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A Demonstration of the Quantitative Approach for Model Credibility on an Electromagnetic Application

Track: VVUQ and Decision Making

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ASME VVUQ Symposium

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U.S. DEPARTMENT OF ENERGY NNSA

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SAND2024-****C

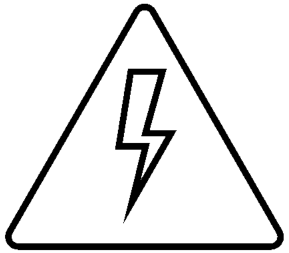
Outline

- Introduce application:
  Electromagnetics

- Review credibility framework:
  PCMM
  Vanderbilt's credibility framework

- Perform credibility assessment:
  Quantitative credibility scores

- Conclusions



PCMM element	Level/M_i	E_i	R_i	w_i	$m_i(S)$	$m_i(F)$	$m_i(\{S,F\})$
Geometric fidelity	1/0.67	0.8	1	0.025	0.54	0.13	0.33
PMMF	3/0.97	0.8	1	0.2	0.78	0.19	0.03
Code verification	1/0.68	1	1	0.05	0.68	0	0.32
Solution verification	1/0.68	1	1	0.025	0.68	0	0.32
Model validation	3/0.97	0.67	0.27	0.5	0.17	0.09	0.74
UQ/SA	3/0.97	0.98	0.27	0.2	0.26	0.01	0.74
Combined BPA					0.36	0.09	0.55

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Importance of Electromagnetic Radiation (EMR) Considerations

- 1967 US Aircraft Carrier "Forrestal"
  - Fully loaded with aircraft equipped with various bombs and missiles.
  - Aircraft missile was inadvertently deployed striking another aircraft.
  - Fuel tank on the aircraft exploded and 134 service people died.

Source: wikipedia.org/1967_USS_Forrestal_fire

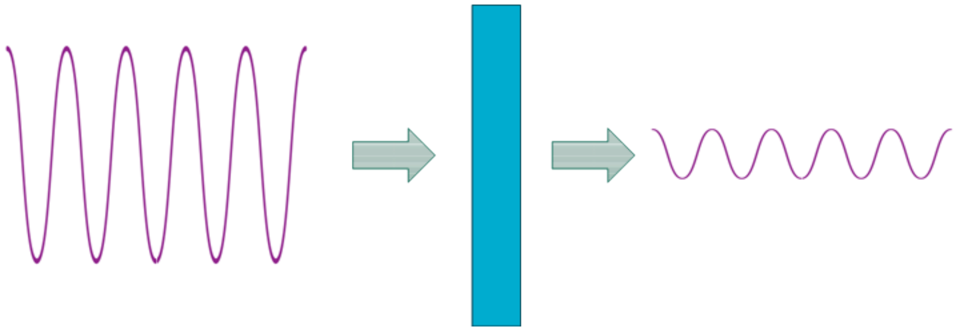
Cause was believed to be an induced voltage across the contact of a shielded connector from the ship's high power search radar.

Importance of Electromagnetic Radiation (EMR) Considerations (2)

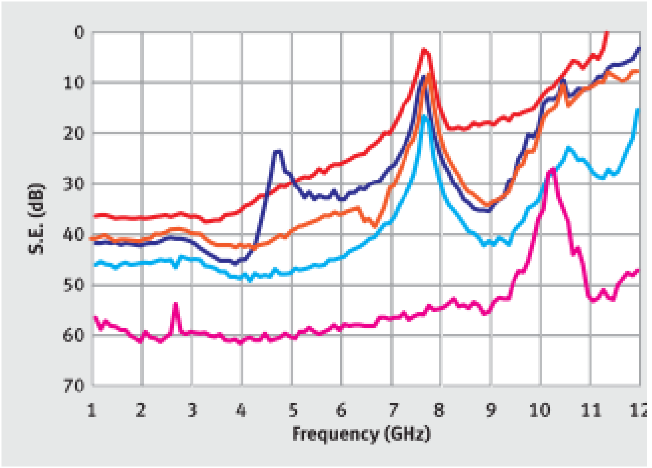
- Toyota Airbag Inflator
  - In 2020, Toyota recalled 3.4M vehicles because power line interference may prevent airbags from inflating.
  - 8 people died due to faulty airbag activation
  - Solution: Dealers retrofitted filters into cable harness

