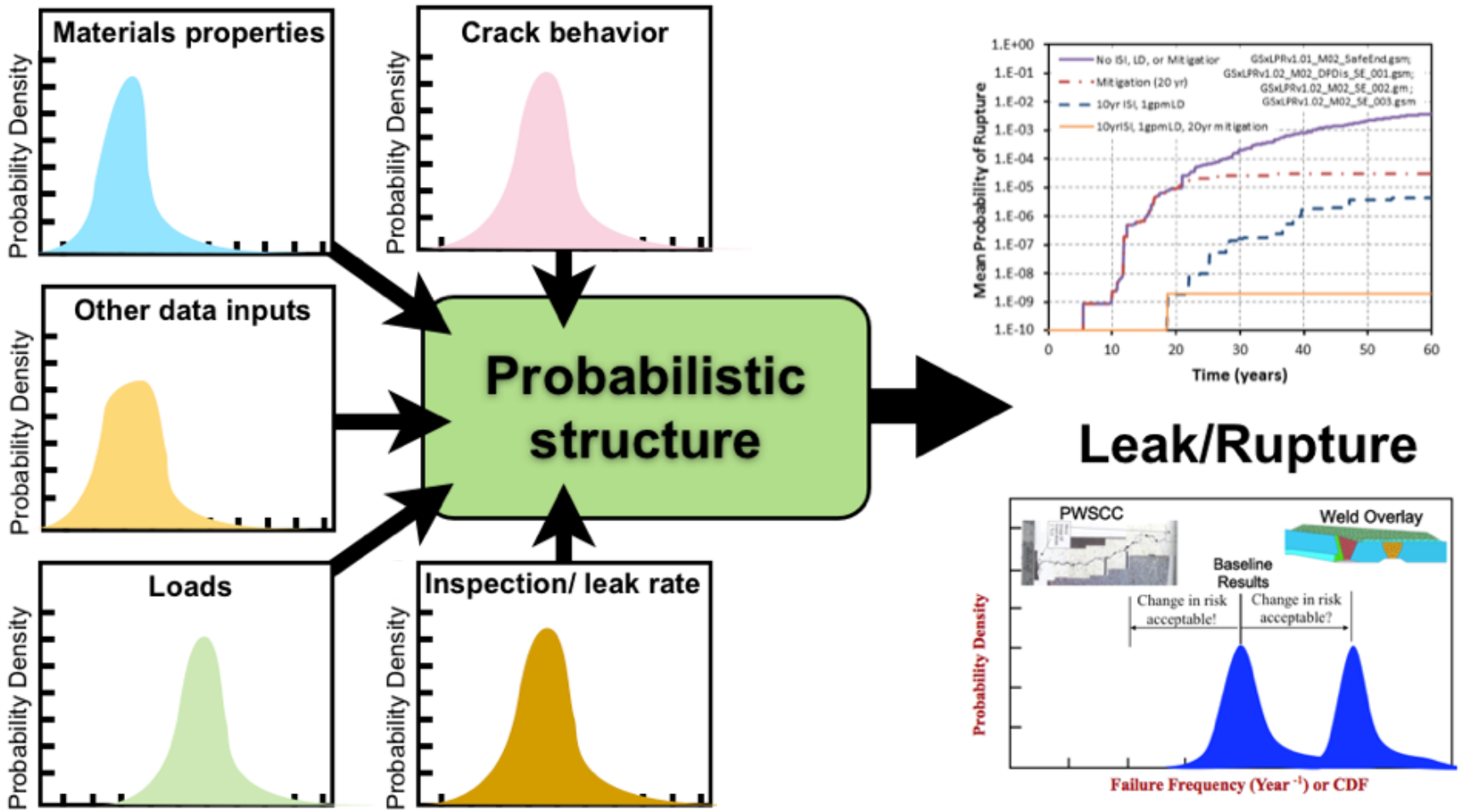
Uncertainty representation

xLPR

xLPR External Review Board Meeting
October 29-30, 2014

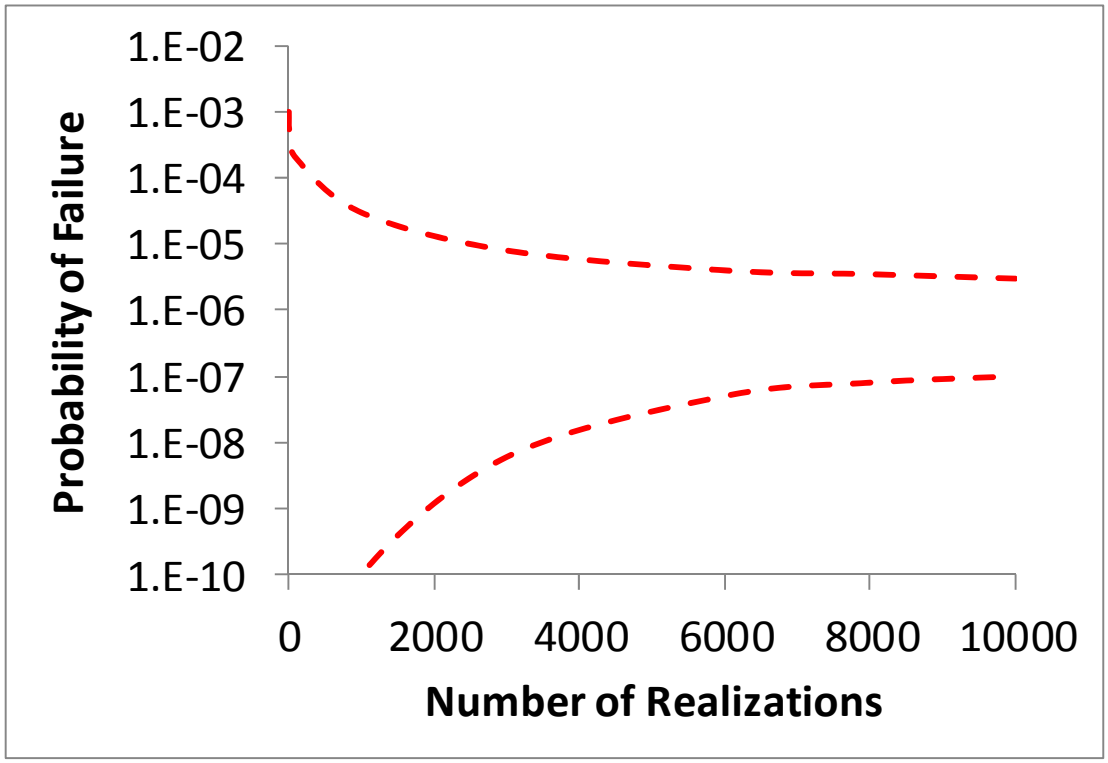
xLPR is a probabilistic assessment tool that can be used directly to demonstrate compliance with 10CFR50App-A GDC-4 requirement of extremely low probability of failure





