COST Action
TU 1402

Quantifying the Value of Structural Health Monitoring

WG3: Methods & Tools

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Final TU1402 Workshop

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Introduction

WG3 Motivation

The concept of the ***Value of Information*** (VoI) concept enables a quantification of the benefits provided via adoption ***of Structural Health Monitoring*** (SHM) systems – *in principle*.

Its implementation is challenging, as it requires explicit modelling of the structural system's life cycle, and in particular of the type and level of decisions that are taken based on the SHM information.

WG3 aims to provide an overview on the different analyses and computations that are involved in the VoI analysis within the context of SHM and give guidelines on implementation

Aims of WG 3

(i) While many methods and tools exist for the individual components of the VoI analysis***, these have seldom been put together for a complete VoI analysis***.

(ii) The objectives of the third working group lie in ***identifying, developing and critically overviewing methods and tools*** required for the utilization of the theoretical VoI framework in practice.

(iii) Considering the multiplicity of methods involved, successful incorporation into actual Operation and Maintenance schemes necessitates ***standardization of the vocabulary, models and methods undertaken***.

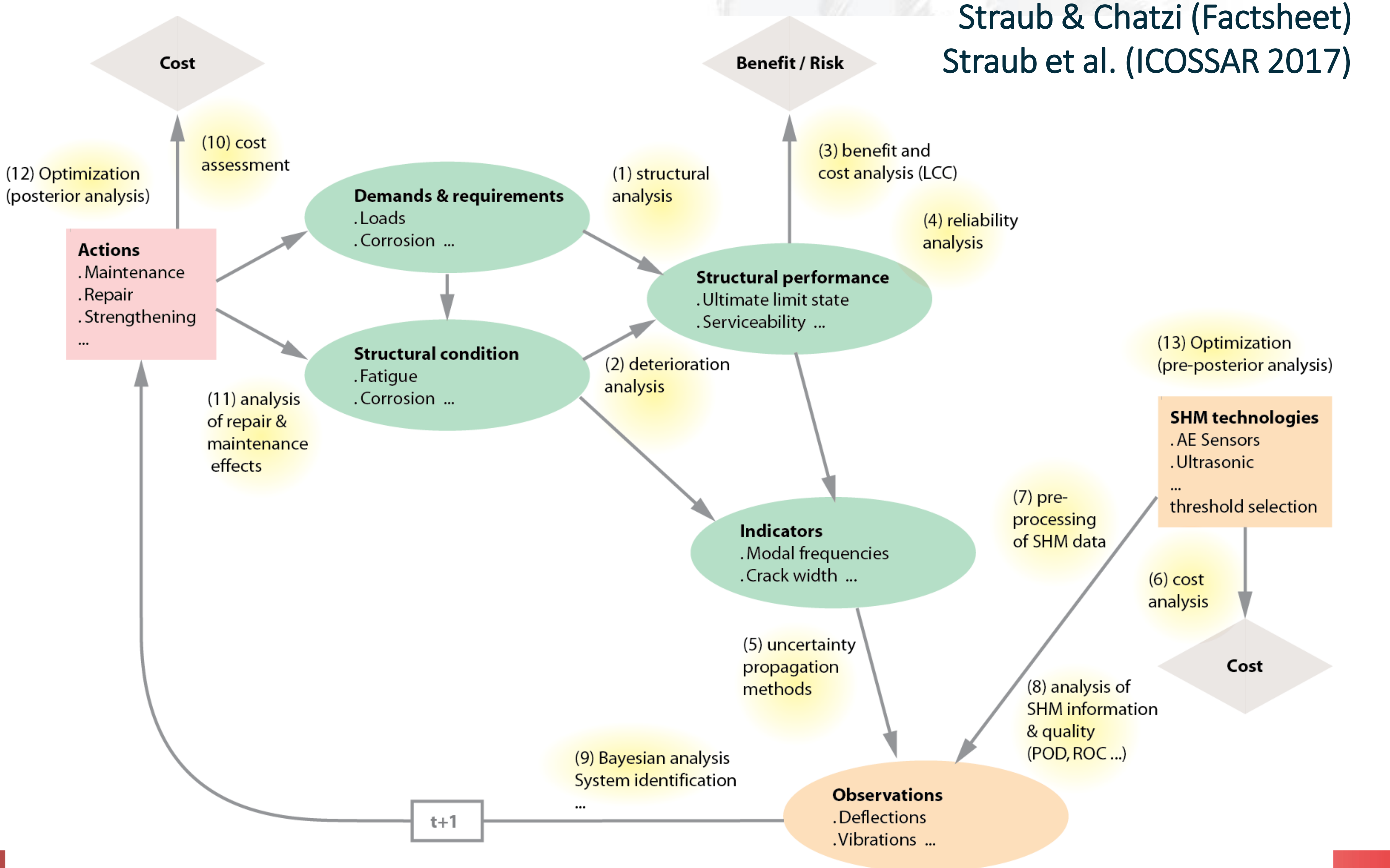
Achievements

dissemination

- The overview provided in the **WG3-related factsheets** contributes toward realization of the specified objectives.
- The scientific content of **WG3 related conference-papers** contribute to development of new methods.
- The "***Software Database on VoI & UQ"*** document, available for download in the members download area (WG3 subfolder), summarizes existing tools that may be used in the context of a VoI analysis.
- The ***toy case-study -"benchmark" -*** to be made available to the scientific community will offer a common platform for V&V of the VoI tools.

The VoI Influence Diagram of the SHM analysis process

Straub & Chatzi (Factsheet)
Straub et al. (ICOSSAR 2017)



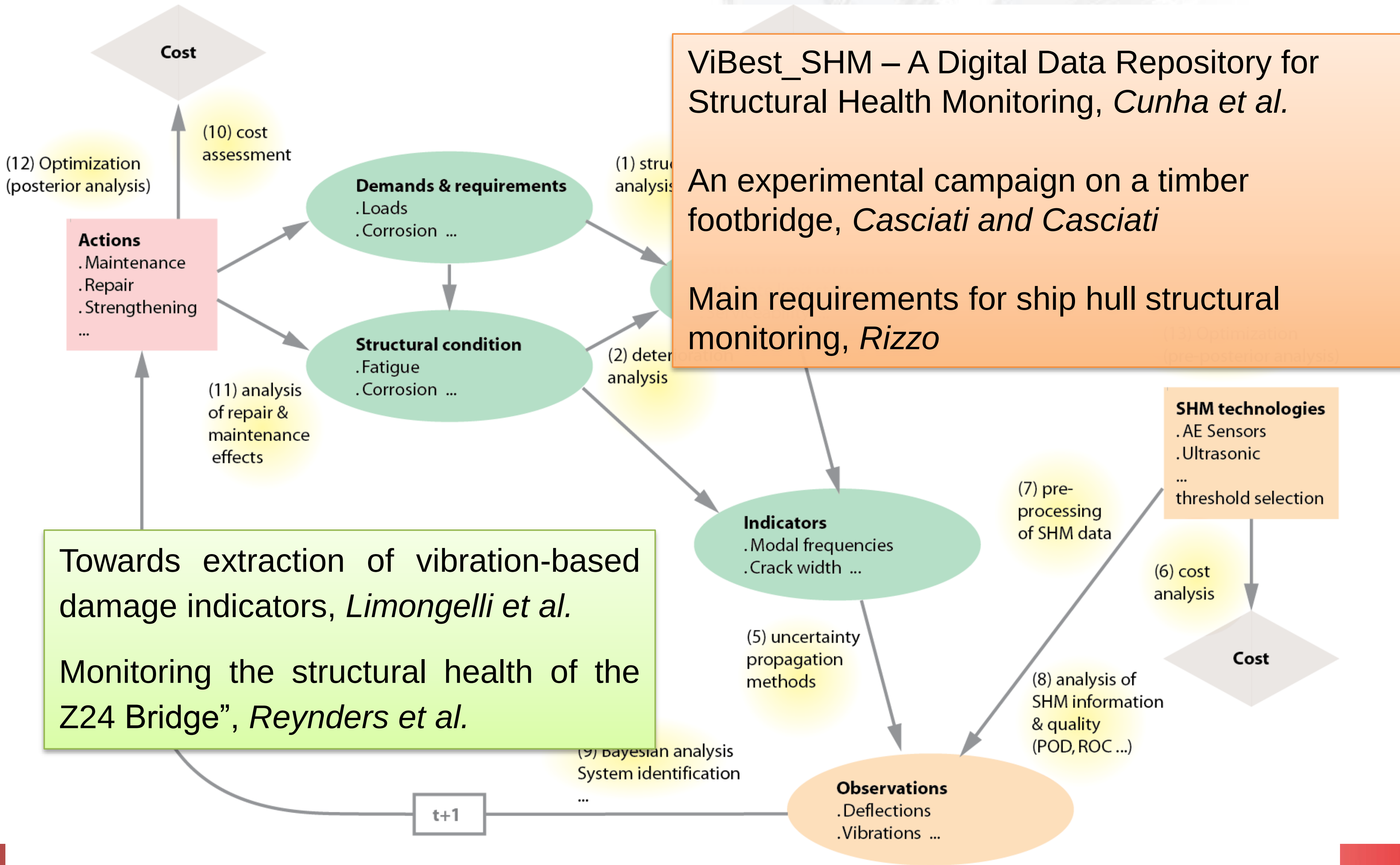
ViBest_SHM – A Digital Data Repository for Structural Health Monitoring, *Cunha et al.*