Source: Elkhorn Media Group

Hardening engineering systems against EMR

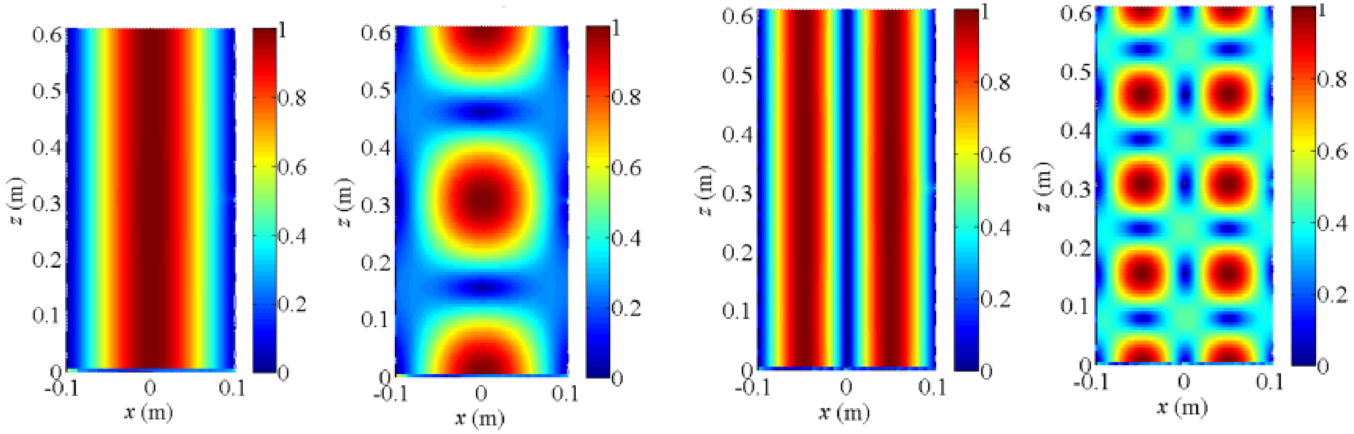


- EMR Shielding
  - Introduce a barrier that provides shielding
- Engineering objective: protect sensitive electronics
  - Design system to achieve some SE requirement
  - Notice SE varies over frequency
- Shielding effectiveness (SE):
  - $$SE = 20\log_{10}\left(\frac{|E_{internal}|}{|E_{external}|}\right)$$



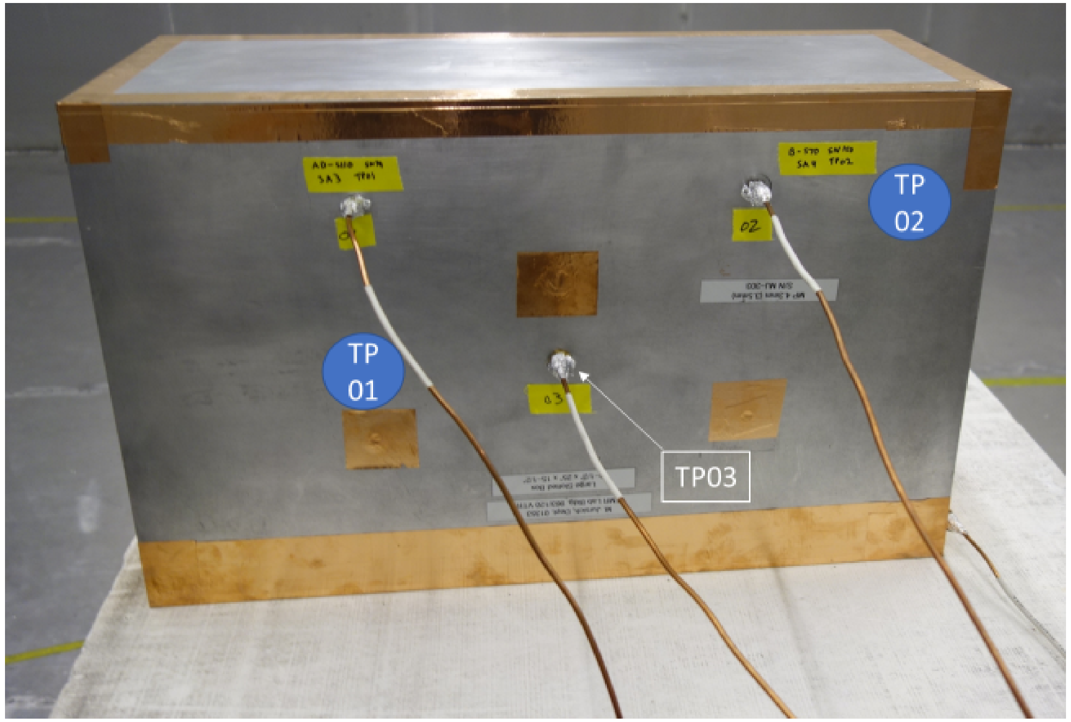
Notional SE for different shielding approaches.
Source: XGR Technologies

