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Presenter: Sai Zhang, Ph.D.

Probabilistic Risk and Reliability Analyst

Nuclear Safety and Regulatory Research Division

Idaho National Laboratory

Developing Component-Specific Prior Distributions for Common Cause Failure Alpha Factors

Sai Zhang, Zhegang Ma, Idaho National Laboratory, USA

Christopher Hunter, United States Nuclear Regulatory Commission, USA

Presentation Outline

- Background
- Research focus and motivation
- Method
  - General steps
  - Case study
- Results and discussions
  - Component-specific priors
  - Posteriors using component-specific priors
- Conclusions and next steps

Background on CCF Modeling

- Common Cause Failures (CCF)
  - A specific category of dependent failure
  - Stemming from shared root cause(s) AND coupling factor(s)
  - Recognized as significant risk contributors from probabilistic risk assessments (PRA) for nuclear power plants
- CCF models
  - Parametric (e.g., alpha factor model)
  - Non-parametric (e.g., failure-mechanism-simulation-based)
- CCF parameter estimations for U.S. commercial nuclear power plants
  - Raw data stored in a CCF database system maintained by Nuclear Regulatory Commission (NRC) and Idaho National Laboratory (INL)
  - CCF parameter estimations periodically updated and published on the NRC Reactor Operational Experience Results and Database website (https://nrcoe.inl.gov/ParamEstSpar/)

Research Focus and Motivation

- CCF parameters are estimated using a Bayesian update method
  - Due to sparsity of new evidences, prior selection can have a strong influence on CCF parameter posteriors
  - Generic priors vs. pool-specific priors
    - To partition raw data into smaller pools (by component type, failure cause, failure mode, etc.)
    - To better represent pool-specific performance
    - To eliminate uncertainties in priors due to pool-to-pool variabilities
- This study, which is an exploratory study, focuses on developing component (type) - specific prior distributions for CCF alpha factors

Developed based on historical CCF events

Newly-occurred CCF events, usually rare at nuclear power plants

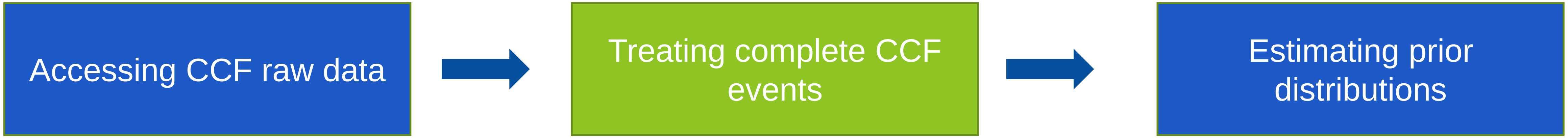
CCF parameter estimates

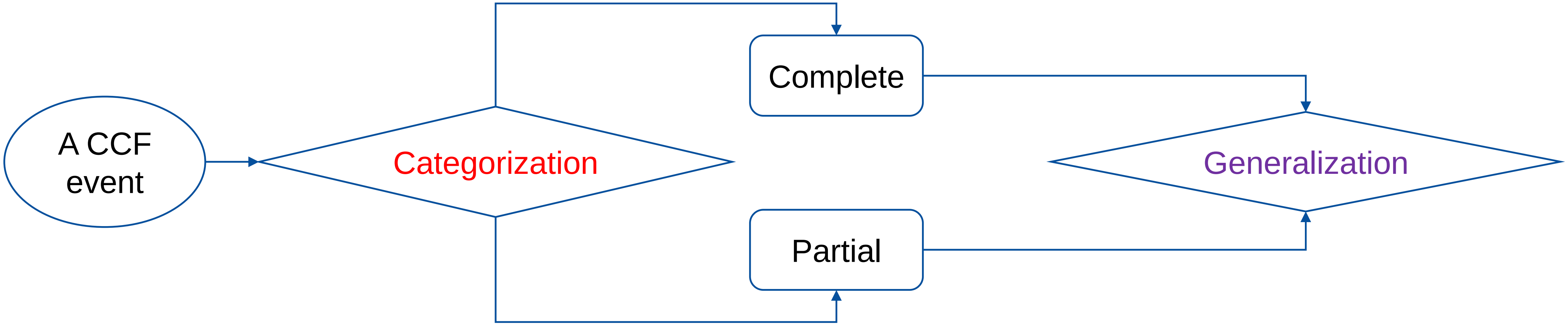
Research Focus and Motivation (cont.)

