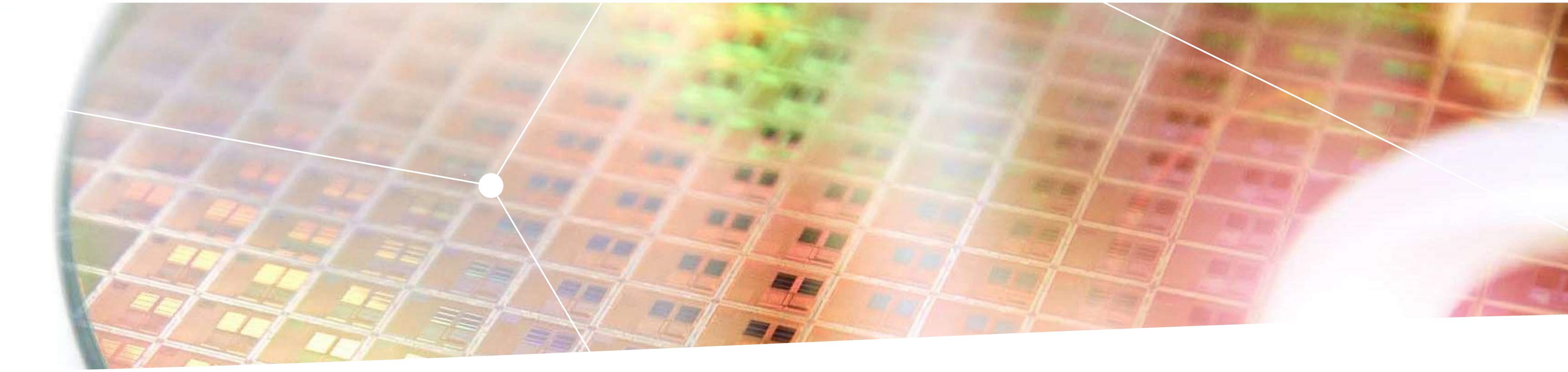

Design for Reliability Approach for Ensuring the Solder Joint Reliability of eWLB Packages in Automotive Radar Applications Using ANSYS optiSLang and ANSYS Mechanical

Martin Niessner[1], Walter Hartner[1], Gerhard Haubner[1], Sebastian Pahlke[1], Roland Niemeier[2] , Bernd Buettner[2] , Michael Eichhorst[3]

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[2]Dynardo GmbH, Steubenstraße 25, 99423 Weimar, Germany

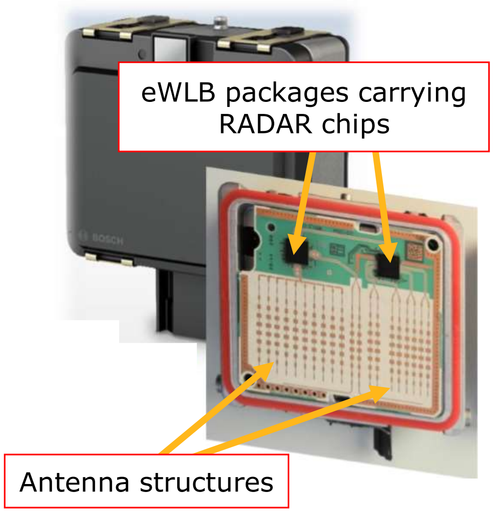
[3]Chemnitzer Werkstoffmechanik GmbH, Technologie-Campus 1, 09126 Chemnitz, Germany

17th Weimar Optimization and Stochastic Days 2020

June 25 – 26, 2020 Virtual Conference

Agenda

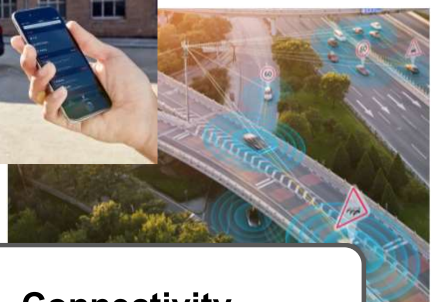
- Design for Reliability: Challenges and Motivation
- Results from WOST2019
- Comparison with Measurements
- Simulations for Three Cases and Metamodels of Optimal Prognosis (MOP)
- Reliability Analyses based on MOP
- Conclusion



Design for Reliability: Challenges and Motivation
Trends influencing reliability requirements

Courtesy of Ulrich Abelein
(Infineon Technologies AG)

© BMW Group



Connectivity

© Audi AG

Autonomous Driving

E-mobility

Urbanization

Design for Reliability: Challenges and Motivation
Contributing factors

Courtesy of Ulrich Abelein
(Infineon Technologies AG)

Table 45: Description General part
Operating situations

Operating situation	Vehicle parked	Charging cable inserted	High-voltage battery pack charging	Power line communication active (if available)
Driving operation	no	no	yes/no	no
Charging operation	yes	yes	yes	yes
Preconditioning	yes	yes/no	yes/no	yes/no
On-grid parking	yes	yes	no	yes
Off-grid parking or parking	yes	no	no	no

Contributing factors:

› Additional operating states beside driving:
  – On-grid parking
  – Vehicle-Preconditioning (battery as well as driver comfort like cabin heating)
  – Charging

Consequences:

› Increase in operating times

➔ Increase in reliability requirements

Requirements based on operating situation

Courtesy of Ulrich Abelein
(Infineon Technologies AG)

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Operating situations

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On-grid parking	yes	yes	no	yes
Off-grid parking or parking	yes	no	no	no

Operating states for e-vehicles according to LV124

Example requirements

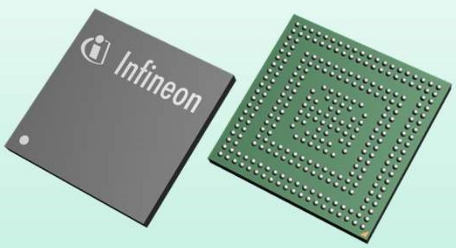
Operating situation	**Hours accumulated hours over lifetime**
Driving operation	**8,000 h**
Charging operation	**30,000 h**
Off-grid parking	**92,000 h**

Note: 5,500 h comfort-preconditioning (e.g. heating the cabin) might be estimated although not required as a state in the table.