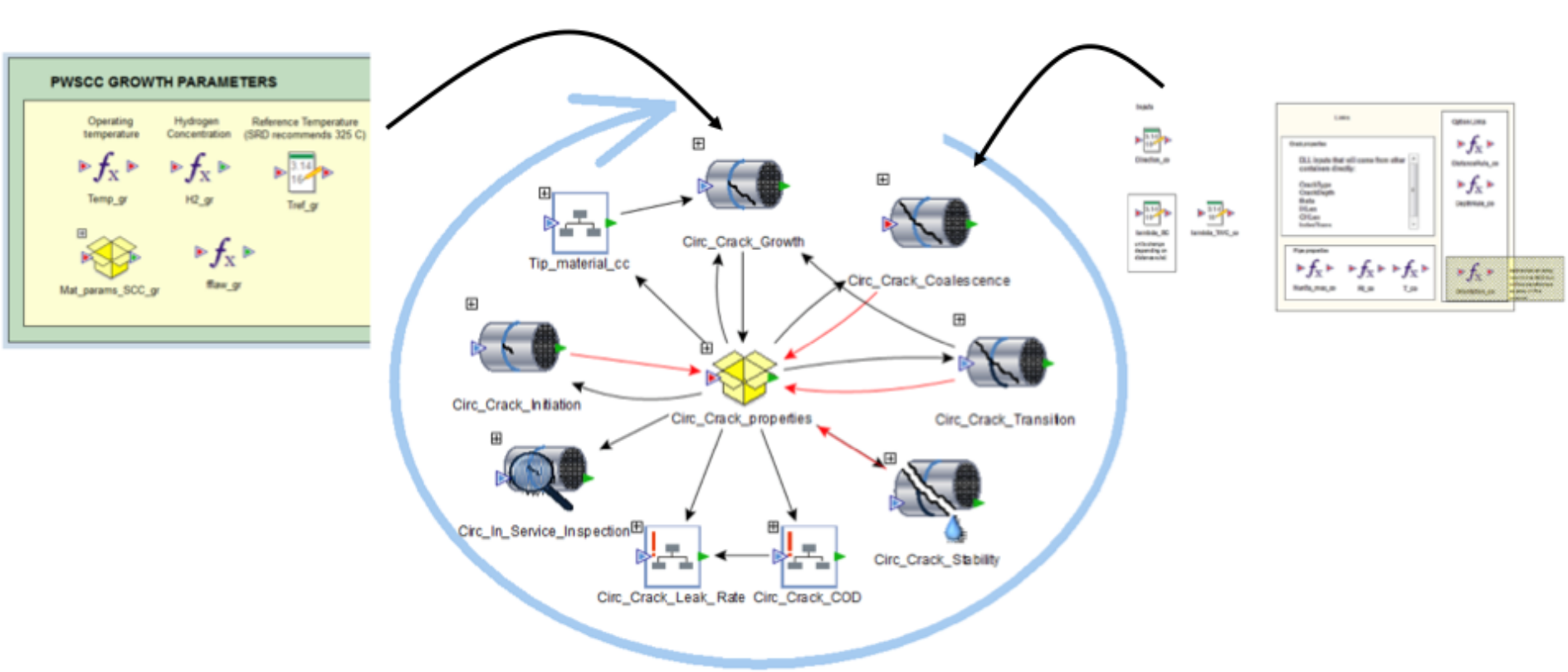
Objectives of the uncertainty representation in xLPR version 2.0

- To capture uncertainty in model predictions
- To reduce (epistemic) uncertainty in predicted pipe rupture frequency
- To be efficient



Uncertainty propagation over multiple modules (1/2)

- Each module has its set of inputs. Each input may or may not be uncertain.



Uncertainty propagation over multiple modules (2/2)

- Each input is sampled only once, so if an input is used in different modules, it will have the same value.
- Output for each module can be checked independently so the influence of uncertainty in a given module can be assessed.
- Known correlation can be input to avoid unrealistic realizations.
  - A set of 53 potential correlations has been identified by the model group and pilot study.

What's a probabilistic complex analysis

- **Every probabilistic complex analysis starts with the same four questions:**

Q1: What can happen?

Q2: How likely is it to happen?

Q3: What are the consequences if it does happen?

Q4: How much confidence do you have in the answers to the first three questions?

Basic concepts (1/5): From the question to the mathematical characterization

EN1: Probabilistic characterization of what can happen in the future

- Answers first two questions
- Provides formal characterization of **aleatory** uncertainty
- E.G. crack initiation

EN2: Mathematical models for predicting consequences

- Answers third question
- This part corresponds to the deterministic model with all DLL modules in xLPR v2.0
- E.G. Crack propagation via analytical equation

EN3: Probabilistic characterization of uncertainty in inputs

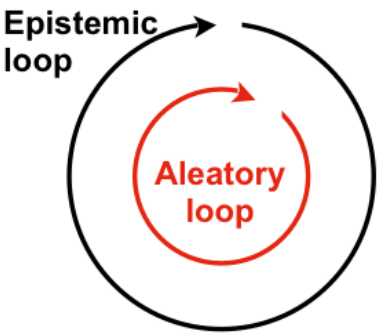
- Basis for answering fourth question
- Provides formal characterization of **epistemic** uncertainty
- E.G. Loads, temperature, pressure

Basic concepts (2/5): Difference between epistemic and aleatory and spatial variability

- **Aleatory uncertainty**
  - Inherent (perceived) randomness. Represented with probability distributions.
- **Epistemic uncertainty**
  - Uncertainty originated from lack of knowledge on a fixed quantity. Represented with probability distributions.
- **Spatial variability**
  - Inherent variability over space of a quantity, that usually cannot be measured precisely or at the expected scale.
- **User chooses which parameters are aleatory and which are epistemic**
- **Inner aleatory loop**
- **Outer epistemic loop**
  - Allows evaluation of epistemic (model) uncertainty.

Aleatory (Irreducible)
• Crack size • POD detection • Material properties • Crack growth parameters (Q/R,c,P)

Epistemic (Lack of knowledge)
• Loads • WRS • Crack growth (fweld) • Crack initiation parameters • POD parameters



Basic concepts (3/5): Spatial variability

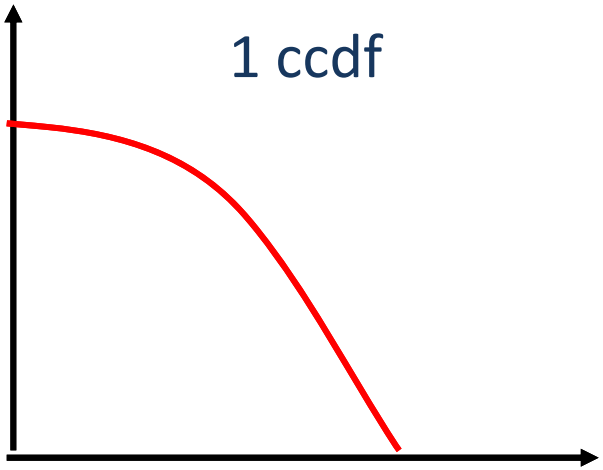
- Spatial variability is **NOT** aleatory or epistemic uncertainty.
- In xLPR V2.0 spatial variability is linked to uncertainty. The distribution can be treated as aleatory or epistemic.
- But a different value is sampled for each sub-unit. As result, value will change for each crack.
- In xLPR v2.0 a total 56 inputs are considered as experiencing spatial variability. As some may vary between axial and circumferential cracks, it represents a combination of 100 spatially variables inputs.