Electric field spatial modes inside a cylinder



Application: Large Slotted Box

- An aluminum box with a small slot cut into the top face
- Experimentation:
  - The box is placed in an EM reverberation chamber
  - 3 probes measure the internal EM fields
- Objective:
  - Compare measured SE with simulation predictions of SE



Jursich, M. (2015). *EMR Coupling into Systems: Calibration of the Sandia Reverberation Chamber and Validation of the Single Slot Aperture Gain Model* (No. SAND2015-10109). Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

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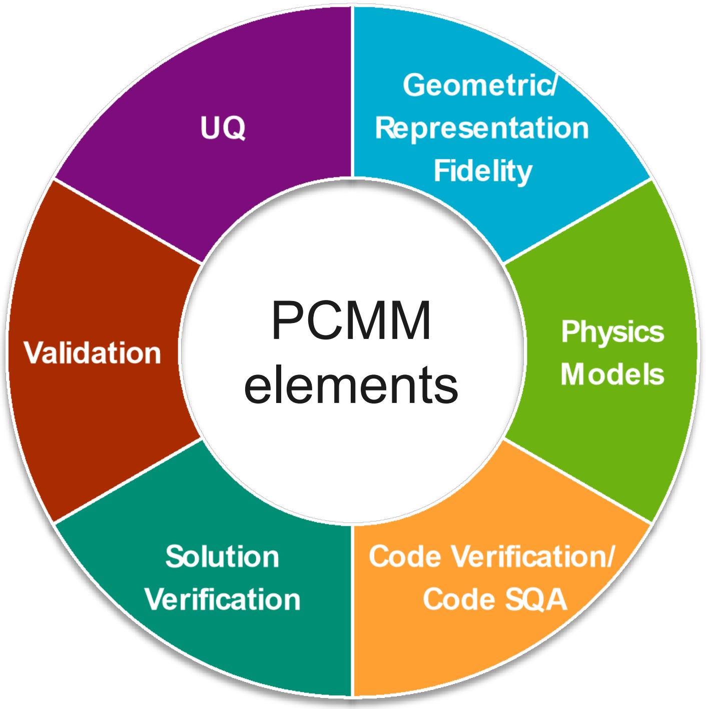
Credibility Framework

- How do we assess the credibility of a computer model?
  - **Model Credibility**: the degree to which a decision maker believes that a model is acceptable for the target application ASME V&V 40

- Predictive Capability Maturity Model (PCMM)
  - Objective: Assess the maturity level of 6 elements for a "Modeling & Simulation" activity

Oberkampf et al. (2007),
Hills et al. (2013),
Mullins (2017)



Evidence Theory-based Quantitative Credibility Approach

- For each of six PCMM elements, a quantitative score (0, 1, 2, or 3) reflects the maturity of evidence (M).
- In addition, compute/assign scores for relevance (R) and strength (E) of evidence.
  - Compute BPAs based on the M, R, and E scores for each PCMM element.
- Basic probability assignment (BPA) for m(S), m(F), m({S,F}) (Evidence theory)
  - S: model is acceptable for intended use
  - F: model is not acceptable for intended use
  - {S,F}: uncertainty about the model's acceptability
- Evidence combination
  - Use Dempster-Shafer combination rule
  - Assign weights to PCMM elements
  - Compute overall BPA scores
- Model credibility score is 3-dimensional
  - m(S), m(F), m({S,F})