Design for Reliability: Challenges and Motivation

Extended mission profiles E-mobility (data from 2018)

Courtesy of Ulrich Abelein
(Infineon Technologies AG)



Example:

Microcontroller for **use in a battery charging system**

Lifetime (same like vehicle): 15 years

› Op. Ambient Temp. Range: -40 °C to 125 °C
› Non-operating time: 91,400 hours
› Operating time: 40,000 hour

Customer's Mission Profile*

$T_{ambient}$ [°C]	Time [h]
Operating	
125	400
120	3,200
76	26,000
23	8,000
-40	2,400
Non Operating	
85	914
80	7,312
60	59,410
23	18,280
-40	5,484

*) Arbitrary chosen, corresponding to "Automotive Application Questionnaire for Electronic Control Units and Sensors", ZVEI, October 2006

Is today's AEC-Q100 qualification covering this lifetime requirement?

More details on AEC: http://www.aecouncil.com/
Example: AEC-Q100 Rev H: http://www.aecouncil.com/Documents/AEC_Q100_Rev_H_Base_Document.pdf

Design for Reliability: Challenges and Motivation
Extended mission profiles E-mobility (data from 2018)

Courtesy of Ulrich Abelein
(Infineon Technologies AG)

Equivalent HTSL stress time

Assumptions:

Arrhenius Model with E_a=0.7 eV, Self heating: 20 °C

Result:

$T_{stress,eq}$@175 °C = 1,521 h

$T_{stress,eq}$@150 °C = 4,437 h

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AEC-Q100 stress test conditions (Grade 1)

500 hours @ 175 °C or

1000 hours @ 150 °C

<30% coverage of extended requirements

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Design for Reliability: Challenges and Motivation
Extended mission profiles E-mobility (data from 2018)

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AEC-Q100 stress test conditions (Grade 1)

500 hours @ 175 °C or

1000 hours @ 150 °C

<30% coverage of extended requirements

AEC-Q100 stress test conditions (Grade 0)

1000 hours @ 175 °C or

2000 hours @ 150 °C

~60% coverage of extended requirements

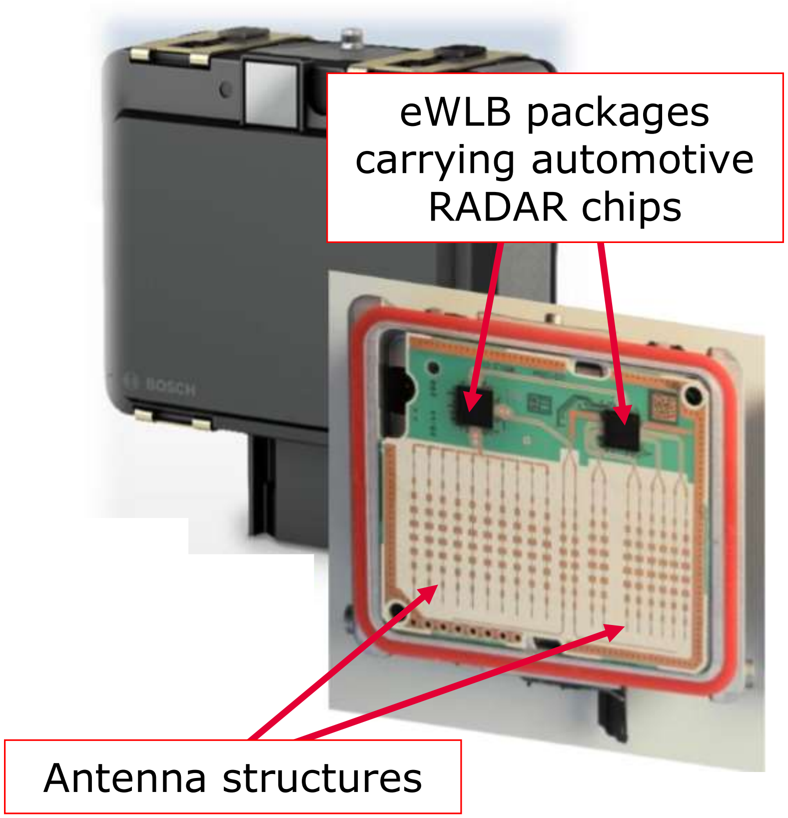
Customer's Mission Profile*

$T_{ambient}$ [°C]	Time [h]
Operating	
125	400
120	3,200
76	26,000
23	8,000
-40	2,400
Non Operating	
85	914
80	7,312
60	59,410
23	18,280
-40	5,484

*) Arbitrary chosen, corresponding to "Automotive Application Questionnaire for Electronic Control Units and Sensors", ZVEI, October 2006

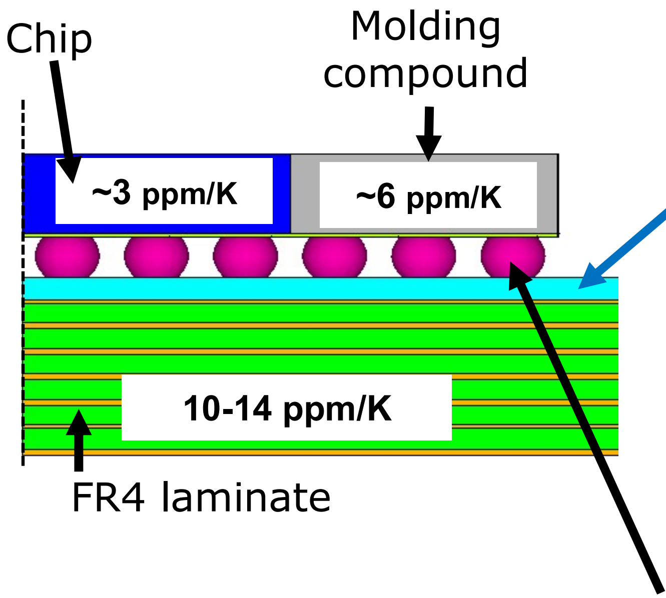
➔ Today's AEC-Q100 qualifications do not cover extended requirements