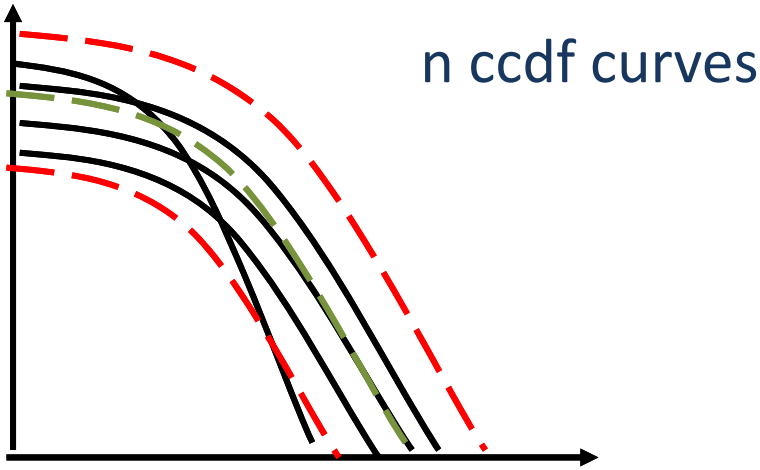
Basic concepts (4/5): From mathematical characterization to implementation

1. Characterization of uncertainty in **e**
   (i.e., definition of $D_1, D_2, \ldots, D_{nE}$)
2. Generation of sample from **e**
   (i.e., generation of $\mathbf{e}_k$, $k = 1, 2, \ldots, n_S$, in consistency with $D_1, \ldots, D_{nE}$)
3. Propagation of sample through analysis
   (i.e., generation of mapping $[\mathbf{e}_k, \mathbf{y}(\mathbf{a}|\mathbf{e}_k)]$, $k = 1, 2, \ldots, n_S$)
4. Presentation of uncertainty analysis results
   (i.e., approximations to the distributions of the elements of **y** obtained from $\mathbf{y}(\mathbf{a}|\mathbf{e}_k)$, $k = 1, 2, \ldots, n_S$)
5. Determination of sensitivity analysis results
   (i.e., exploration of the mapping $[\mathbf{e}k, \mathbf{y}(\mathbf{a}|\mathbf{e}_k)]$, $k = 1, 2, \ldots, n_S$)

Basic concepts (5/5) Representation and interpretation of results

- User chooses which parameters are aleatory and which are epistemic.
- Inner vs. outer loop.





Aleatory uncertainty represents the probability

Epistemic uncertainty represents the level of knowledge we have w.r.t. this probability

Treatment of uncertainty

- Uncertainty (both aleatory and epistemic) characterized using **probability distributions**.
- Model and input groups responsible to recommend treatment of uncertain parameters.
- Distribution may depend on the type of uncertainty selected (aleatory or epistemic) which in turn depends on the problem considered (study of one weld vs. collection of welds).
- In order to ensure that the combination of inputs leads to physically acceptable set, **correlations** may be required amongst some parameters.
- A description of traditional techniques to generate distribution follows.

Input uncertainty characterization in xLPR

- Model and input groups responsible to recommend treatment of uncertain parameters.
- See vertical slice presentation (Rob Tregoning) for more information.
- An Excel spreadsheet has been developed to help characterize (i.e. selecting a distribution) based on the available data.
  - If no or almost no data available: expert judgment is assisted by using questions asked to the user.
  - If a small number of data is available questions as well as representation is used to select distribution.
  - If a large enough number of data (>12) is available, (first two) moment matching distributions are created with a recommendation based on third and fourth moments proximity.

Sampling techniques

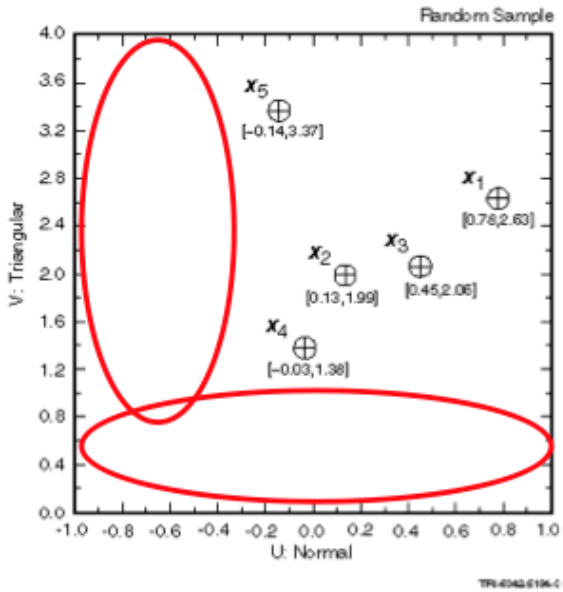
- **R**andom **S**ampling
- **L**atin **H**ypercube **S**ampling
- **D**iscrete **P**robability **D**istribution
- Importance sampling

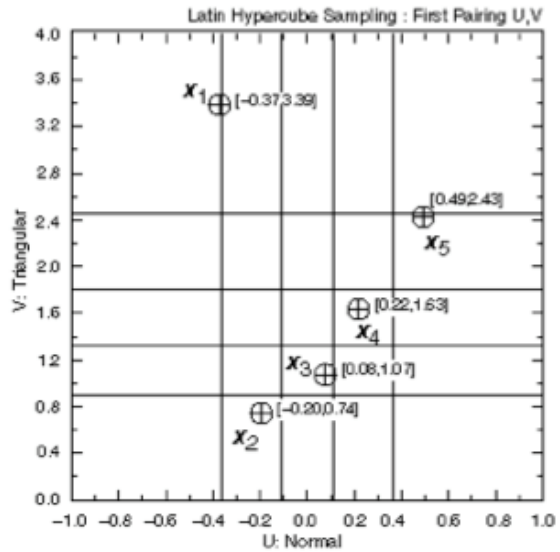
- Other methods exist (Quasi-MC sampling, etc.) but not considered in xLPR v2.0

RS vs. LHS vs. DPD

- **R**andom **S**ampling is the original Monte Carlo approach.
  (usually not recommended for xLPR analysis)
- **L**atin **H**ypercube **S**ampling: dense stratification of each input (projection of input space to one value) – better if variables are important *by themselves* and full spectrum of values for input is needed.
- **D**iscrete **P**robability **D**istribution: better multidimensional coverage – better if variables are important *conjointly* and a reasonable range of values (not as dense as LHS) is required/sufficient.