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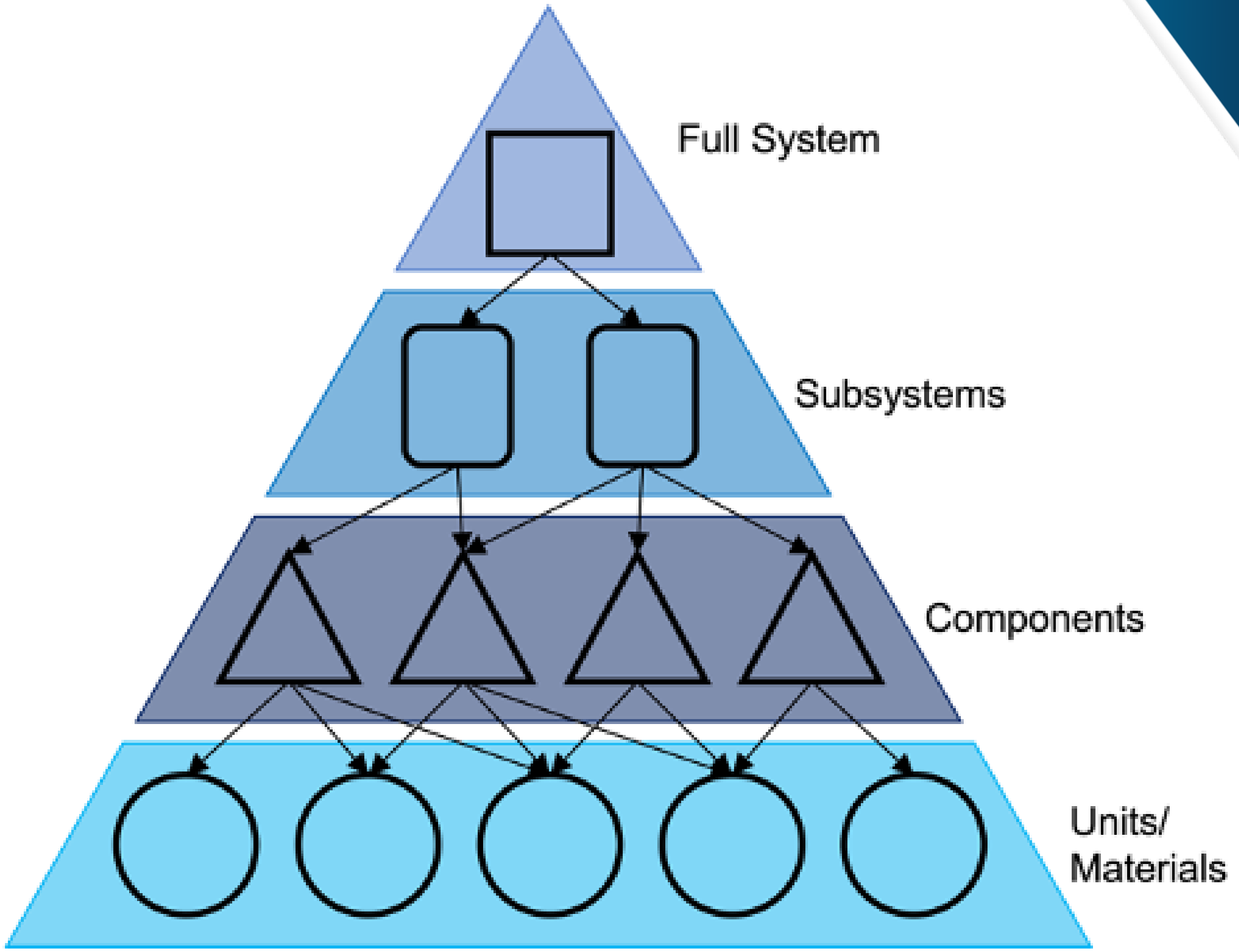
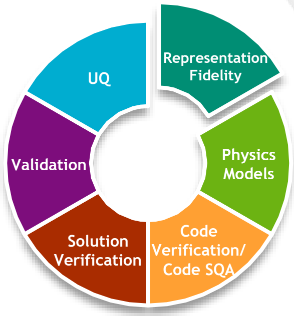
Mullins, Josh, et al. 2020. "Predictive Capability Maturity Model (PCMM)." Technical Presentation, *SAND2020-9688 TR*. Unclassified Unlimited Release.