- Five component types
  - Pump
  - Valve
  - Strainer
  - Generator
  - All else

Component Type for Component-Specific Prior Development	Number of CCF Events	Component Type Used in the NRC CCF Database		
		Broad Type	Detailed Type	
Pump	47	Pump	MDP	motor-driven pump
			TDP	turbine-driven pump
Valve	123	Valve	AOV	air-operated valve
			CKV	check valve
			HOV	hydraulic-operated valve
			MOV	motor-operated valve
			MSV	main-steam stop valve
			PRV	power-operated relief valve
			RVL	low-capacity relief valve
			SRV	safety relief valve (dual activation)
			SVV	safety valve (single acting)
Strainer	51	Filter	STR	strainer
Generator	15	Emergency power	GEN	generator
All else	33	Electrical	BAT	battery
			BCH	battery charger
			CRB	circuit breaker
			TFM	transformer
		Other	CMP	compressor
			HTX	heat exchanger
			VAC	vacuum breaker valve
Total Number of CCF Events (occurred between 1997 and 2015): 269				

Method to Develop CCF Parameter Prior Distributions





- A complete CCF event is a "perfect" CCF event meeting all three conditions:
  - Component degradation factor = 1.0
  - Timing factor = 1.0
  - Shared cause factor = 1.0

- Generalization is to create "synthetic" CCF events of all common-cause component group sizes (e.g., 2 to 16)
  - For partial events: mapping method
  - For complete events: regression method

Method to Develop CCF Parameter Prior Distributions (cont.)

Accessing CCF raw data → Treating complete CCF events → Estimating prior distributions

1. For each common cause component group (CCCG) size, tabulate the number of all (i.e., complete and partial) CCF events and complete CCF events. Code each CCF event as an impact vector.
2. Map up and down impact vectors and calculate the n_k values for each group size (2–16), using all partial (i.e., incomplete) CCF events.
3. Using the information obtained in Step 1, perform a binomial regression to obtain the probability of complete CCF events for a given group size.
4. Using the results from Step 3, obtain the estimated number of complete CCF events. Add this number to the final n_k for each group size.
5. Using the final n_k values, estimate (1) maximum likelihood estimators (MLEs) of alpha factors and (2) beta prior distributions for each group size. The beta distribution is denoted by Beta(α, β). A computer code, **CalcPrior.exe**, was developed by INL to estimate the beta prior distributions.
6. As a check, calculate the mean of each prior distribution and compare them with the values obtained in Step 5. The mean value is obtained via the formula $\mu = \alpha / (\alpha+\beta)$.

Pump Example – Accessing CCF Data

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events
2	9	11	20
3	12	5	17
4	28	2	30
5	3	0	3
6	10	0	10
7	2	0	2
8	28	1	29
9	0	0	0
10	0	0	0
11	5	0	5
12	2	0	2
13	0	0	0
14	1	0	1
15	0	0	0
16	4	0	4
Total	104	19	123

Pump Example – Accessing CCF Data (cont.)

Group Size	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}	n_{16}
2	28.12	6.827														
3	26.62	15.563	1.639													
4	23.96	19.400	5.727	0.730												
5	25.50	16.408	9.359	3.247	0.399											
6	26.75	14.616	10.487	5.370	1.925	0.224										
7	27.88	13.514	10.473	6.809	3.378	1.169	0.128									
8	28.86	12.952	10.004	7.551	4.573	2.225	0.722	0.075								
9	29.71	12.731	9.451	7.762	5.434	3.180	1.497	0.453	0.045							
10	30.45	12.720	8.976	7.647	5.950	3.966	2.263	1.019	0.287	0.0273						
11	31.10	12.831	8.628	7.375	6.172	4.551	2.943	1.631	0.699	0.1849	0.0169					
12	31.68	13.006	8.407	7.060	6.177	4.929	3.504	2.210	1.184	0.4832	0.1204	0.0106				
13	32.20	13.211	8.290	6.770	6.049	5.124	3.929	2.720	1.671	0.8640	0.3361	0.0792	0.0068			
14	32.67	13.427	8.251	6.535	5.853	5.172	4.218	3.143	2.124	1.2693	0.6333	0.2352	0.0526	0.0043		
15	33.09	13.642	8.263	6.363	5.640	5.118	4.382	3.467	2.523	1.6644	0.9675	0.4662	0.1656	0.0352	0.0028	
16	33.48	13.852	8.309	6.250	5.440	5.000	4.443	3.692	2.853	2.0294	1.3070	0.7399	0.3446	0.1171	0.0237	0.0018

- Each (“real”) CCF event is first coded as an impact vector consisting of a set of n_k values
- Each “real” CCF event is then mapped up/down to multiple “synthetic” CCF events represented as multiple impact vectors
- Impact vectors of “real” and “synthetic” CCF events add up to the results shown in the table.