LHS may be used in place of RS when desired





RS:

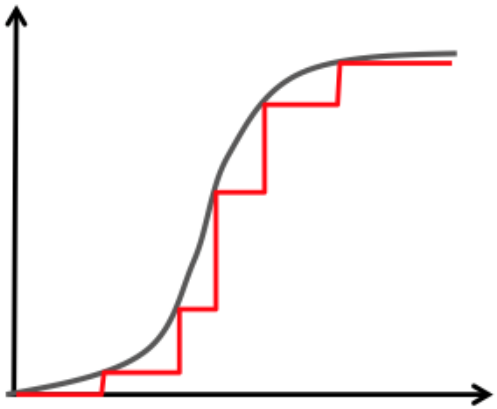
- Preferred when sufficiently large samples are possible
- Easy to implement
- Easy to explain
- Unbiased estimates for means, variances and distribution functions
- Sufficient large samples may not be possible

LHS:

- Preferred when sufficiently large samples are possible.
- Dense stratification across range of each variable.
- Used when large samples not computationally practicable and estimation of high quantiles not required.
- Preceding is typically the case in uncertainty/sensitivity analyses to assess effects of subjective uncertainty
- Uncertainty/sensitivity results robust with relatively sample size.

Discrete probability distributions (DPD) can be used to increase the resolution of regions of interest within probability distributions for importance sampling

- DPD uses discrete values from probability distributions
  - Each value can be equally probable or of different likelihood



- Difference with LHS:
  - Less dense stratification. Worse than LHS if events of interest occur more fro extreme values of inputs.
  - Higher combination (i.e. better multidimensional coverage). Better than LHS if events of interest occur more for combination of inputs.

Importance sampling

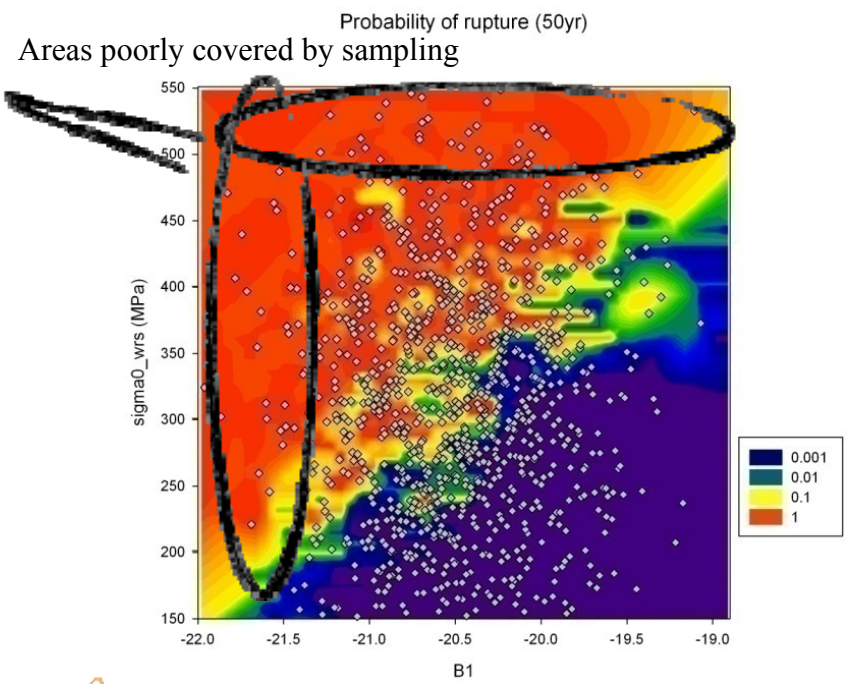
- When the sample size is not big enough to represent the required extreme values of some input, importance sampling may be used to improve their resolution.
- Requires knowledge of:
  - Which input variables are important
  - Which area of these inputs variables needs to be over-covered.
- May be a necessary step when dealing with extremely low values.
- Cannot be applied to all variables! (selection must be made).
- DPD can be used in <u>importance sampling</u>
- For now, only internal approach available. In the future, external and adaptive approach will be added.

The pilot study underlined the importance of focusing sampling on regions of interest to accurately estimate extremely low probabilities

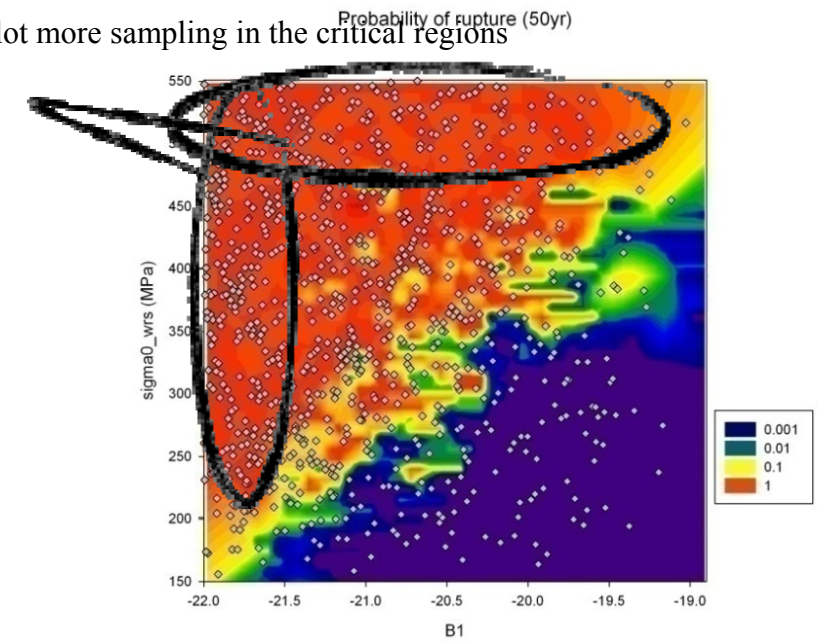
- **For example, looking at the probability of rupture as a function of two variables (crack initiation and weld residual stress) using regular sampling vs. importance sampling highlights the shortcoming of regular sampling.**

In red: region of interest in the input space (leading to pipe rupture)