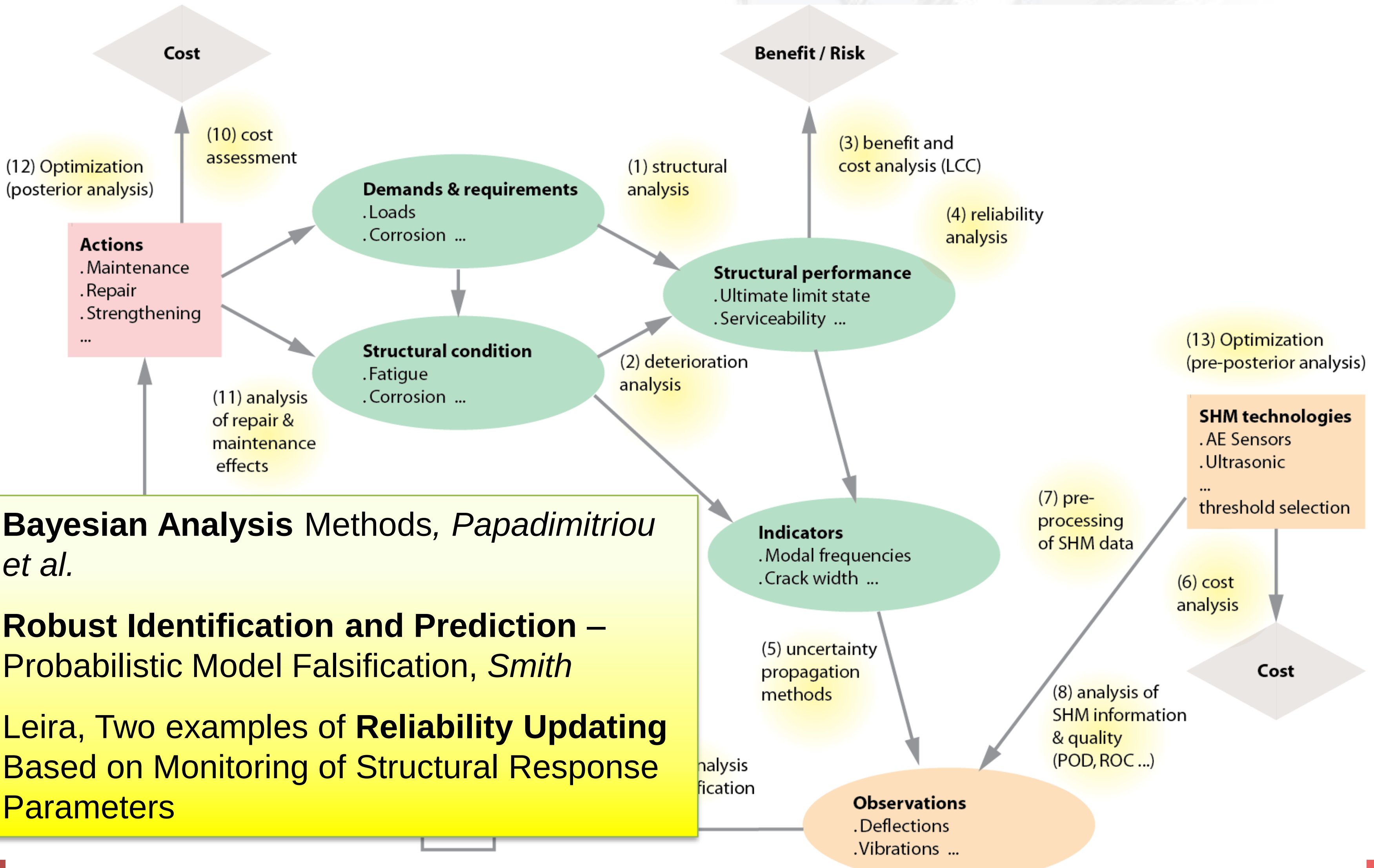
An experimental campaign on a timber footbridge, *Casciati and Casciati*