Caveats to this credibility assessment

- The target application
  - The large slotted box is low on the validation hierarchy
  - The target application is intentionally left ambiguous
  - Therefore, the relevance will be assumed as 1
- Strengths/weaknesses of the EM simulation software will not be identified
  - So we will assume the strength of evidence about the EM simulation software exclusively supports belief in the model



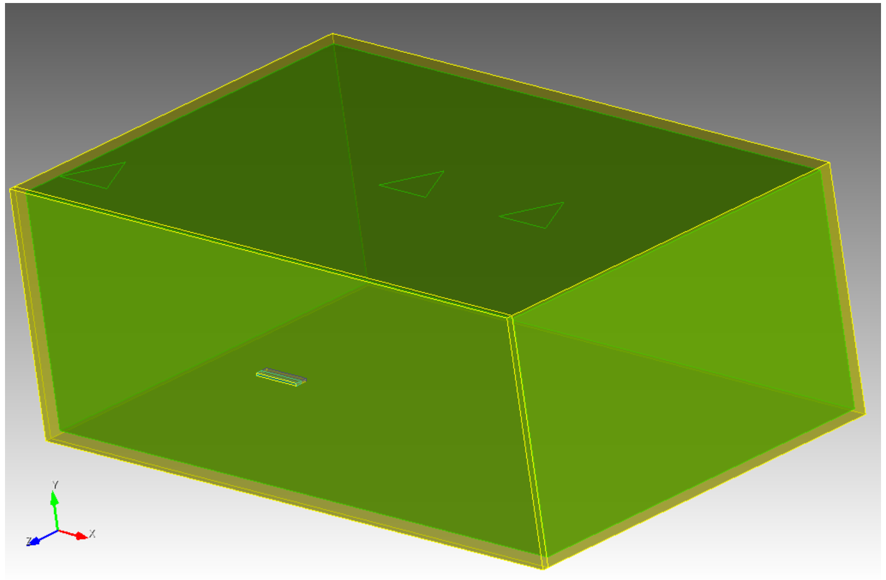
Representation and Geometric Fidelity



- Aluminum box is welded along the seams
  - The welds are not included in the simulation

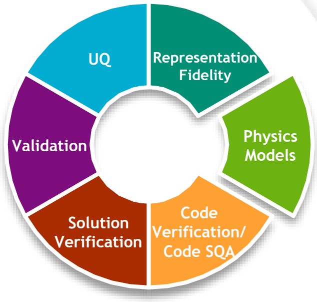
As-Modeled   As-Designed

How are geometric feature simplifications influencing simulation results and QoIs?



PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity	2	0.7	1
PMMF			1
Code Verification			1
Sol. Verification			1
Model Validation			1
UQ/SA			1

Physics and Material Model Fidelity (PMMF)



- Completed a PIRT (Phenomena Identification and Ranking Table)
  - Actual results intentionally not shown
- The physics phenomena (e.g. slot model, wave propagation, interior wave reverberation) have been rigorously tested previously
- The box is made of aluminum which is well understood

PIRT

Phenomena	Importance	Adequacy for Intended Use			
		Math Model	Code	Validation	Model Parameter
Phenomena 1	H	H	M	L	L
Phenomena 2	M	H	M	L	L
Phenomena 3	L	H	M	L	L