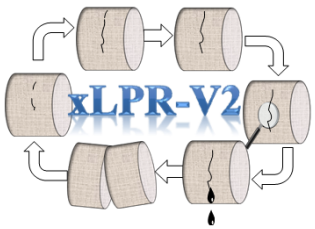
Areas poorly covered by sampling

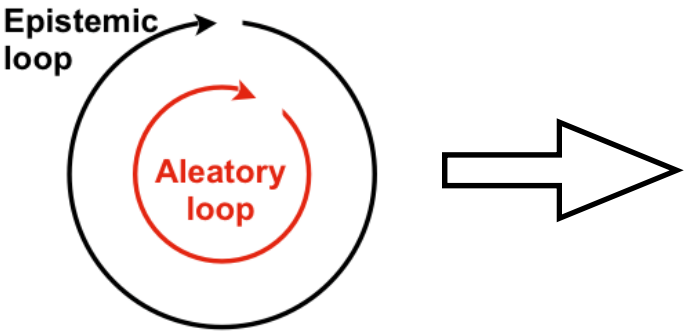


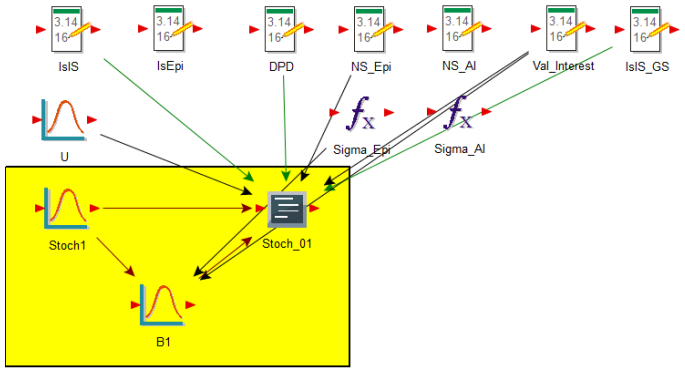
A lot more sampling in the critical regions



In xLPR v2.0, the sampling strategy is optimized and disassociated 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 or Latin Hypercube Sampling (LHS).
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  - Importance sampling applied to selected values.
  - Use of optimization instead of importance sampling for selected values (in development)
- **Possibility of creating 12 sampling combination:**
  [LHS vs. RS]x[DPD vs. no DPD] x[No importance vs. importance vs. adaptive] for each loop (totaling 12^2 combinations).

xLPR v2.0: a modular probabilistic computational Framework for calculating the probability of LBB

- xLPR v2.0 represents uncertainty in hundreds of model parameters:
  - Parameters may be represented by numerous types of distributions.
  - Sim editor interface to facilitate usability and option selection.
  - Separation of aleatory and epistemic uncertainty, as defined by user.

- Several sampling methods are included to investigate low probability outcomes:
  - Importance sampling (for selected parameters) included in xLPR v2.0. Plan to include also Adaptive sampling (external to GoldSim)
  - Sampling strategy to reduce the number of realization needed to quantify low probability outcomes (pipe rupture).

- Sampling strategy in xLPR v2.0 highly versatile:
  - [LHS vs RS] x [DPD vs. no DPD] x [No importance vs. importance vs. adaptive].
  - The modular structure of the Framework enables the inclusion of additional optimization techniques in the future.

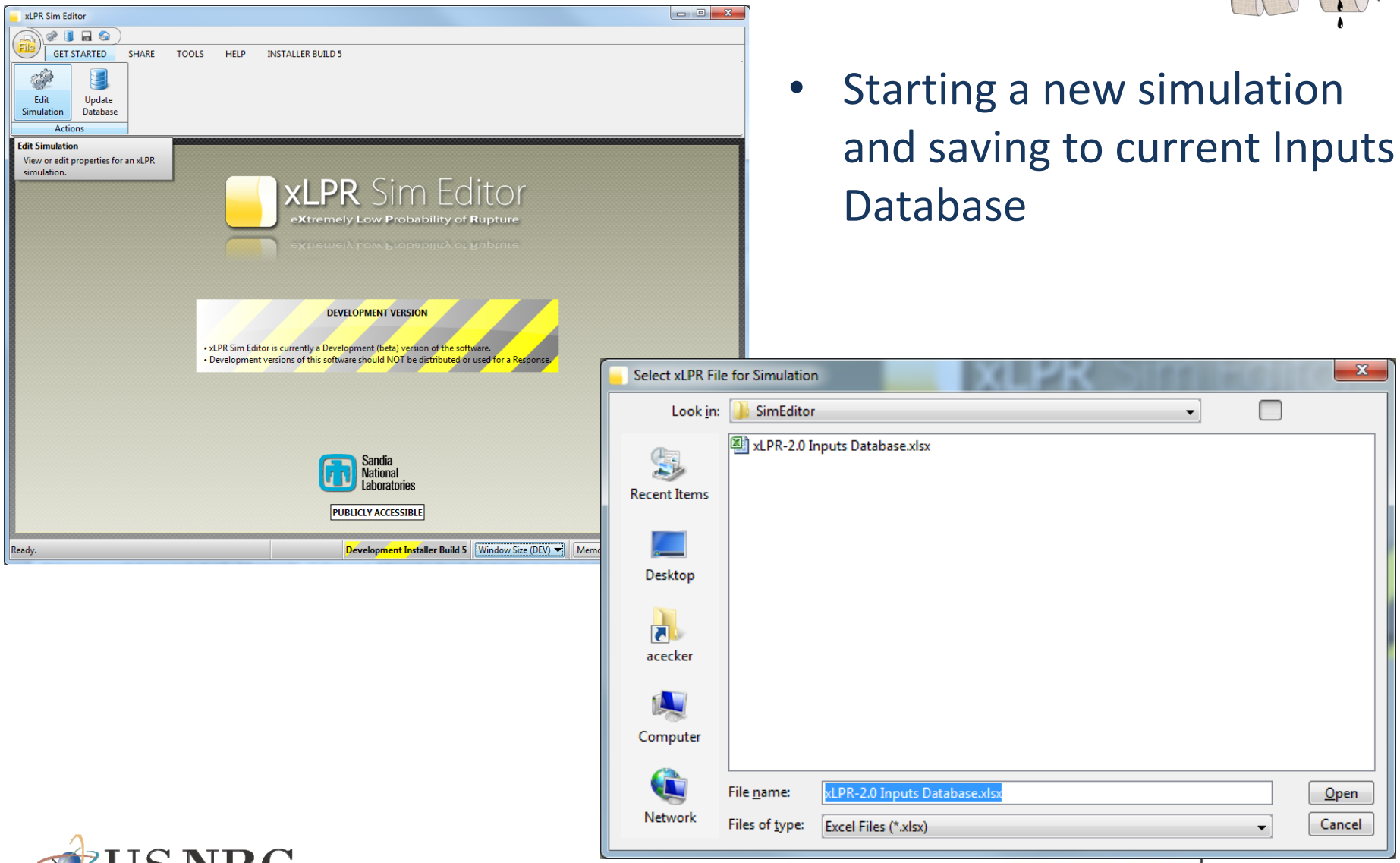
Extremely Low Probability of Rupture (xLPR) Project