Investigated application
Automotive RADAR



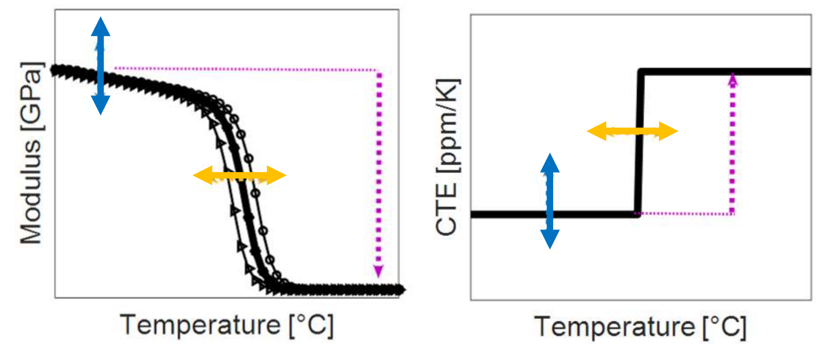
Source: M. Eichhorst *et al.*, VII. SGW-Forum, 2019

Key findings WOST2019
Solder joint reliability of eWLB radar package



RF laminate (top layer)

Material properties

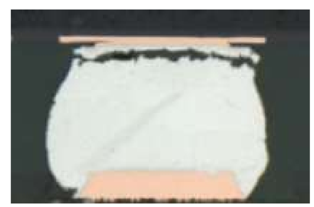


CTE mismatch

⇩

Cyclic Stress

Solder ball (healthy)

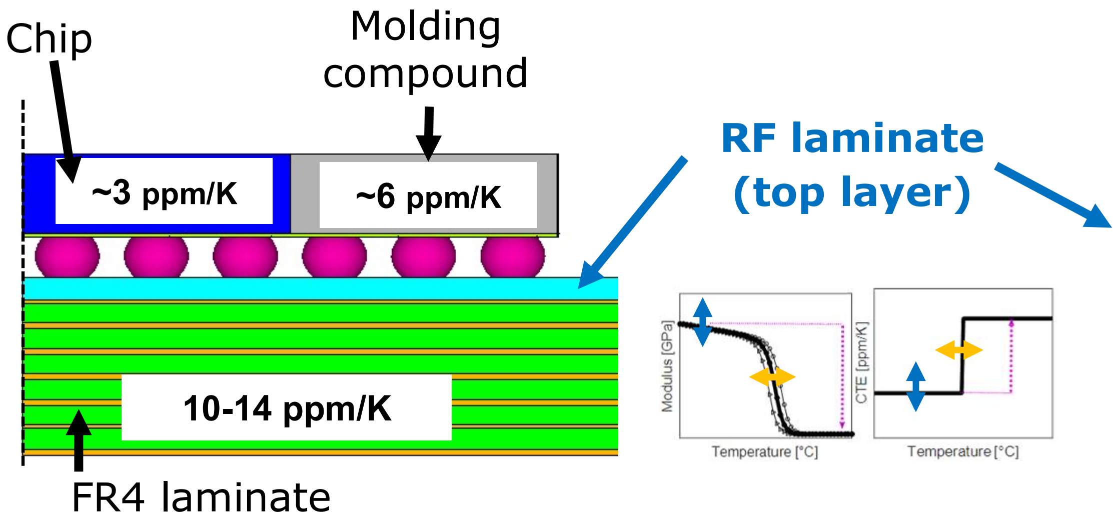


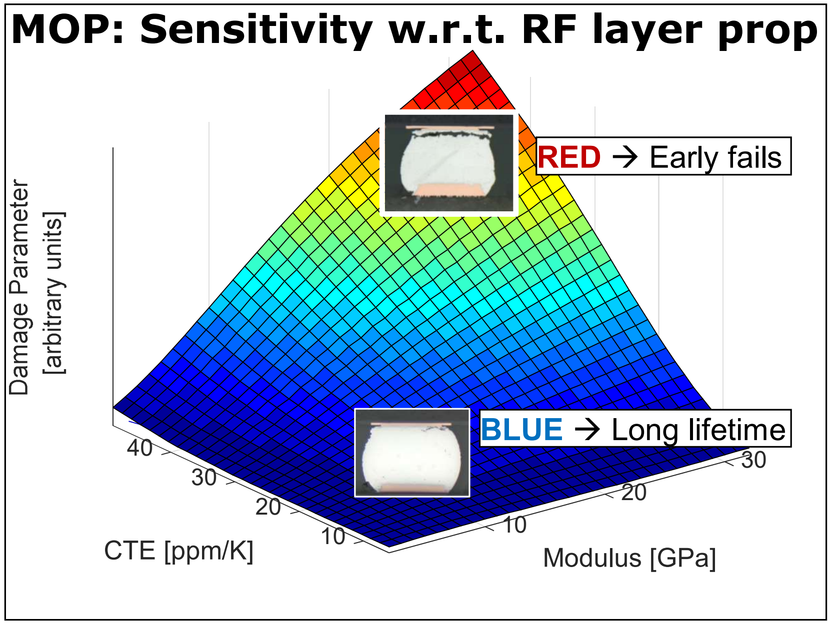
Solder ball (broken)

- **Impact of material properties of RF laminate on solder joint reliability was investigated**

For more details see archive of WOST2019:
https://www.dynardo.de/fileadmin/Material_Dynardo/bibliothek/WOST16/4_WOST2019_Session_3_Niessner.pdf