Main requirements for ship hull structural monitoring, *Rizzo*

Towards extraction of vibration-based damage indicators, *Limongelli et al.*

Monitoring the structural health of the Z24 Bridge", *Reynders et al.*



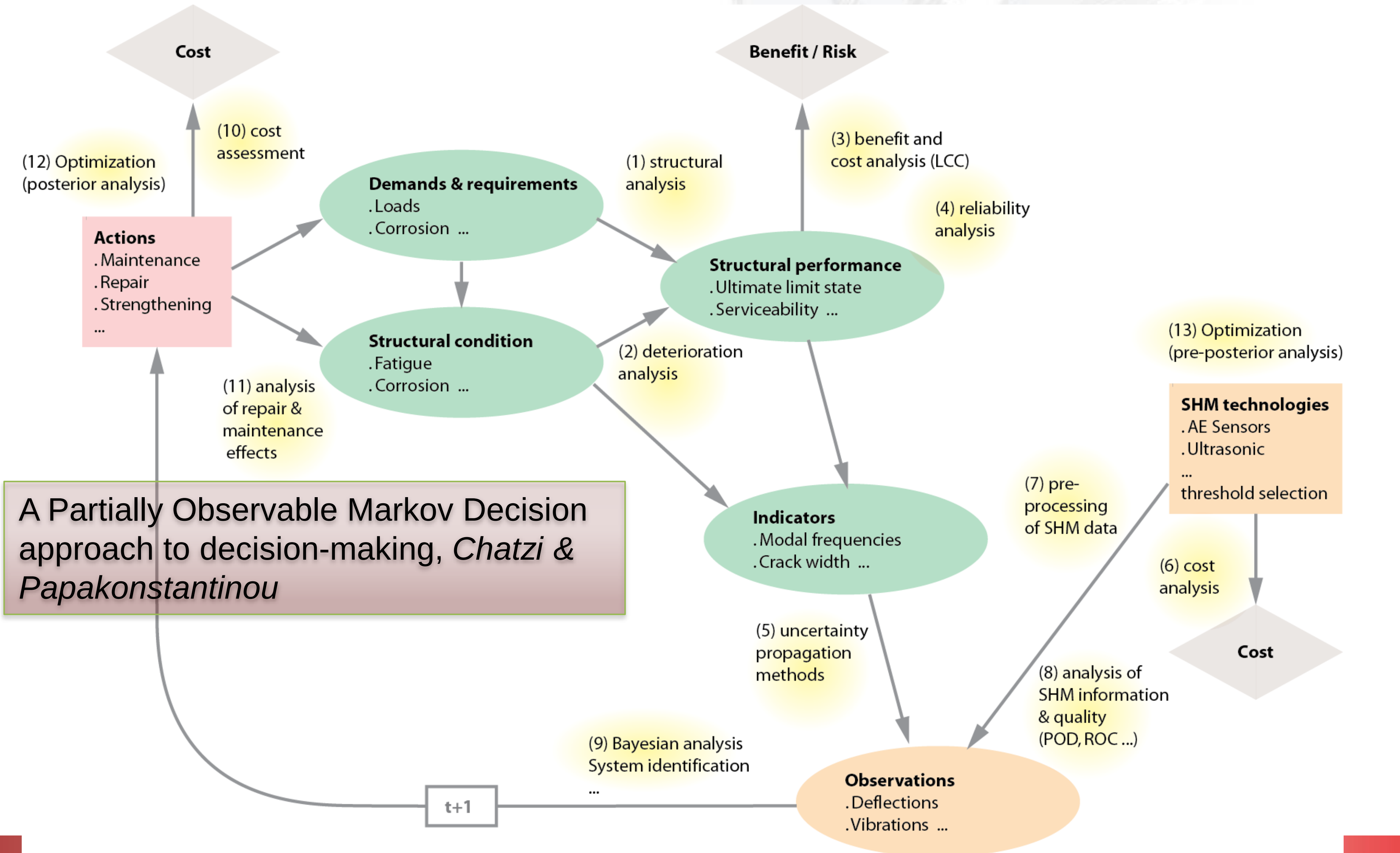


Bayesian Analysis Methods, *Papadimitriou et al.*

Robust Identification and Prediction – Probabilistic Model Falsification, *Smith*

Leira, Two examples of **Reliability Updating** Based on Monitoring of Structural Response Parameters

A Partially Observable Markov Decision approach to decision-making, *Chatzi & Papakonstantinou*



Achievements

- The overview provided in the **WG3-related factsheets** contributes toward realization of the specified objectives.

dissemination

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Dissemination - WG3 related papers

- D. Straub, E. Chatzi, E. Bismut, W.M.G. Courage, M. Döhler, M.H. Faber, J. Köhler, G. Lombaert, P. Omenzetter, M. Pozzi, S. Thöns, D. Val, H. Wenzel and D. Zonta, "Value of Information: A roadmap to quantifying the benefit of structural health monitoring", 2th international conference on Structural Safety & Reliability (ICOSSAR2017), August 6-10, 2017, Vienna, Austria.

- E. Chatzi, K. G. Papakonstantinou, D. Straub and R. Hajdin. ‘’ Observation-based Decision-making for Infrastructure’’. In Proceedings of the Joint COST TU1402 - TU1406 - IABSE WC1 WORKSHOP: The Value of Structural Health Monitoring for the Reliable Bridge Management, March, 02 and 03, 2017, Zagreb, Croatia. DOI: https://doi.org/10.5592/CO/BSHM2017.4.1

- Luque J., Straub D. (2019). Risk-based optimal inspection strategies for structural systems using dynamic Bayesian networks. Structural Safety, 76: 68-80, https://doi.org/10.1016/j.strusafe.2018.08.002

- R. Schneider, S. Thöns and D. Straub. ,‘’Reliability analysis and updating of deteriorating systems with subset simulation’’. Structural Safety 64: 20-36. DOI: 10.1016/j.strusafe.2016.09.002.

- B.J. Leira, S. Thöns. ‘’System reliability of concrete structures subjected to chloride ingress’’. European Safety and Reliability Conference (ESREL 2017); Portoroz, Croatia.

- P. Omenzetter, M.P. Limongelli, U. Yazgan and S. Soyoz, "Quantifying the value of SHM for emergency management of bridges at-risk from seismic damage based on their performance indicators". In Proceedings of the JOINT COST TU1402 - COST TU1406 - IABSE WC1 WORKSHOP: The Value of Structural Health Monitoring for the Reliable Bridge Management. March, 02 and 03, 2017, Zagreb, Croatia. DOI: https://doi.org/10.5592/CO/BSHM2017.4.5

- M. Pozzi, C. Malings and A. Minca, "Negative value of information in systems’ maintenance", 12th international conference on Structural Safety & Reliability (ICOSSAR2017), August 6-10, 2017, Vienna, Austria.
- A. A. Irman, S. Thöns and B. J. Leira. ‘’Value of information-based inspection planning for offshore structures’’. 36th International Conference on Ocean, Offshore and Artic Engineering (OMAE), Trondheim, Norway, 25-30 June, 2017.

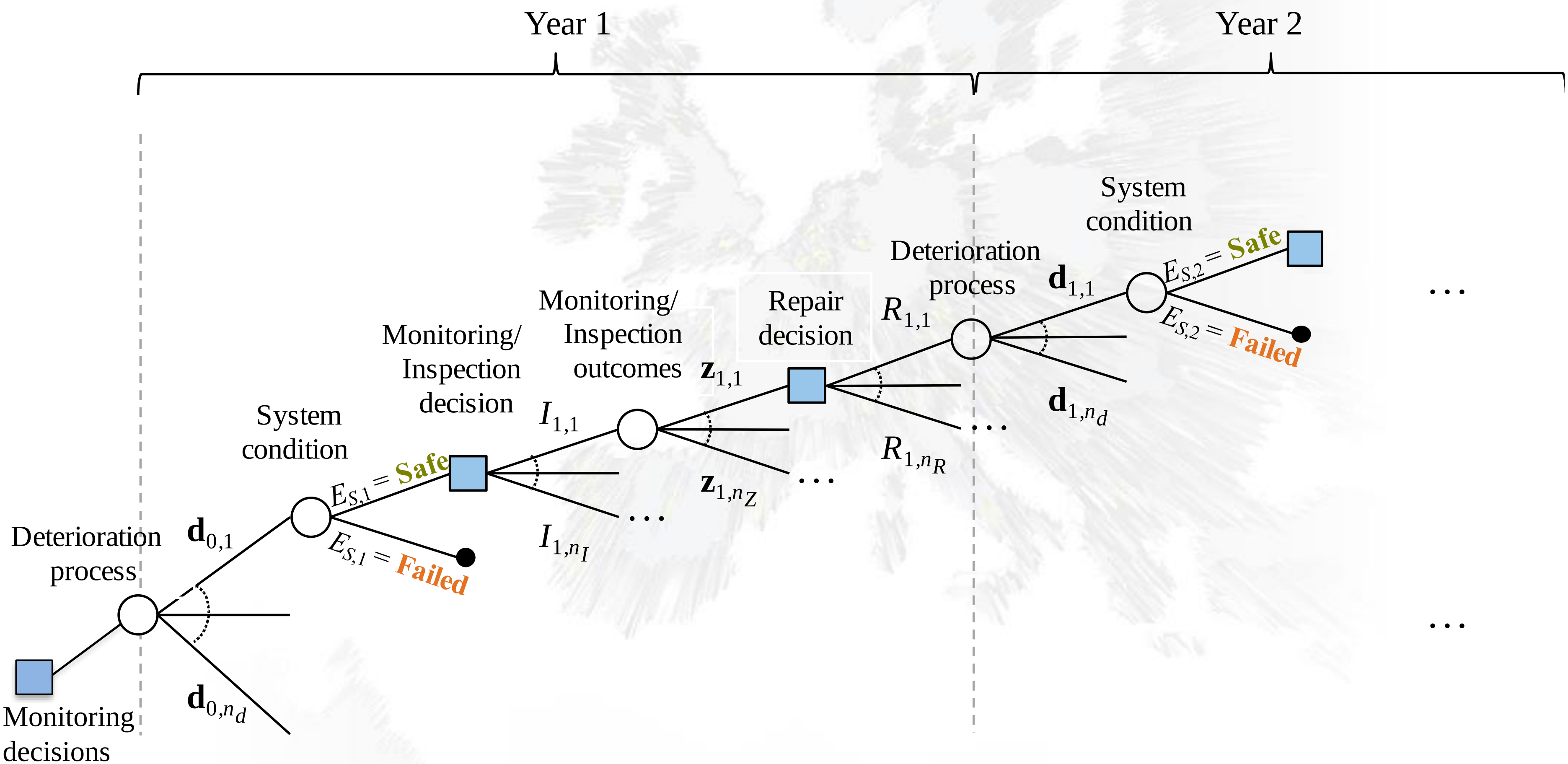
and more found on the ***TU1402 webpage***: https://www.cost-tu1402.eu/resources-downloads/journal-and-conference-papers