Upcoming advances

xLPR

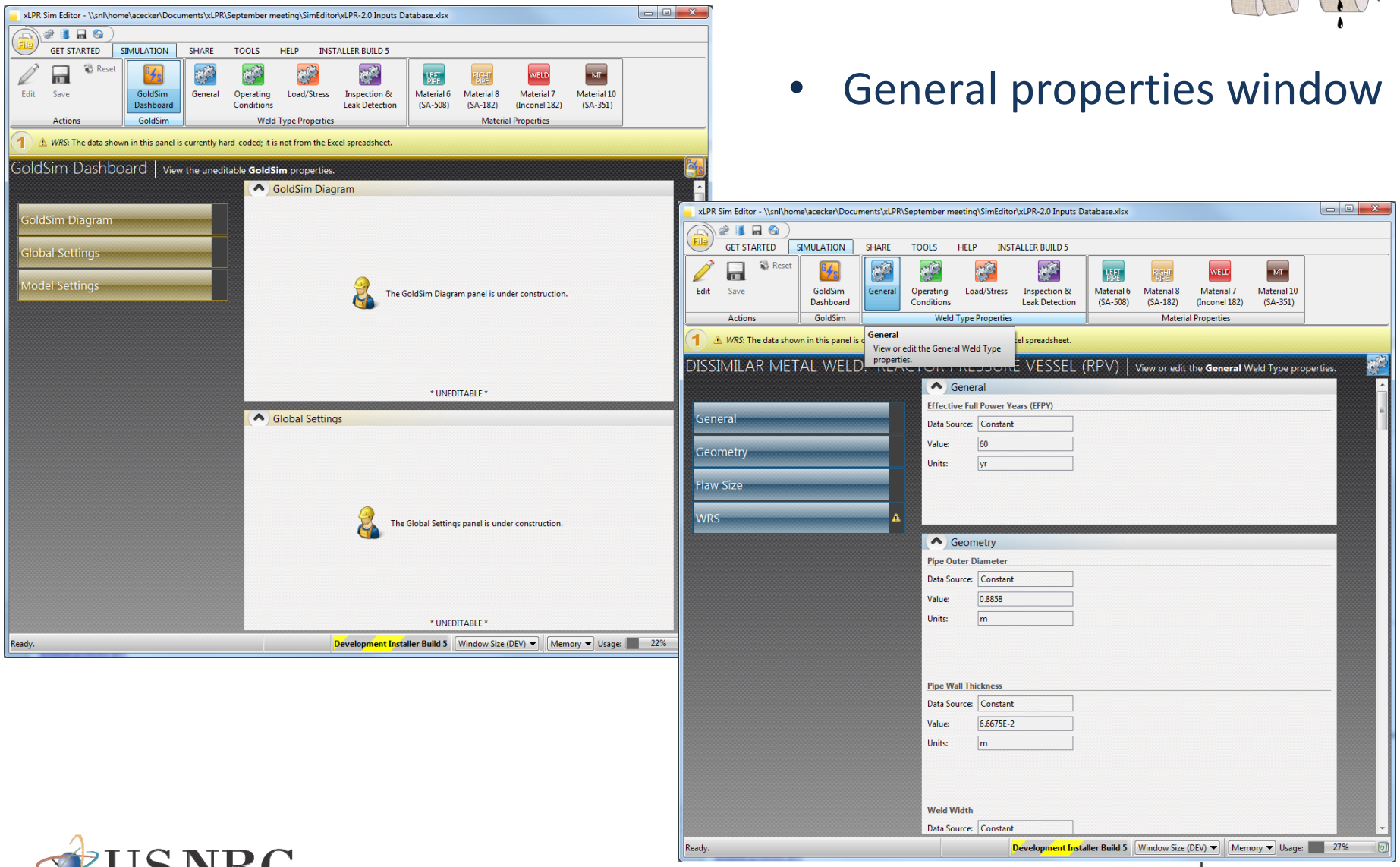
xLPR External Review Board Meeting
October 29-30, 2014