Key findings WOST2019
Solder joint reliability of eWLB radar package



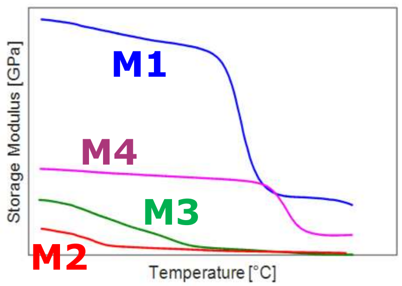


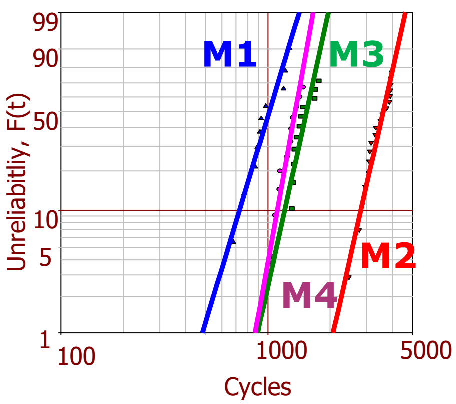
- **Summary of sensitivity study:**
  - For low CTE, the RF laminate generates a “CTE transition” between the PCB and the package
  - For low E modulus, the RF laminate becomes a “buffer”

For more details see archive of WOST2019: https://www.dynardo.de/fileadmin/Material_Dynardo/bibliothek/WOST16/4_WOST2019_Session_3_Niessner.pdf

Key findings WOST2019 (continued)
Experimental validation 2019 and 2020

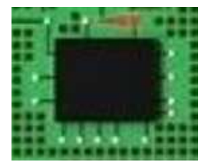
Reliability experiment



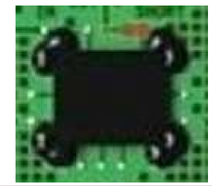


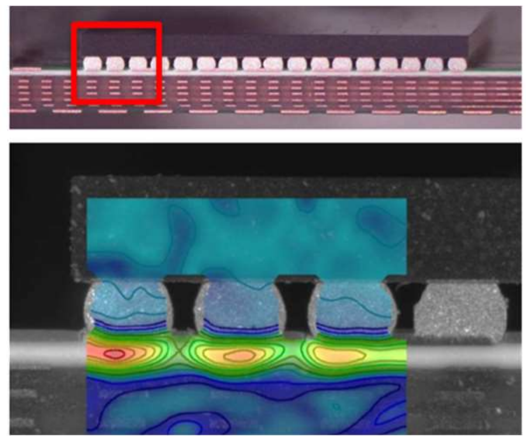
In-plane DIC

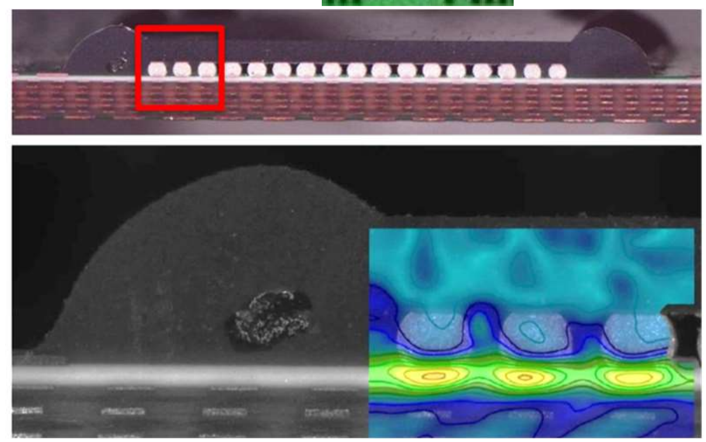
Free PCB No Cornerbond



Free PCB With Cornerbond







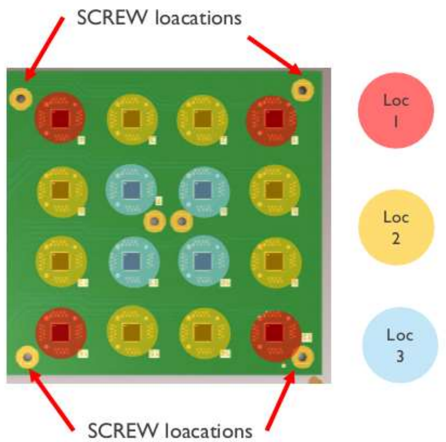
Courtesy of Chemnitzer Werkstoffmechanik GmbH

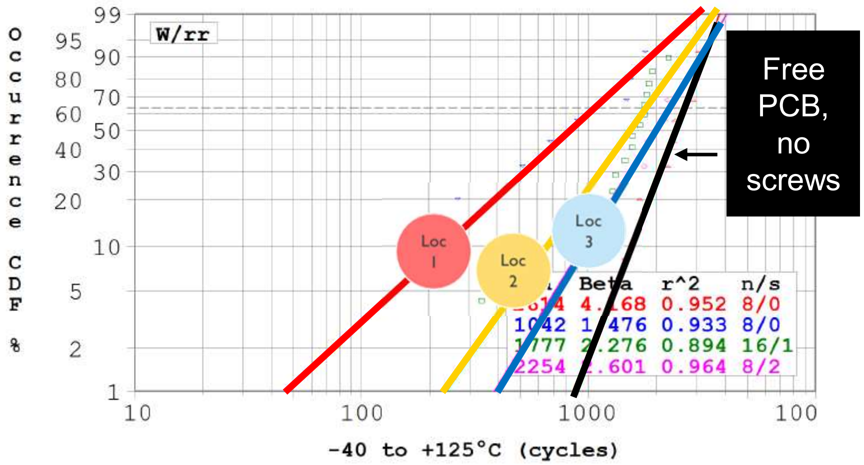
radar4FAD

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

- **Findings from sensitivity study are experimentally verified**

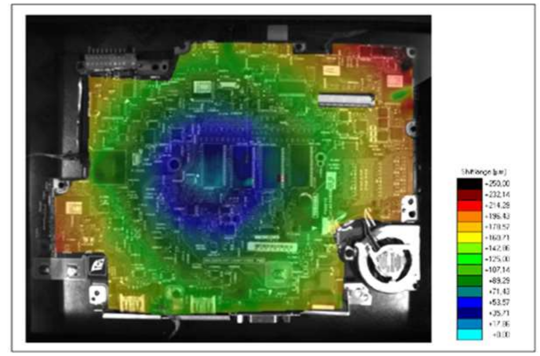
Next steps in WOST2020
Investigation along value chain