Achievements

- Methods and tools developed by members of the COST action

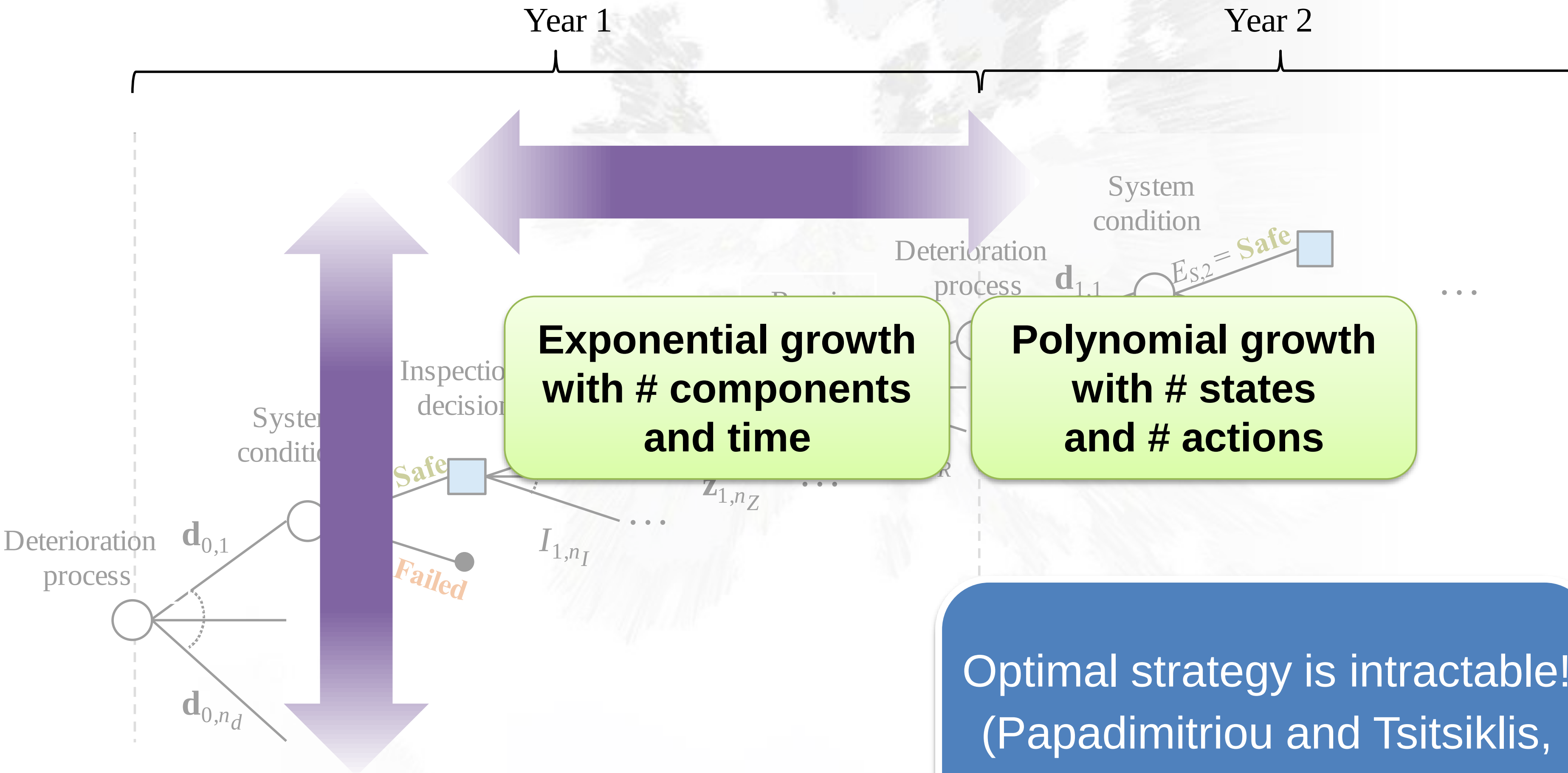
- Two examples of works addressing fundamental challenges:
  - Heuristic rules for SHM optimization
  - Efficient Bayesian analysis for system reliability

Optimal I&M planning: a sequential decision problem



(Luque and Straub 2019; Bismut and Straub 2019)

Optimal I&M planning: a sequential decision problem



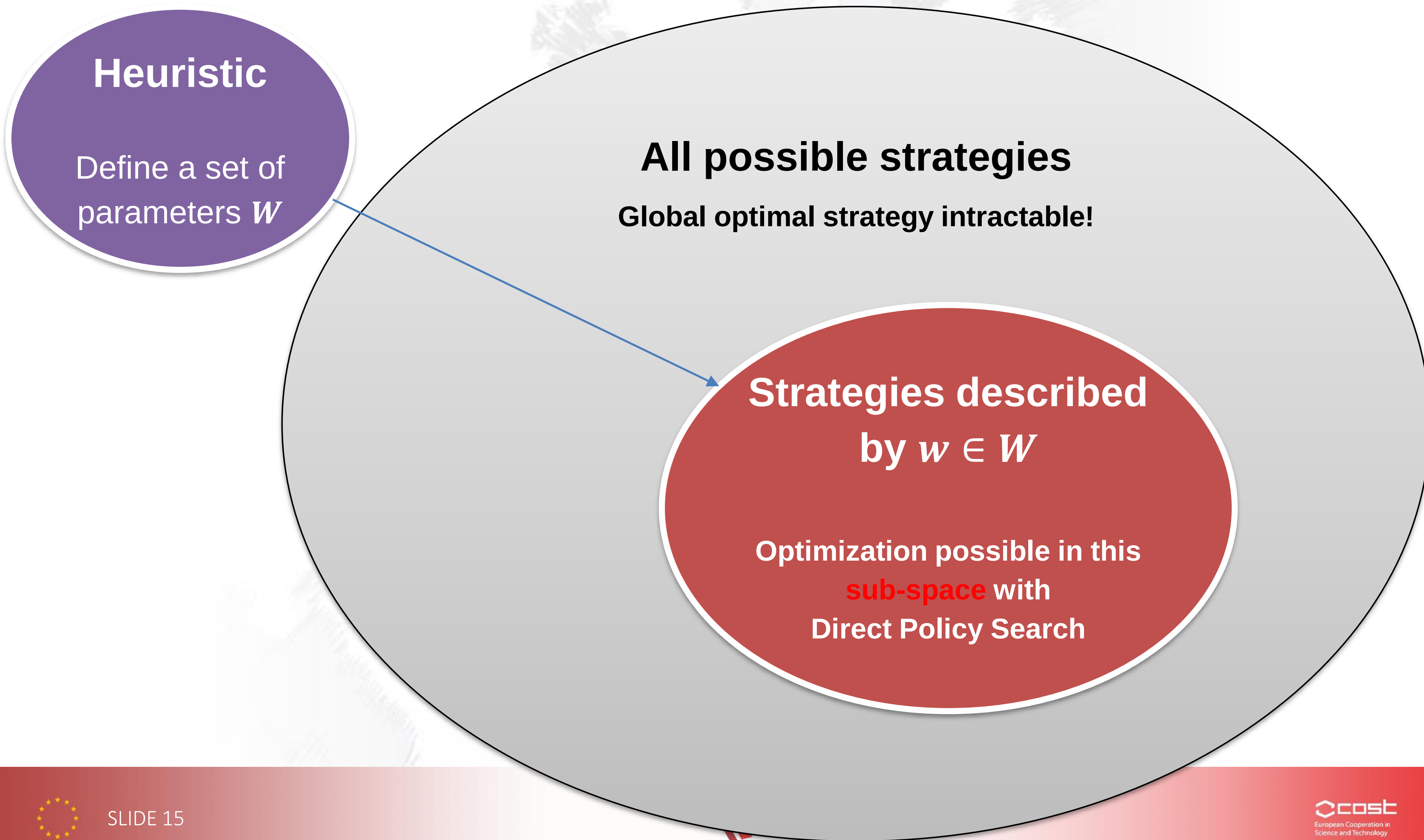
Exponential growth with # components and time