xLPR simulation editor



- Starting a new simulation and saving to current Inputs Database

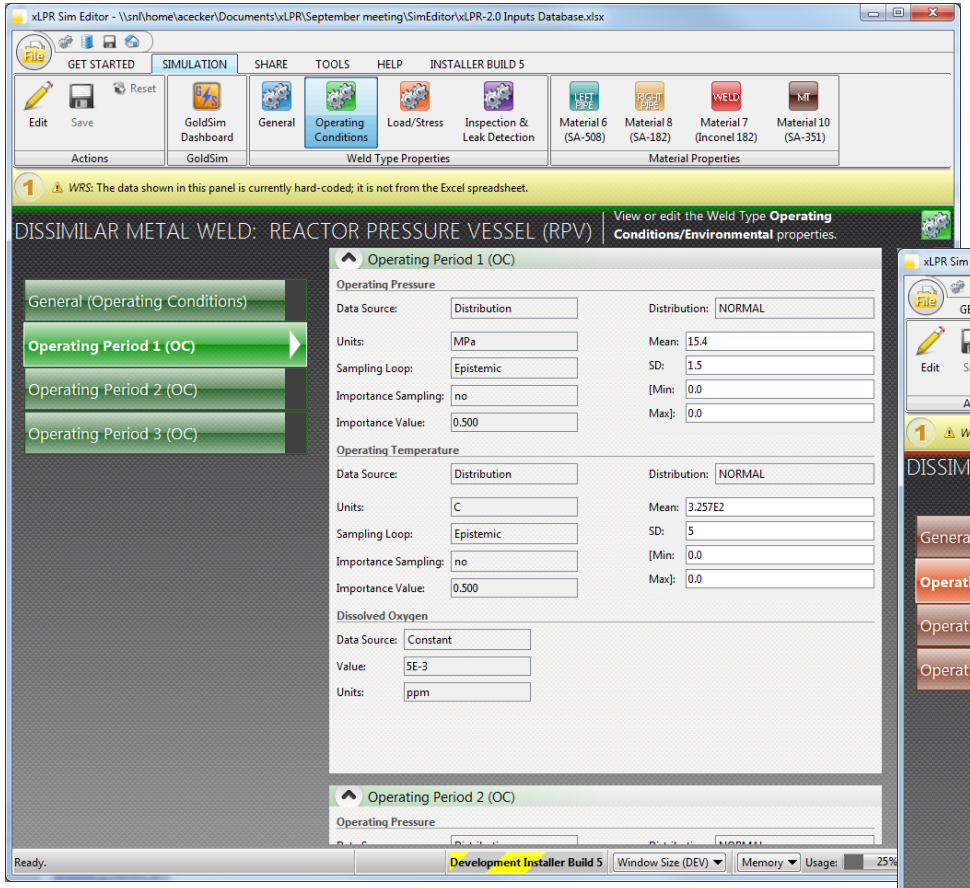
xLPR simulation editor

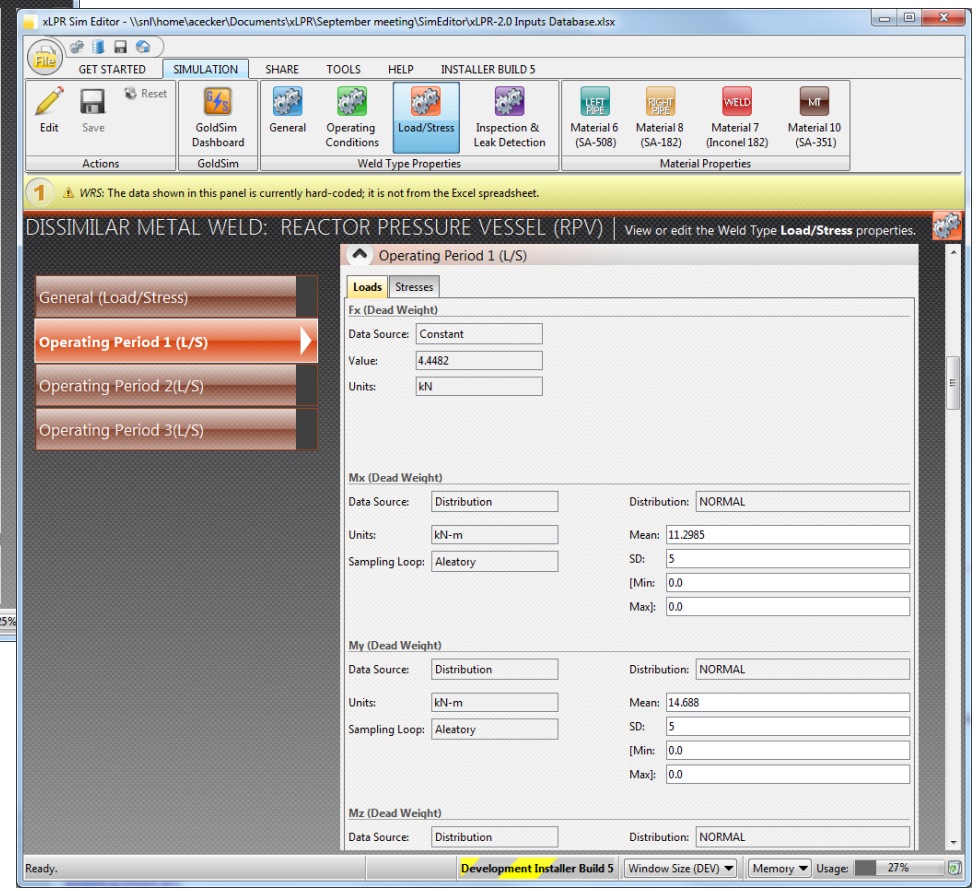


- General properties window

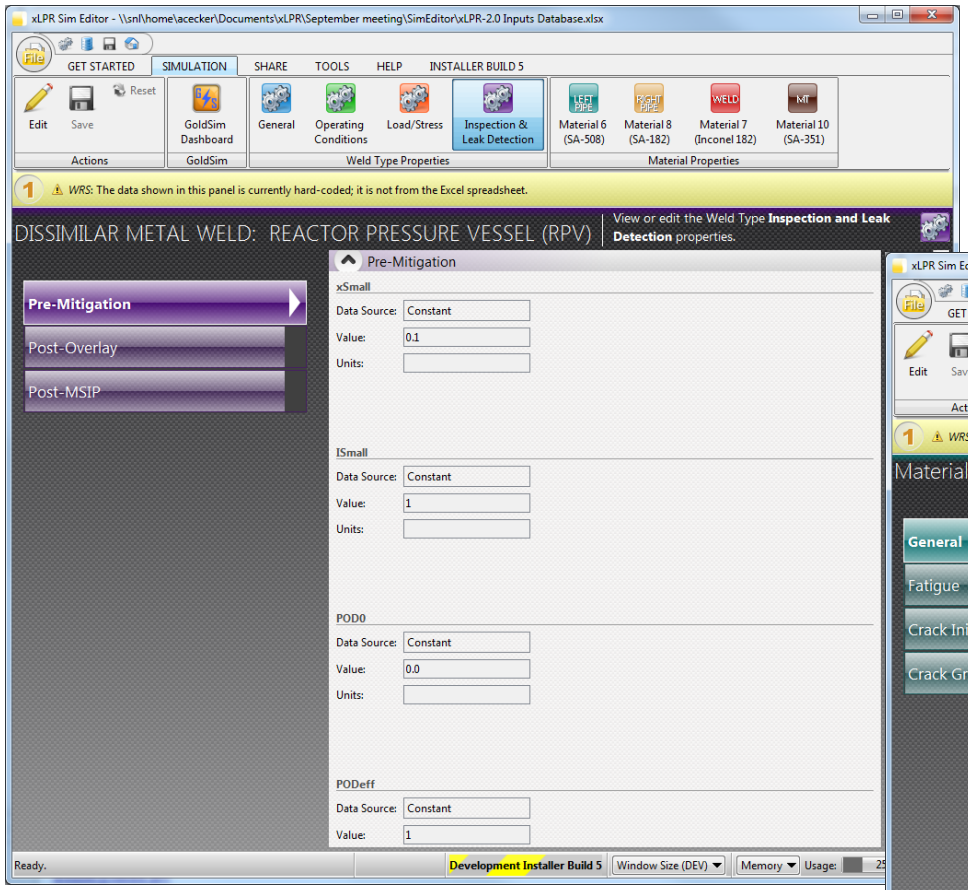
xLPR simulation editor

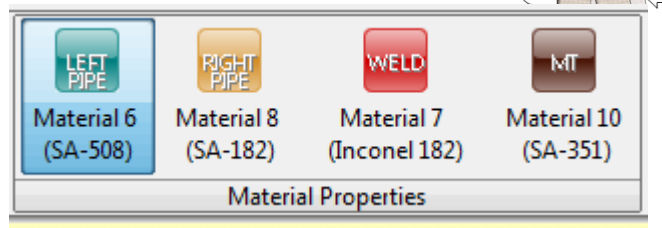
- Operating conditions and loads/stress windows