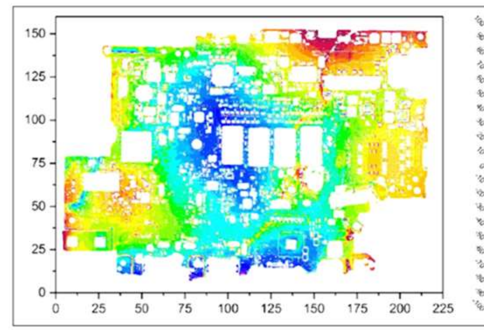


Source: Bart Vandevelde, EuWoRel 2019

- Experiments show that solder joint reliability is locally reduced when the PCB is no longer free, but mounted in a housing
- **Limitation:** Suppliers of electrical components can only do testing on free, non-mounted PCBs as module design unknown
- **Consequence:** Delta between Tier2 and Tier1 reliability results



In-plane deformation

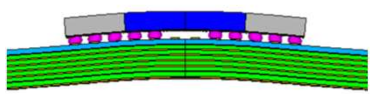
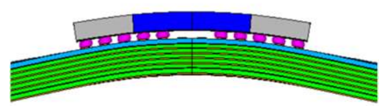
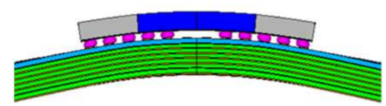
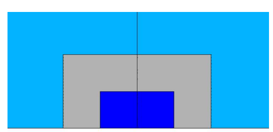
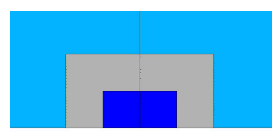
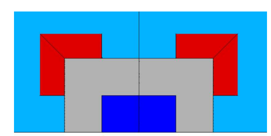


Out-of-plane deformation

Chemnitzer Werkstoffmechanik GmbH

Source: M. Eichhorst et al., VII. SGW-Forum, 2019

Next steps in WOST2020
Investigation along value chain using MOP

Case	#1	#2	#3
Situation	Tier2 type reliability test	Tier1 type module loading	Tier1 type module loading + cornerbond
Temperature loading	Yes	Yes	Yes
Bending because PCB is fixed to housing	No	Yes	Yes
View of deformation during loading	 100x over-scaled	 100x over-scaled	 100x over-scaled
Top view (half model)			

- MOPs are used for studying the solder joint reliability along the value chain, especially regarding the RF material design space

Next steps in WOST2020
Investigation along value chain using MOP

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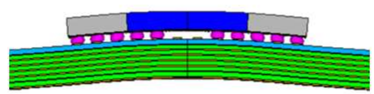
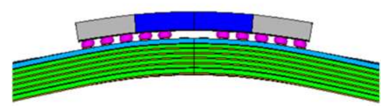
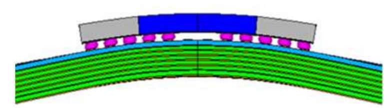
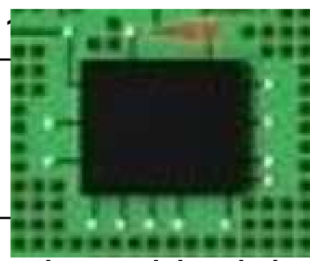
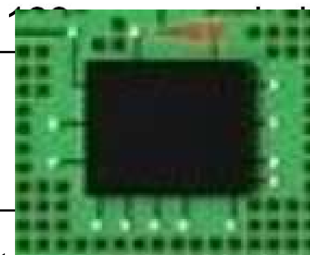
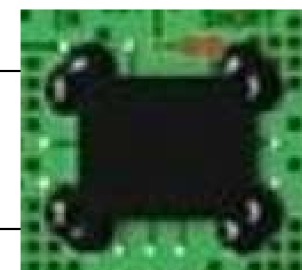
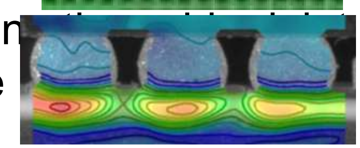
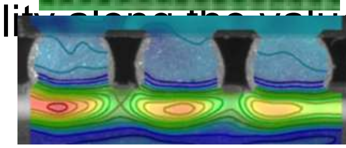
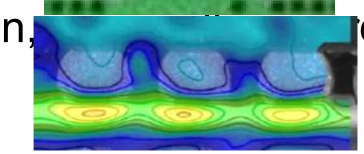
View of deformation during loading			
Top view (half model)			

› MOPs are used for studyin … reliabili … e chain, … ding the RF material design space

Reliability Analysis based on MOP

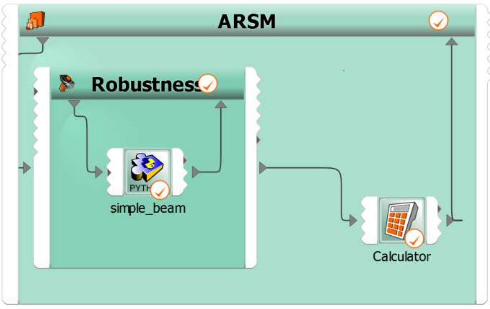
17th Weimar Optimization and Stochastic Days 2020