Polynomial growth with # states and # actions

Optimal strategy is intractable! (Papadimitriou and Tsitsiklis, 1987)

Direct Policy Search: a heuristic approach

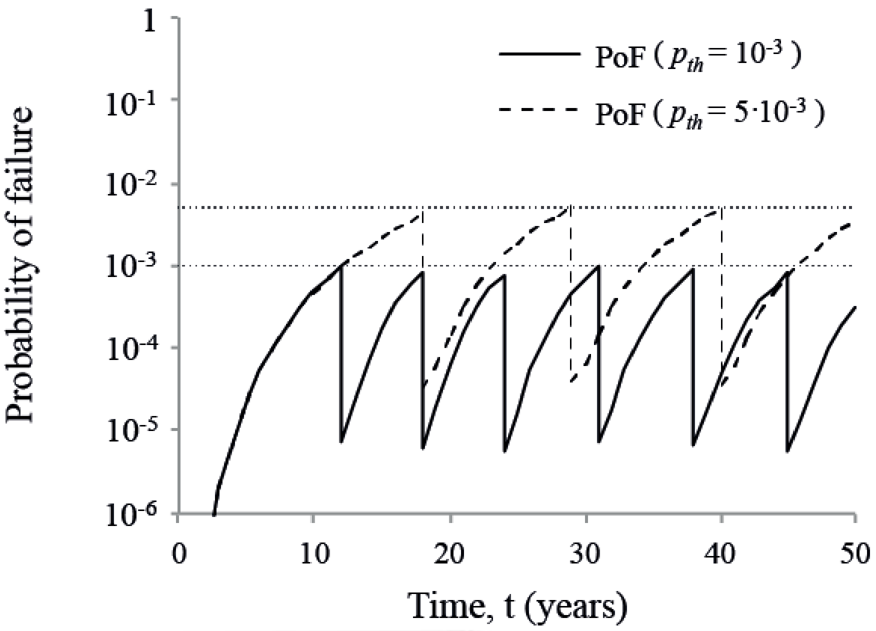
(Luque and Straub 2019; Bismut and Straub 2019)



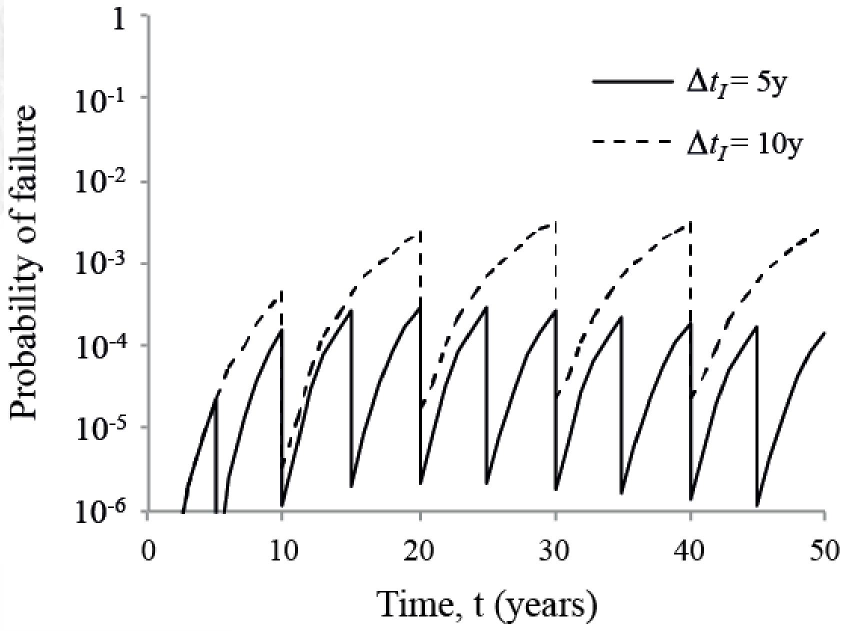
Heuristic approaches

- Heuristic approach well known at the component level (e.g. Faber et al 2000; Nielsen & Sorensen, 2010)

Threshold approach



Constant inspection intervals



Direct Policy Search: a heuristic approach

(Luque and Straub 2019; Bismut and Straub 2019)

Heuristic

Define a set of parameters $\boldsymbol{W}$

Example of heuristic parameters:

- Fixed inspection interval ΔT
- Annual reliability threshold
- Number of components to inspect
- …