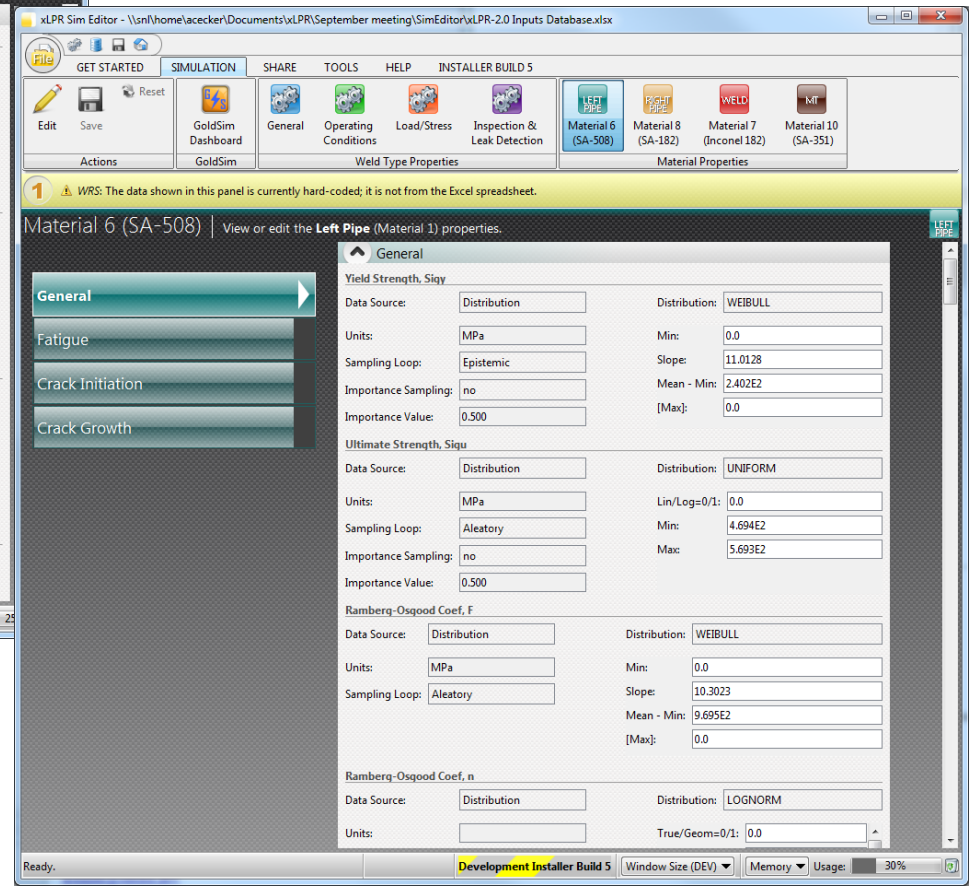




xLPR simulation editor







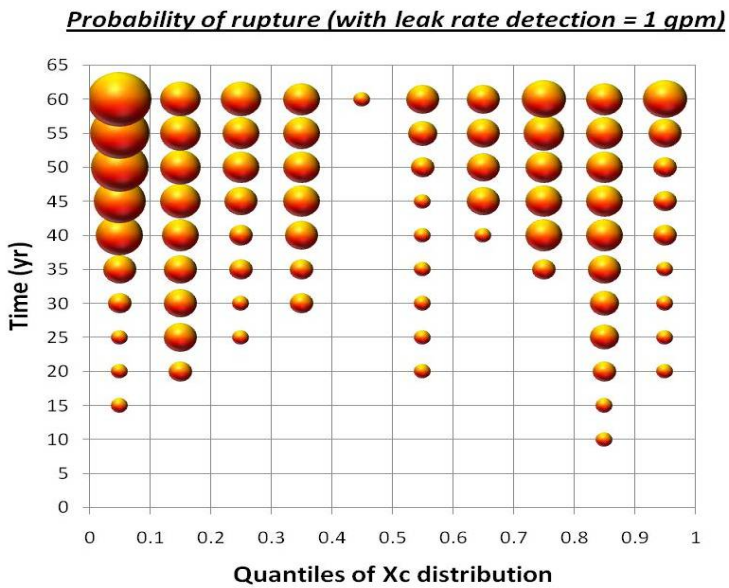
- Inspection & Leak Detection

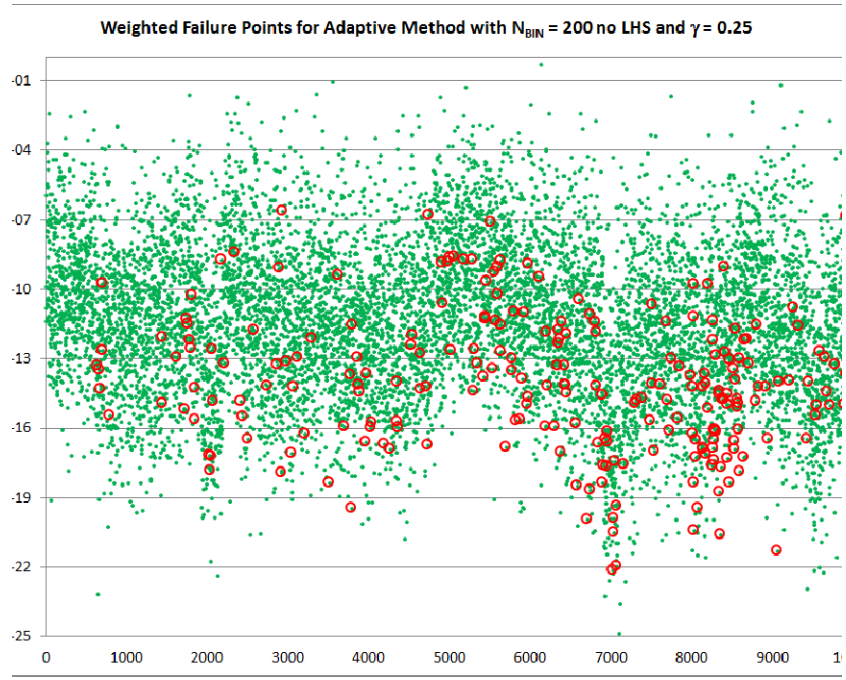
xLPR simulation editor

- Clarifications for user including consistent display of information, inputs, and options, descriptions of inputs, general instructions at "Get Started" command, and clear distinction among sets of commands (e.g. Reset, Save, Update).
- Determine user interaction with default distribution parameters, further explanation of these parameters, warning message for invalid distribution parameters, relationship between constant and distribution mean values.
- Specific requirements for changes on a per-module basis.
- Generation of PRO-LOCA input deck based on xLPR input deck (not part of the official release).
- Built-in filtering of displayed inputs based on selected model options.

Adaptive sampling promotes importance sampling by using model results to identify and focus on sampling space that leads to pipe rupture

- In xLPR v2.0, the sampling strategy is not uniquely based on the user knowledge; rather adaptive and optimized strategies are adopted to cover relevant regions of the input space
- Adaptive sampling can cover more densely disparate regions in the input space, and reduces the number of samples needed to confidently estimate low probability (~10^{-6})





Adaptive DPD can be used to predict pipe rupture with orders of magnitude fewer realizations than Monte Carlo

- In this example, to predict pipe rupture with high confidence
  - Adaptive DPD needs 10,000 to 20,000 realizations
  - Monte Carlo needs at least 4,000,000 realizations (i.e., >200 times more)

Graph compares xLPR v1.0 median and 95th confidence intervals for:

- DPD adaptive (red) up to 10,000 realizations
- Monte Carlo (black) up to 5,000,000 realizations
- LHS 3
- LHS 5

DPD adaptive:

- More efficient
- Much better resolution