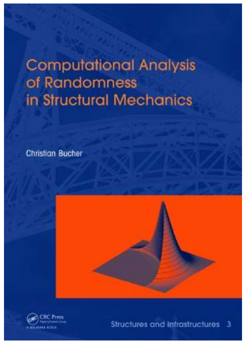
June 25 – 26, 2020
Virtual Conference

Ansys

Reliability and the Probability of Failure

- Optimization is introduced into virtual prototyping for more than 20 years
- Robustness evaluation and reliability analysis are key methodologies for safe, reliable and robust products
- The combination leads to robust design optimization (RDO) strategies

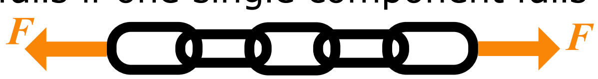




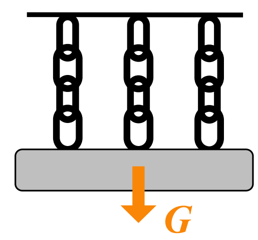
- The complementary of reliability is the probability of failure. This can be computed taking into account the scattering, variations of the input.
- Applications for example in ADAS, Microelectronics, ...:
  - Driving Scenarios
  - Solder Joint Fatigue

Probability of Failure Calculations in Microelectronics

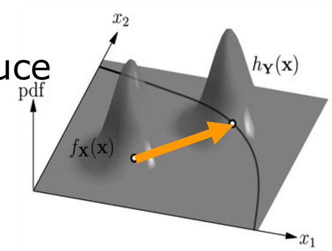
- The complementary of *Reliability* is the *Probability of Failure*
- This can be computed for different failure mechanism, like
  - Solder Joint Fatique (e.g. solder balls)
  - Delamination
  - Interconnect failure (e.g. wire lift-off inside package)
- Total Probability of Failure of the system depends on redundancy, dependencies for example
  - Series system: fails if one single component fails



  - Parallel system: fails if all components fail



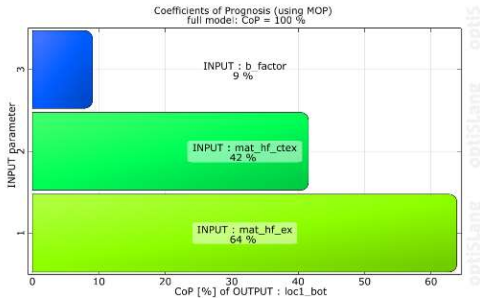
- Criteria need to be defined for the failure
  - This leads to limit state function(s)
  - Algorithms to detect this limit state function reduce the number of necessary simulation significantly

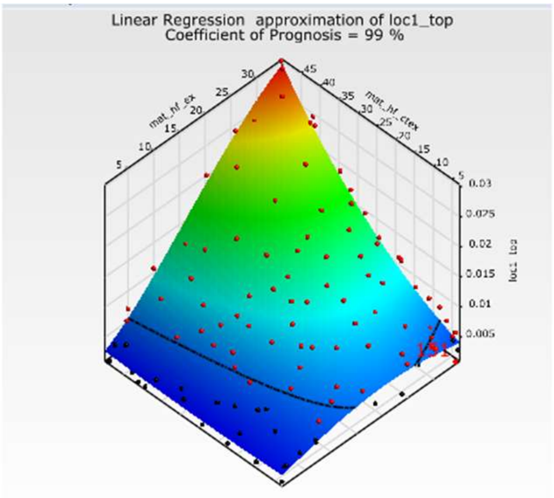


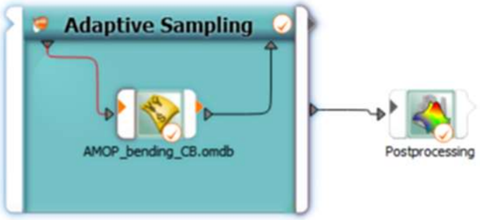
Ansys

Metamodel of Optimal Prognosis (MOP)

- Selection of the **important variables** by sensitivity indices
- Determination of **best surrogate model** without overfitting
- Objective measure of **prognosis quality**
- Fast **Optimization** based on MOP
- Fast ***Reliability Analysis*** based on MOP







MOP Surface: Case 3 with b_factor = 1.5; isoline loc1_top = 0.0055

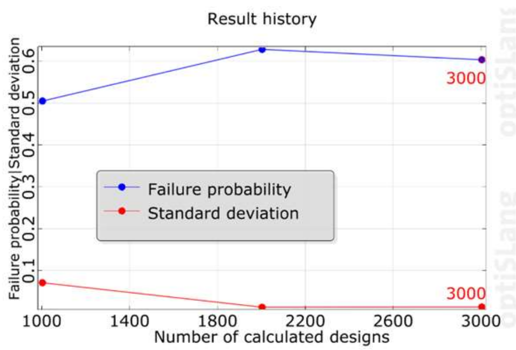
Probability of Failure at a constant damage limit level
using uniform distribution across full design space

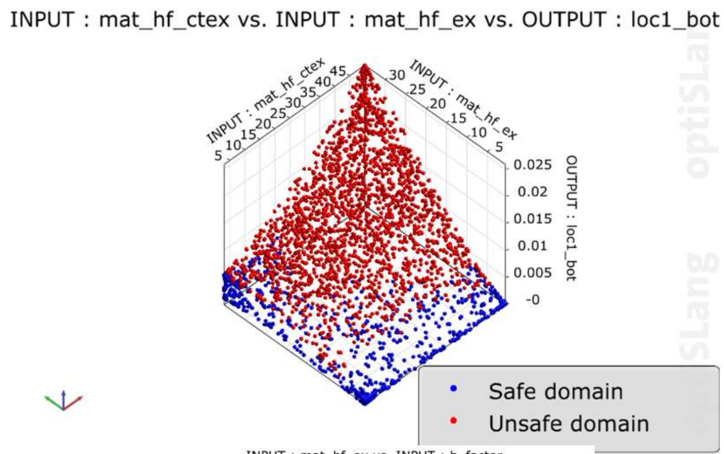
Method : Adaptive Sampling (AS)