All possible strategies

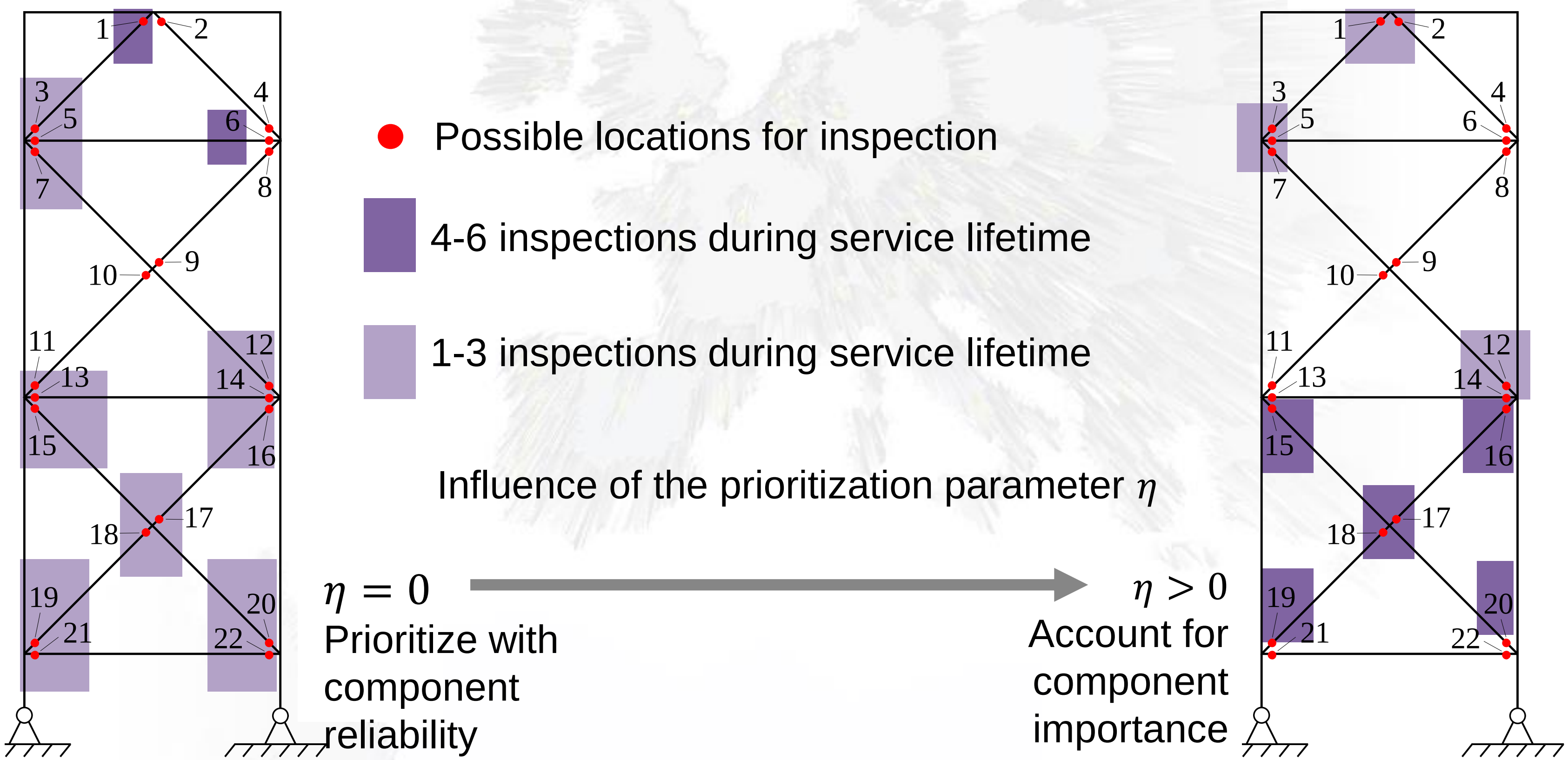
Global optimal strategy intractable!

Strategies described by $\boldsymbol{w} \in \boldsymbol{W}$

Optimization possible in this sub-space with Direct Policy Search

Heuristic parameters at the system level

- Approximate VoI for prioritizing components (Bismut et al. 2017, Luque & Straub 2019)



Efficient evaluation of life-cycle costs in preposterior analysis

(Luque and Straub 2019; Bismut and Straub 2019)

Total life-time risk:

$$R_F(\mathcal{S},\mathbf{Z}) = \sum_{t=1}^{T} c_F(t) \cdot \Pr\left(F_{a,t} \middle| \mathcal{S},\mathbf{Z}_{0:t-1}\right)$$

Efficient reliability method

Total life-time cost and risk:

$$C_T(\mathcal{S},\mathbf{Z}) = C_I(\mathcal{S},\mathbf{Z}) + C_R(\mathcal{S},\mathbf{Z}) + R_F(\mathcal{S},\mathbf{Z})$$

Heuristic strategy

SHM outcomes

Efficient evaluation of life-cycle costs in preposterior analysis

(Luque and Straub 2019; Bismut and Straub 2019)

Total life-time risk:

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Efficient reliability method

Total life-time cost and risk:

$$C_T(\mathcal{S},\mathbf{Z}) = C_I(\mathcal{S},\mathbf{Z}) + C_R(\mathcal{S},\mathbf{Z}) + R_F(\mathcal{S},\mathbf{Z})$$

Expected total life-time cost and risk:

$$\mathrm{E}[C_T|\mathcal{S}] = \mathrm{E}_{\mathbf{Z}}[C_T(\mathcal{S},\mathbf{Z})] = \int_{\Omega_{\mathbf{Z}(\mathcal{S})}} C_T(\mathcal{S},\mathbf{z})\, f_{\mathbf{Z}}(\mathbf{z})\, d\mathbf{z}$$

Monte Carlo

Efficient evaluation of life-cycle costs in preposterior analysis

(Luque and Straub 2019; Bismut and Straub 2019)

Total life-time risk:

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Monte Carlo

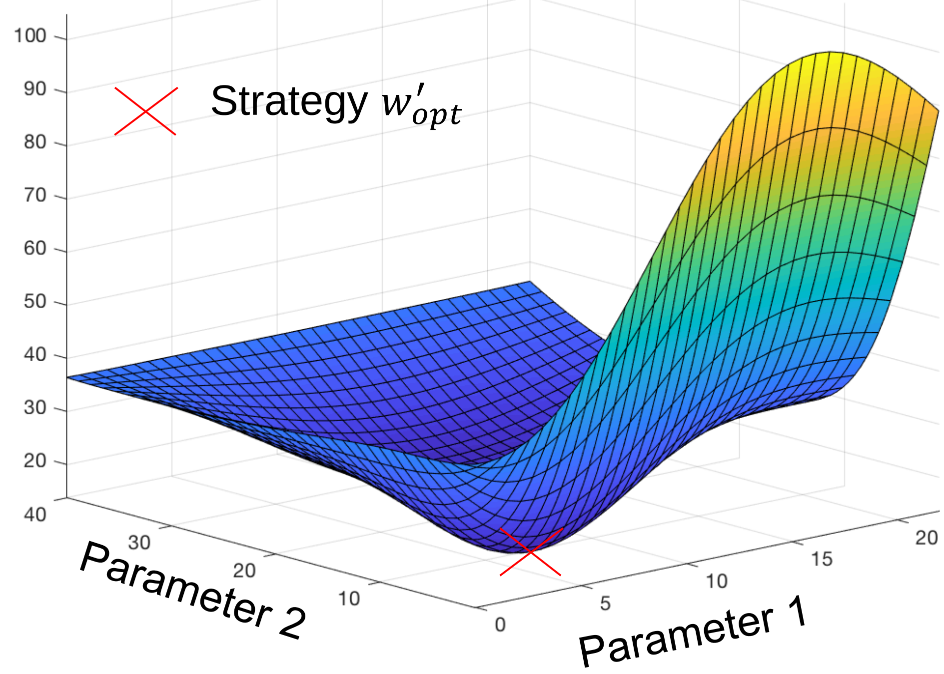
Optimal inspection-repair strategy:

$$\mathcal{S}^* = \arg\min_{\mathcal{S}} \mathrm{E}_{\mathbf{Z}}[C_T(\mathcal{S},\mathbf{Z})]$$

Heuristics with few parameters

Optimization

Standard stochastic optimization algorithms are applicable (here Cross Entropy)



Optimal strategy:

$n_I = 9$

$\Delta T = 7$

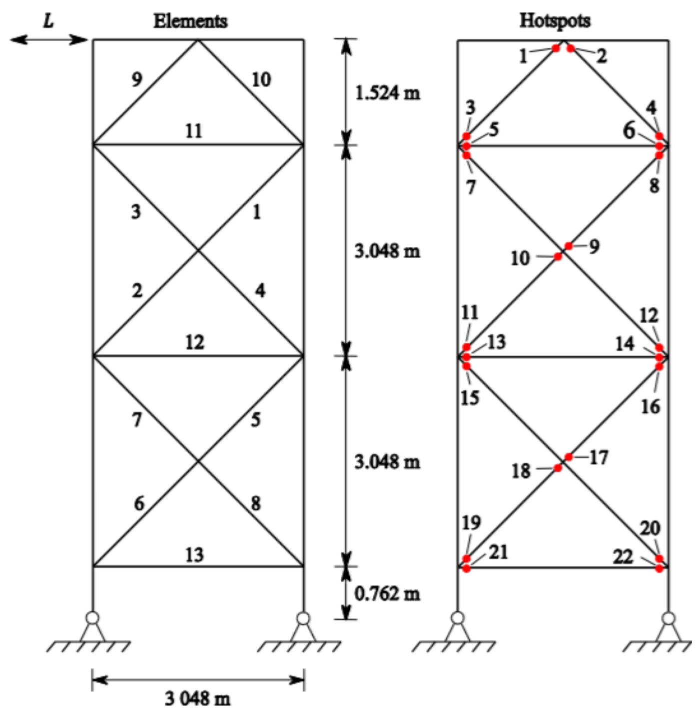
$p_{th} = 1.8\ 10^{-2}$

$\eta = 1.3$

Bismut & Straub (2019). Optimal Adaptive Inspection and Maintenance Planning for Deteriorating Structural Systems. Working paper.