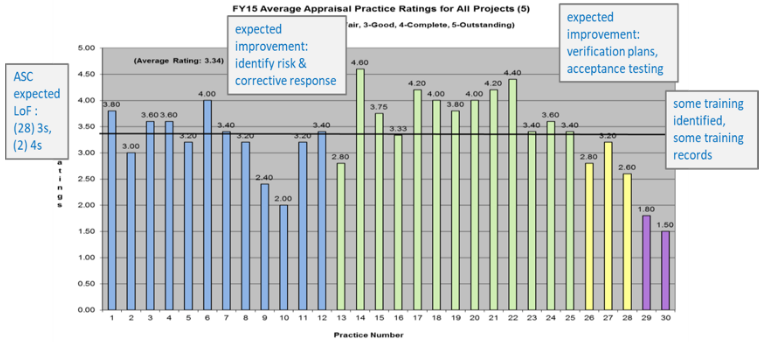
Are important physics models adequate? Key gaps mitigated?

PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity	2	0.7	1
PMMF	3	1.0	1
Code Verification			1
Sol. Verification			1
Model Validation			1
UQ/SA			1

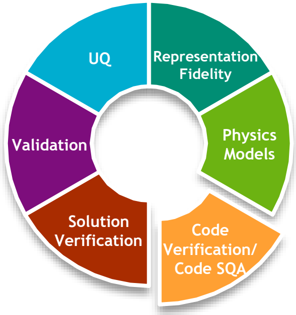
Code Verification

- Extensive use of unit testing in EM software
- Brian Freno has done extensive code verification using the governing equations

Summary of Verification Test Coverage



What is the evidence for code credibility?

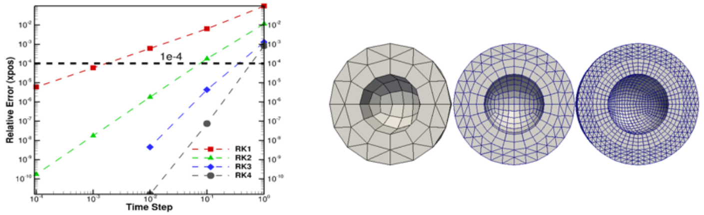


PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity	2	0.7	1
PMMF	3	1.0	1
Code Verification	3	1.0	1
Sol. Verification			1
Model Validation			1
UQ/SA			1

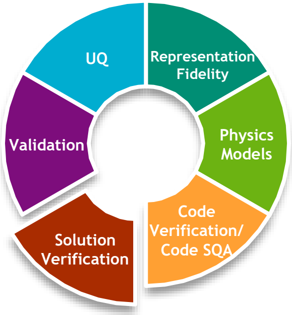
Solution Verification

- Rational interpolation is used to handle frequency stepping
- Aaron Krueger has done extensive solution verification studies

Mesh Refinement Study



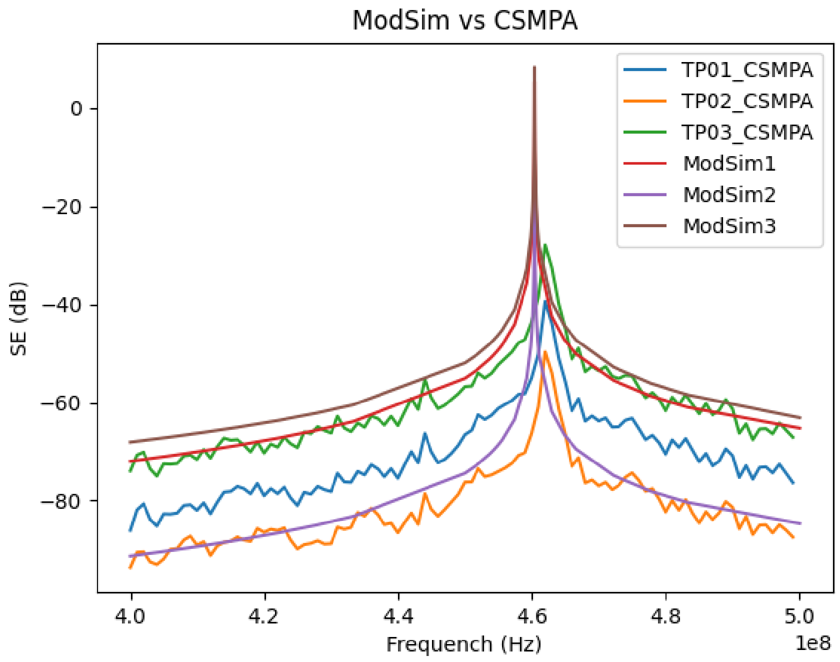
How do numerical solution or human errors affect simulation results?