Pump Example – Treating Complete CCF Events

Group Size	No. Partial CCF Events	No. Complete CCF Events	Total No. CCF Events	Prob. of Complete CCF Event - Data	Prob. of Complete CCF Event - Curve Fitting	Estimated No. Complete CCF Events
2	9	11	20	0.550	0.618	12.350
3	12	5	17	0.294	0.156	2.650
4	28	2	30	0.067	0.077	2.300
5	3	0	3	0.000	0.058	0.170
6	10	0	10	0.000	0.053	0.530
7	2	0	2	0.000	0.051	0.100
8	28	1	29	0.034	0.050	1.450
9	0	0	0	NA	0.050	0.000
10	0	0	0	NA	0.050	0.000
11	5	0	5	0.000	0.050	0.250
12	2	0	2	0.000	0.050	0.100
13	0	0	0	NA	0.050	0.000
14	1	0	1	0.000	0.050	0.050
15	0	0	0	NA	0.050	0.000
16	4	0	4	0.000	0.050	0.200
Total	104	19	123			20.150

- Binomial regression is to find relationship between:
  - Group size (column #1)
  - Probability of complete CCF event estimated from raw data (column #5)
- Results (last column) will be added back to the nk values on last slide

Pump Example – Estimating Prior Distributions

Define/View Prior

Name: CCF2015VALVEIN Independent Event Count: 2056.800 Average CCCG Size: 5.850

Description: 1997-2015, include LS

CCCG Size	Sum of N	Adj. Ind. Events	N1	N2	N3	N4	N5	N6	N7
2	781.9115	703.18	51.0500	27.6820					
3	1139.2752	1054.77	46.4200	30.6560	7.4300				
4	1500.7560	1406.36	40.9600	35.3790	13.5630	4.4950			
5	1858.1727	1757.95	39.7700	32.8290	18.3090	7.9400	1.3760		
6	2216.6715	2109.54	39.2700	29.8290	20.5160	11.4540	4.8490	1.2150	
7	2573.4742	2461.13	39.5000	28.1570	19.0250	14.1470	8.0990	2.9010	0.517
8	2931.2960	2812.72	39.1100	27.8740	17.6690	14.1160	10.8440	5.5080	1.728
9	3285.7337	3164.31	38.6500	27.8850	16.7250	13.9590	11.2850	7.6720	3.903
10	3641.1128	3515.90	37.9600	28.0070	16.3490	13.3210	11.4660	8.7660	5.639
11	3996.3296	3867.49	37.1100	28.1640	16.3680	12.6210	11.2880	9.3560	6.809
12	4350.8142	4219.08	36.5300	28.0810	16.2900	12.2790	10.8050	9.6540	7.530
13	4705.0751	4570.67	36.0700	27.7650	16.3740	12.1490	10.2040	9.6130	8.100
14	5059.2580	4922.26	35.5400	27.5480	16.4160	12.1640	9.8530	8.9350	8.828

Calculate Save Cancel

CalcPrior Input

Prior Distribution Constants

Param Name	CCCG Size : 2	CCCG Size : 3	CCCG Size : 4	CCCG Size : 5	CCCG Size : 6	CCCG Size : 7
a1	1.2091E+001	3.4575E+001	5.3945E+001	9.7356E+001	1.2583E+002	1.8340E+002
b1	4.4375E-001	1.1958E+000	1.9917E+000	3.2739E+000	3.9740E+000	5.3427E+000
a2	4.4375E-001	9.6253E-001	1.3187E+000	1.7779E+000	1.7467E+000	2.0651E+000
b2	1.2091E+001	3.4808E+001	5.4618E+001	9.8852E+001	1.2806E+002	1.8668E+002
a3		2.3329E-001	5.0553E-001	9.9153E-001	1.2014E+000	1.3953E+000
b3		3.5537E+001	5.5431E+001	9.9638E+001	1.2860E+002	1.8735E+002
a4			1.6754E-001	4.2999E-001	6.7073E-001	1.0376E+000
b4			5.5769E+001	1.0020E+002	1.2913E+002	1.8771E+002
a5				7.4517E-002	2.8395E-001	5.9400E-001
b5				1.0056E+002	1.2952E+002	1.8815E+002
a6					7.1149E-002	2.1277E-001
b6					1.2973E+002	1.8853E+002
a7						3.7918E-002
b7						1.8871E+002
a8						
b8						
a9						
b9						
a10						
b10						
a11						