System reliability for VoI analysis

- Methodological challenge, because:
  - large number of conditional (Bayesian) reliability analyses necessary for preposterior analysis
  - Standard Bayesian analysis methods not suitable for reliability analysis of systems without modications
  - Different approaches proposed within COST action

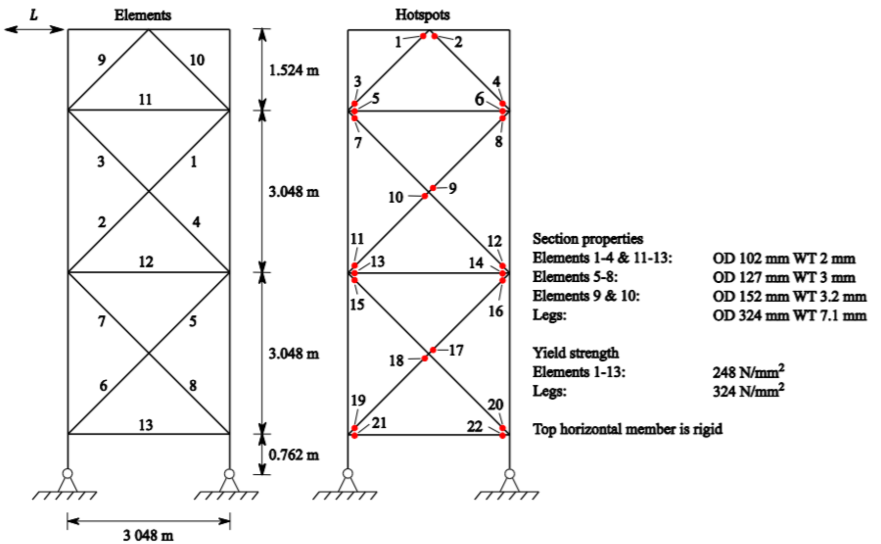


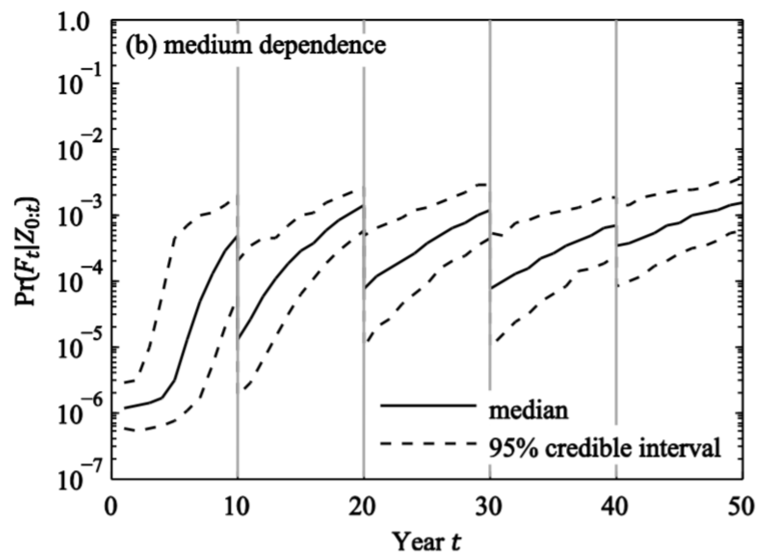
System reliability for VoI analysis

- Example Schneider et al. (Structural Safety, 2017):

System failure limit state: $G_F(\mathbf{u},t) = u_0 - \Phi^{-1}\left(p_F(\mathbf{T}^{-1}(u_1,\ldots,u_n),t)\right)$

BUS with subset simulation to address the high dimensionality





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Methods & tools library

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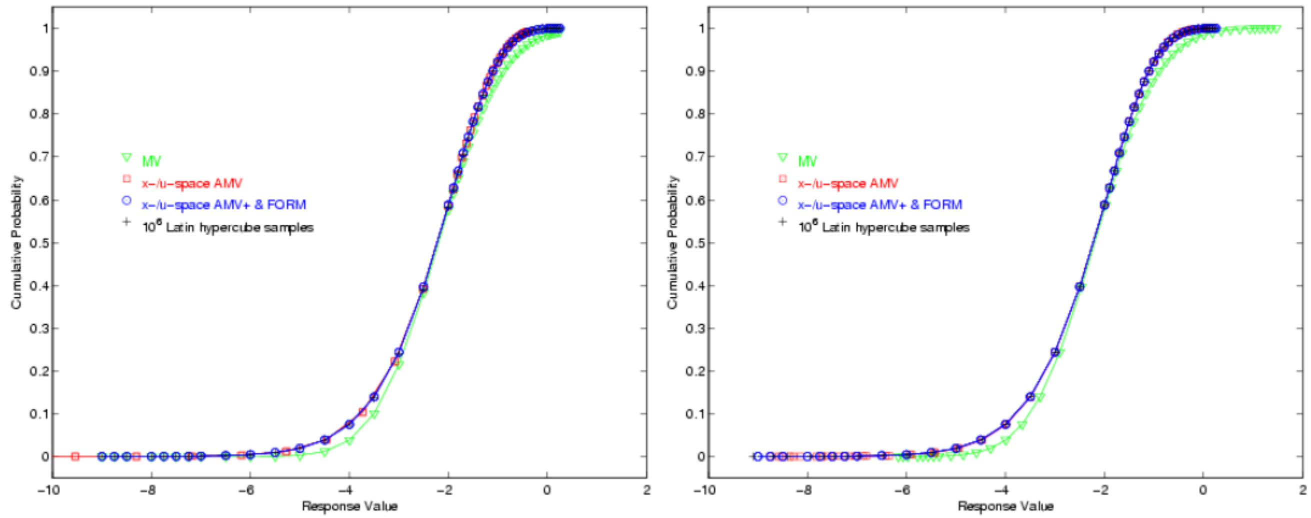
Software Database on VoI & UQ

ETH zürich

TUM

Name	Short Description
DAKOTA SANDIA National Laboratories	The Dakota toolkit provides a flexible, extensible interface between analysis codes and iterative systems analysis methods. Dakota contains algorithms for: optimization with gradient and nongradient-based methods; uncertainty quantification with sampling, reliability, stochastic expansion, and epistemic methods; parameter estimation with nonlinear least squares methods; and sensitivity/variance analysis with design of experiments and parameter study methods.