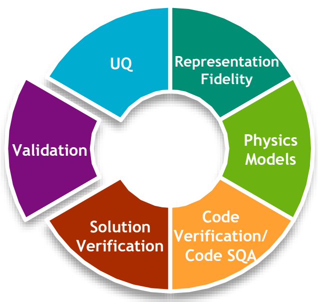


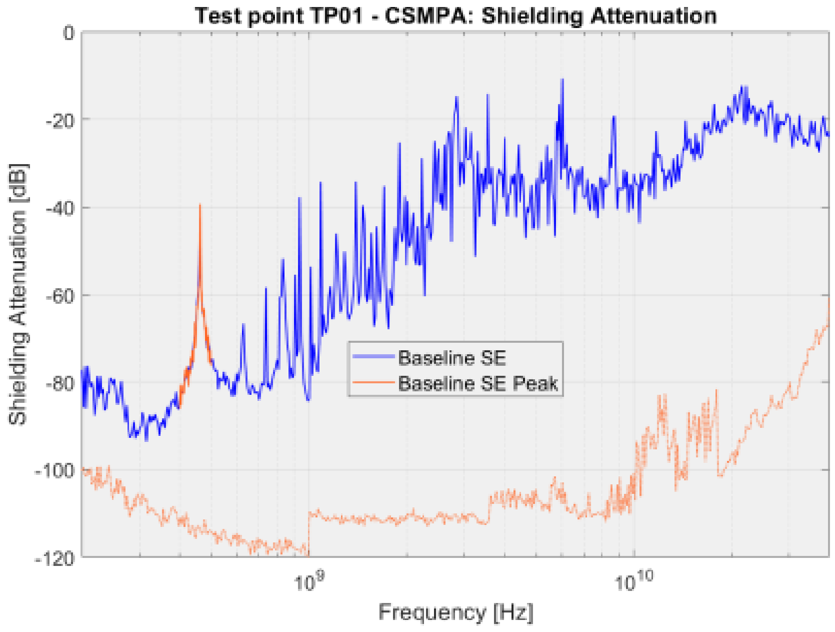
PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity	2	0.7	1
PMMF	3	1.0	1
Code Verification	3	1.0	1
Sol. Verification	3	1.0	1
Model Validation			1
UQ/SA			1

Model Validation

- General trend captured at all 3 locations
- Modeling only performed for the 1st resonant peak
- No formal validation metric employed







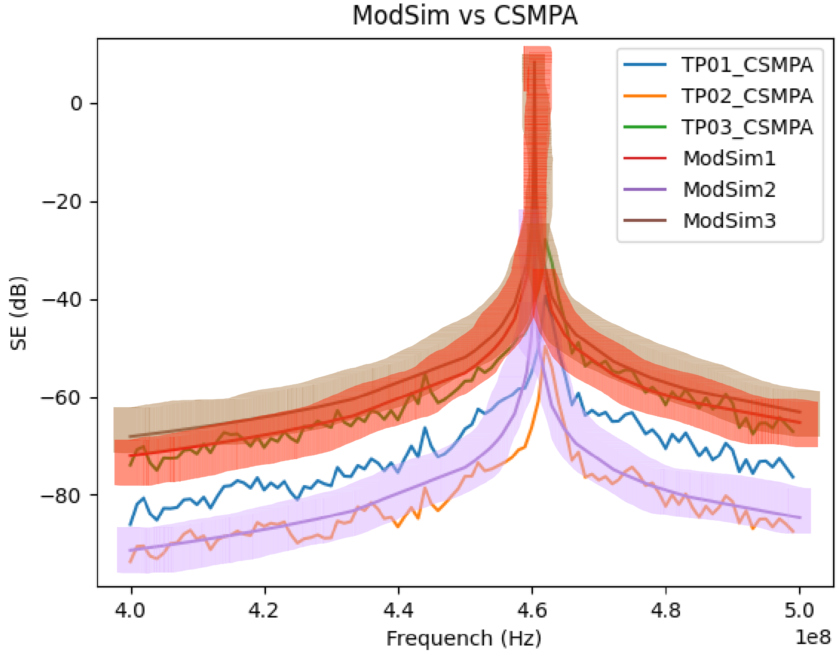
PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity	2	0.7	1
PMMF	3	1.0	1
Code Verification	3	1.0	1
Sol. Verification	3	1.0	1
Model Validation	2	0.8	1
UQ/SA			1