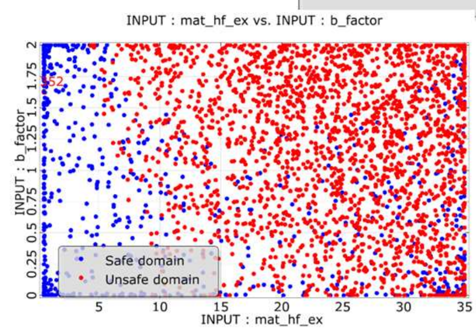
Complete iterations : 3 / 3
Selected data : All designs

Probability of Failure : 0.603392
Standard deviation error : 0.01331
Reliability Index : -0.262136

Number of designs
Total : 3000
Safe domain : 810
Unsafe domain : 2190
Failure strings : 0
Failed : 0







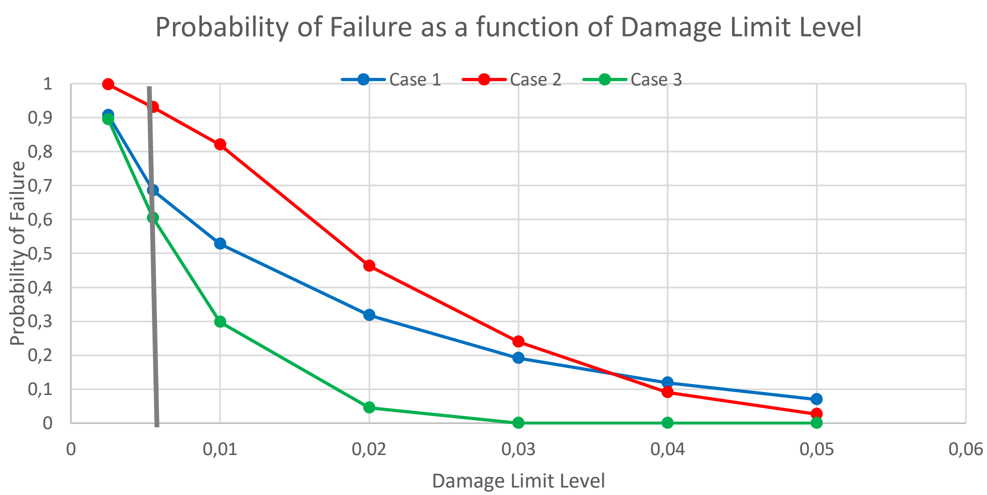
Limit State Function defined by loc1_top < 0.0055
Reliability Algorithm: Adaptive Sampling
Probability of Failure for whole design space with uniform distribution Case 1: 0,69; Case 2: 0,95; Case 3: 0,60
for Case 3 displayed: Reliability Information, Cloud plot, Result History and Anthill Plot

Probability of Failure as a function of damage limit level using uniform distribution across full design space

Adaptive Sampling

Parameter | Start designs | Nominal design | Criteria | Adaptive Sampling | Other | Result de

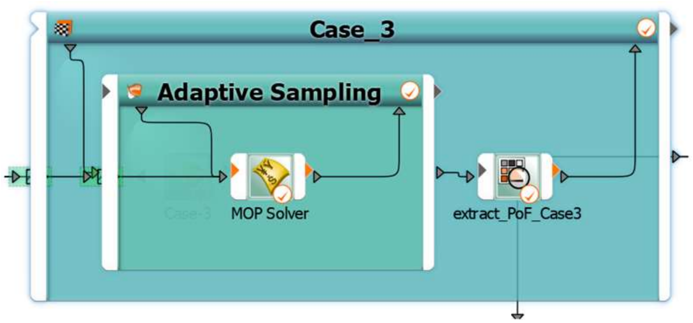
	Name	Parameter type	Reference value	PDF	Type	Distribution parameter
1	b_factor	Stochastic	1		UNIFORM	0; 2
2	mat_hf_ctex	Stochastic	26.5		UNIFORM	3; 50
3	mat_hf_ex	Stochastic	17.75		UNIFORM	0.5; 35

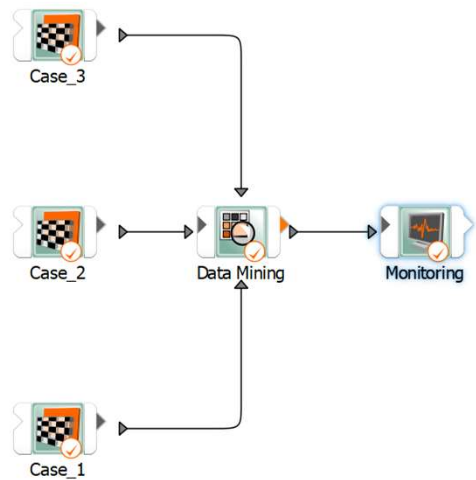


Higher damages are much more probable in Case 2 than in Case 3

Automated Workflows for Reliability Analyses

- Using Reliability Methods Integrated in Workflows
- Loop over threshold values to calculate Probability of Failure curves
- Branches for different cases
- Data Mining to extract relevant information
- Customized Visualization





Case_3 - Sensitivity

Parameter | Start designs | Criteria | Dynamic sampling | Other | Result designs

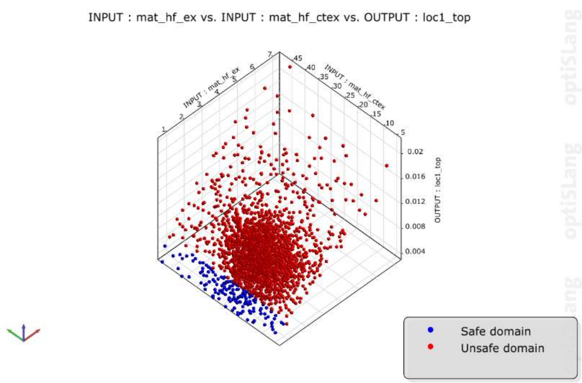
	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range	Range plot	PDF	Type	Distribution pa
1	criteria_limit_state	Optimization	0.003	☐	REAL	Discrete by value	0.00...				
2	b_factor	Stochastic	1	☐	REAL	Continuous				UNIFORM	0; 2