Geometric Mean Arithmetic Mean Export Return Intermediate Parameter CCCG

CalcPrior Output

- What CalcPrior.exe does:
  - Calculate MLEs of alpha factors based on adjusted n_k values
  - Assign MLEs as mean values of beta distributions, then estimate beta distribution parameters
  - Based upon Dirichlet methodology to make sure all alpha factors in the same group add up to 1

CCF Alpha Factor Prior Results

Group Size	Alpha Factor	2015 Generic Priors (INL/EXT-21-43723)	2015 Pump Priors		2015 Valve Priors		2015 Strainer Priors		2015 Generator Priors		2015 All Else Priors	
		Mean	Mean	Delta	Mean	Delta	Mean	Delta	Mean	Delta	Mean	Delta
2	α_2	2.05E-02	1.12E-02	-45%	3.54E-02	73%	9.60E-02	368%	7.92E-03	-61%	9.32E-03	-55%
3	α_2	1.44E-02	8.57E-03	-40%	2.69E-02	87%	5.06E-02	251%	5.17E-03	-64%	6.69E-03	-54%
	α_3	4.68E-03	2.00E-03	-57%	6.52E-03	39%	2.20E-02	370%	2.16E-03	-54%	1.20E-03	-74%
4	α_2	1.36E-02	7.97E-03	-41%	2.36E-02	74%	4.89E-02	260%	4.02E-03	-70%	7.33E-03	-46%
	α_3	4.35E-03	2.35E-03	-46%	9.04E-03	108%	1.73E-02	298%	2.10E-03	-52%	1.10E-03	-75%
	α_4	2.50E-03	9.46E-04	-62%	3.00E-03	20%	9.88E-03	295%	8.02E-04	-68%	1.56E-03	-38%

- The alpha factor mean values are observed to vary significantly with component type
- Those for pump, generator, all else are about 40% to 70% lower than generic priors.
- Those for valve are about 20% higher, and for strainer about 2 to 3 times higher.
- Understanding needs to be based upon physical meaning of alpha factors.

CCF Alpha Factor Posterior Results (Pump Example)

Group Size	Alpha Factor	ALL-MDP-FS1 Posterior Mean Values			AFW-MDP-FS Posterior Mean Values			ALL-TDP-FS Posterior Mean Values			Delta of Pump Prior and Generic Prior Means
		Mean using 2015 Generic Priors	Mean using 2015 Pump Priors	Delta	Mean using 2015 Generic Priors	Mean using 2015 Pump Priors	Delta	Mean using 2015 Generic Priors	Mean using 2015 Pump Priors	Delta	
2	α_2	1.08E-02	9.69E-03	-10%	3.65E-02	2.46E-02	-33%	2.79E-03	2.57E-03	-8%	-45%
3	α_2	5.51E-03	5.03E-03	-9%	1.01E-02	7.06E-03	-30%	4.17E-03	3.86E-03	-7%	-40%
	α_3	5.05E-03	4.04E-03	-20%	1.51E-02	8.55E-03	-43%	1.36E-03	9.00E-04	-34%	-57%
4	α_2	5.85E-03	5.19E-03	-11%	9.98E-03	6.77E-03	-32%	5.30E-03	4.51E-03	-15%	-41%
	α_3	3.01E-03	2.49E-03	-17%	7.15E-03	4.24E-03	-41%	1.69E-03	1.33E-03	-21%	-46%
	α_4	2.07E-03	1.55E-03	-25%	5.79E-03	3.05E-03	-47%	9.74E-04	5.35E-04	-45%	-62%

- Overall trends (i.e., increase or decrease) of posterior are consistent with those of prior.
- Posterior delta ranges are usually narrower than prior delta ranges.
- The more evidences are, the less impact is prior delta on posterior delta.

Conclusions and Next Steps

- Conclusions
  - Categorized components as five types
  - Developed alpha factor prior distributions for all five component types
  - Examined impacts of using component-specific priors on alpha factor posterior distributions for representative failure modes
- Next steps
  - Improving and establishing better understanding of underlying statistical models, e.g.,
    - Binomial regression suffers from lack of sufficient data points
    - Needs to revisit the process of estimating beta distribution parameters based on Dirichlet distribution
  - Developing a more integrated software tool for the whole process of developing CCF priors
    - Currently done by querying from NRC CCF database, manual calculations, and running CalcPrior.exe

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