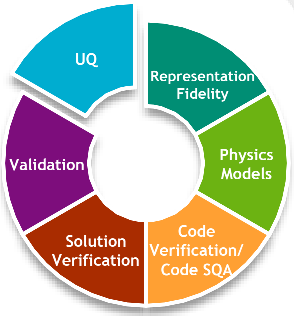
Uncertainty Quantification

- 2 parameters
  - Slot width
    - Uniform(1e-4, 1e-2)
  - Electrical conductivity
    - Uniform(3.5e6, 3.5e8)

- Sensitivity Analysis
  - Slot width is the dominant uncertainty source

- Bayesian model calibration to experimental data is underway





PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity	2	0.7	1
PMMF	3	1.0	1
Code Verification	3	1.0	1
Sol. Verification	3	1.0	1
Model Validation	2	0.8	1
UQ/SA	1	0.3	1

Overall credibility score

- Define weights across different PCMM elements
  - Which elements have greatest impact on credibility?
    - Discussion between credibility partner and other stakeholders
- Construct a BPA for each element

Rules for constructing BPAs

- $m_i(S) = E_i * M_i * R_i$
- $m_i(\mathrm{F}) = (1 - E_i) * M_i * R_i$
- $m_i(\{S, F\}) = 1 - (m_i(S) + m_i(F)) = 1 - M_i * R_i$
- $m_i(S) + m_i(F) + m_i(\{S, F\}) = 1$

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PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)	Weight (W_i)	Support $m_i(S)$	Failure $m_i(F)$	Uncertainty $m_i(\{S,F\})$
Geometric Fidelity	2 (0.9)	0.7	1	0.1	0.63	0.27	0.1
PMMF	3 (1.0)	1.0	1	0.1	1	0	0
Code Verification	3 (1.0)	1.0	1	0.1	1	0	0
Sol. Verification	3 (1.0)	1.0	1	0.2	1	0	0
Model Validation	2 (0.8)	0.8	1	0.2	0.64	0.16	0.2
UQ/SA	1 (0.4)	0.3	1	0.3	0.12	0.28	0.6
Combined BPA					0.627	0.143	0.23

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Conclusions

- We demonstrated Vanderbilt's quantitative credibility approach for an EM application
  - The credibility approach is comprehensive: maturity, strength, and relevance
  - The approach nicely partitions the credibility activity
  - Scoring is useful during the credibility process to guide next steps
  - For this EM exemplar, results from the credibility assessment for the acceptability of the model for its intended application are:

Support $m_i(S)$	Failure $m_i(F)$	Uncertainty $m_i(\{S,F\})$
0.627	0.143	0.23

Future Work

- Define a target application (which will introduce relevance considerations)
- Continue to mature the credibility activities for this EM application

Thank You!

PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)
Geometric Fidelity			
PMMF			
Code Verification			
Solution Verification			
Model Validation			
UQ/SA			

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Geometric Fidelity				
PMMF				
Code Verification				
Solution Verification				
Model Validation				
UQ/SA				

PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)	Weight (W_i)	Support $m_i(S)$	Failure $m_i(F)$	Uncertainty $m_i(\{S,F\})$
Geometric Fidelity							
PMMF							
Code Verification							
Solution Verification							
Model Validation							
UQ/SA							

PCMM Element	Maturity (M_i)	Evidence (E_i)	Relevance (R_i)	Weight (W_i)	Support $m_i(S)$	Failure $m_i(F)$	Uncertainty $m_i(\{S,F\})$
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UQ/SA							
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