Specific Design Point with a Probability Distribution
- Walking on the unsafe side, Case 2

Adaptive Sampling

Parameter | Start designs | Nominal design | Criteria | Adaptive Sampling | Other | Result designs

	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot	PDF	Type	Mean	Std. Dev.	CoV	Distribution para
1	b_factor	Optimization	1.5	☑	REAL	Continuous	0	2							
2	mat_hf_ctex	Opt.+Stoch.	21	☐	REAL	Continuous	3	50			NORMAL	21	6.3	30 %	21; 6.3
3	mat_hf_ex	Opt.+Stoch.	2	☐	REAL	Continuous	0.5	35			NORMAL	2	0.6	30 %	2; 0.6



Method : Adaptive Sampling (AS)

Complete iterations : 3 / 3
Selected data : All designs

Probability of Failure : 0.920722
Standard deviation error : 0.00766578
Reliability Index : -1.40994

Number of designs
Total : 3000
Safe domain : 149
Unsafe domain : 2456
Failure strings : 0
Failed : 395

Criteria

Name	Type	Expression	Criterion	Limit	Evaluated expression
lim_st_loc1_top	Limit state	loc1_top	≤	0.0055	0.00830161 ≤ 0.0055

Assuming the b_factor of 1.5 in Case 2 we have a design on the unsafe side

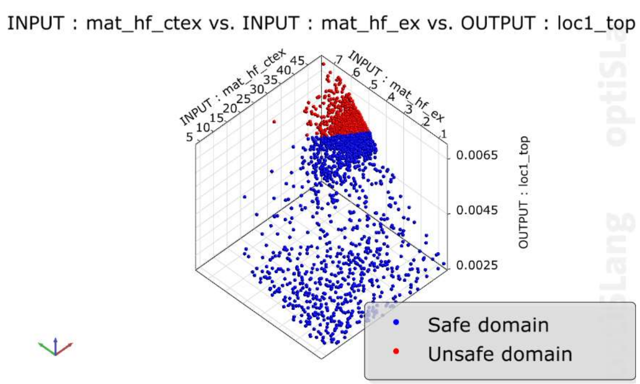
Ansys

Same Design Point with same Probability Distribution
- Walking on the safe side, Case 3

Adaptive Sampling

Parameter | Start designs | Nominal design | Criteria | Adaptive Sampling | Other | Result designs

	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range		Range plot	PDF	Type	Mean	Std. Dev.	CoV	Distribution parameter
1	b_factor	Optimization	1.5	☑	REAL	Continuous	0	2							
2	mat_hf_ctex	Opt.+Stoch.	21	☐	REAL	Continuous	3	50			NORMAL	21	6.3	30 %	21; 6.3
3	mat_hf_ex	Opt.+Stoch.	2	☐	REAL	Continuous	0.5	35			NORMAL	2	0.6	30 %	2; 0.6



Method : Adaptive Sampling (AS)

Complete iterations : 3 / 3
Selected data : All designs

Probability of Failure : 1.65916e-12
Standard deviation error : 1.36946e-13
Reliability Index : 6.96354

Number of designs
Total : 3000
Safe domain : 1443
Unsafe domain : 644
Failure strings : 0
Failed : 913

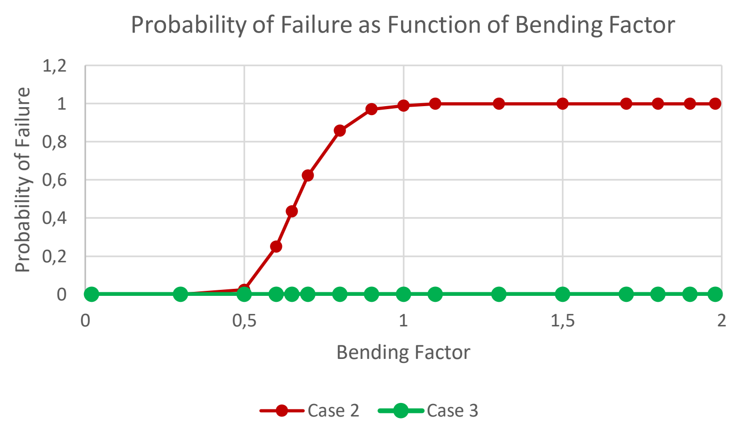
Criteria

Name	Type	Expression	Criterion	Limit	Evaluated expression
lim_st_loc1_top	Limit state	loc1_top	≤	0.0055	0.00298585 ≤ 0.0055

Algorithm using MOP detects with only 3000 runs very low probability of failure: $1.7 * 10^{-1}$

Examples of Fragility Curves:

Studying the Probability of Failure in dependance of important parameters for a specific design



Parameter	Start designs	Nominal design	Criteria	Adaptive Sampling	Other	Result designs

	Name	Parameter type	Reference value	Constant	PDF	Type	Mean	CoV
1	mat_hf_ex	Opt.+Stoch.	2	☐		NORMAL	2	10 %
2	mat_hf_ctex	Opt.+Stoch.	21	☐		NORMAL	21	10 %

Specific design with mean E, CTE const.; Gaussian distribution; CoV 10%; bending factor varying from 0 to 2; limit level loc1_top = 0.0055

Conclusions and Outlook

- *Superior reliability using additional corner bonds is shown by the reliability analysis*
- *The probability of failure has been used in calculations as the complementary of reliability*
- *This analysis has been done based on MOP as an example for a possible important exchange mechanism between companies*
- *Efficient workflows are developed using the MOP that can be used for simulation runs to calculate probability of failures based directly from simulation runs (i.e. detailed analysis for transition regions, verification)*
- *Fragility Curves are useful to understand the design behavior*

Future possible research include extension of Fragility Curves to several dimensions: Metamodels of Probabilities of Failures

High quality Metamodels of Probabilities of Failures can be an essential component for Digital Twins

Thanks !