(a) RIA methods (b) PMA methods

WG3: Methods &

Achievements

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Verification / demonstration

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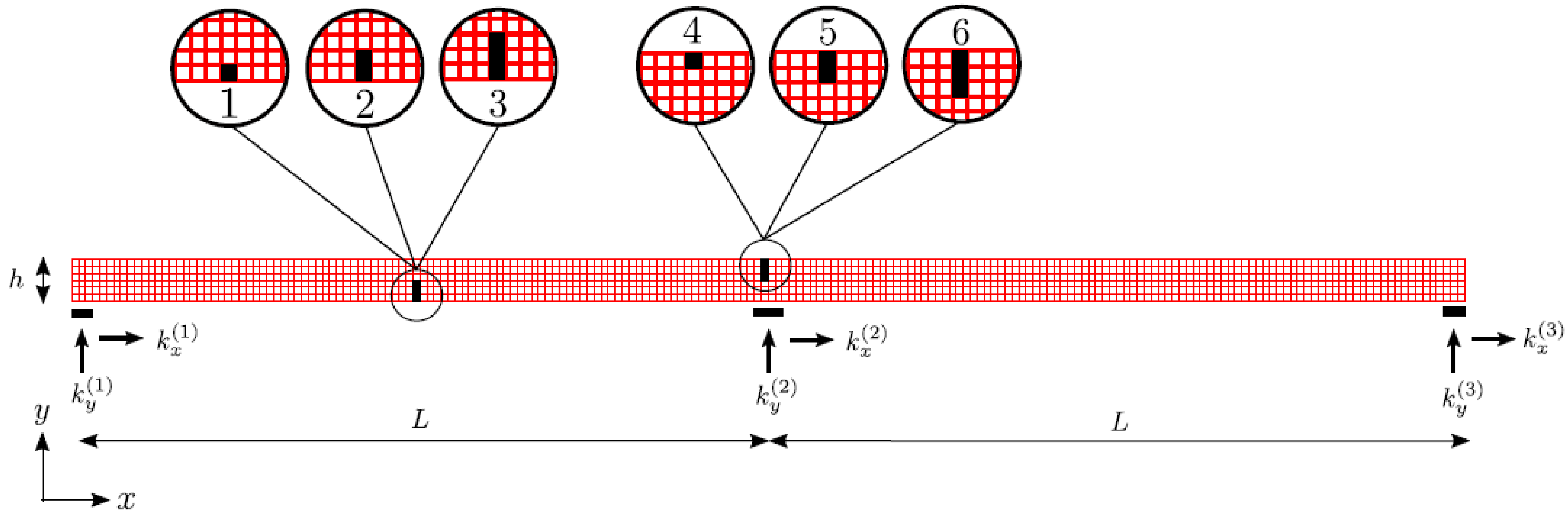
Verification Tools – The TU1402 Benchmark

2-span beam, modeled via 2D plane stress elements



Verification Tools – The TU1402 Benchmark

Generation of measurement data

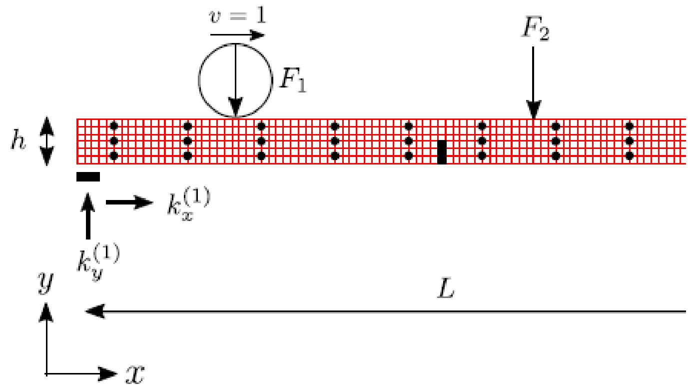


Figure 2: Loa

Tatsis K., Chatzi E. (2019). A numerical benchmark for system identification under operational and environmental variability. *Proc. IOMAC'19*

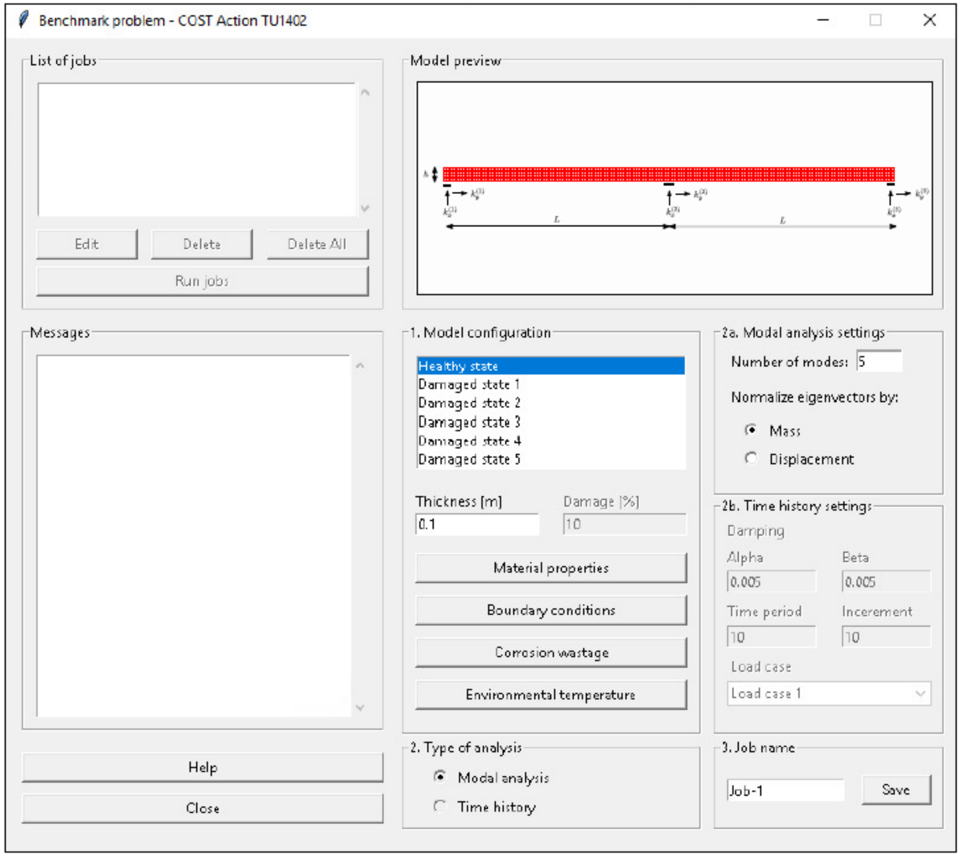
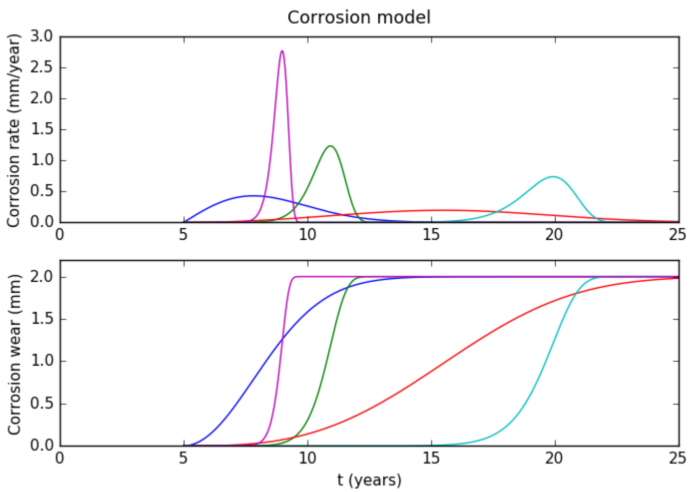


Figure 3: Graphical user interface for generation of simulated data.

Verification Tools – The TU1402 Benchmark

Corrosion-induced degradation



Tatsis K., Chatzi E. (2019). A numerical benchmark for system identification under operational and environmental variability. *Proc. IOMAC'19*

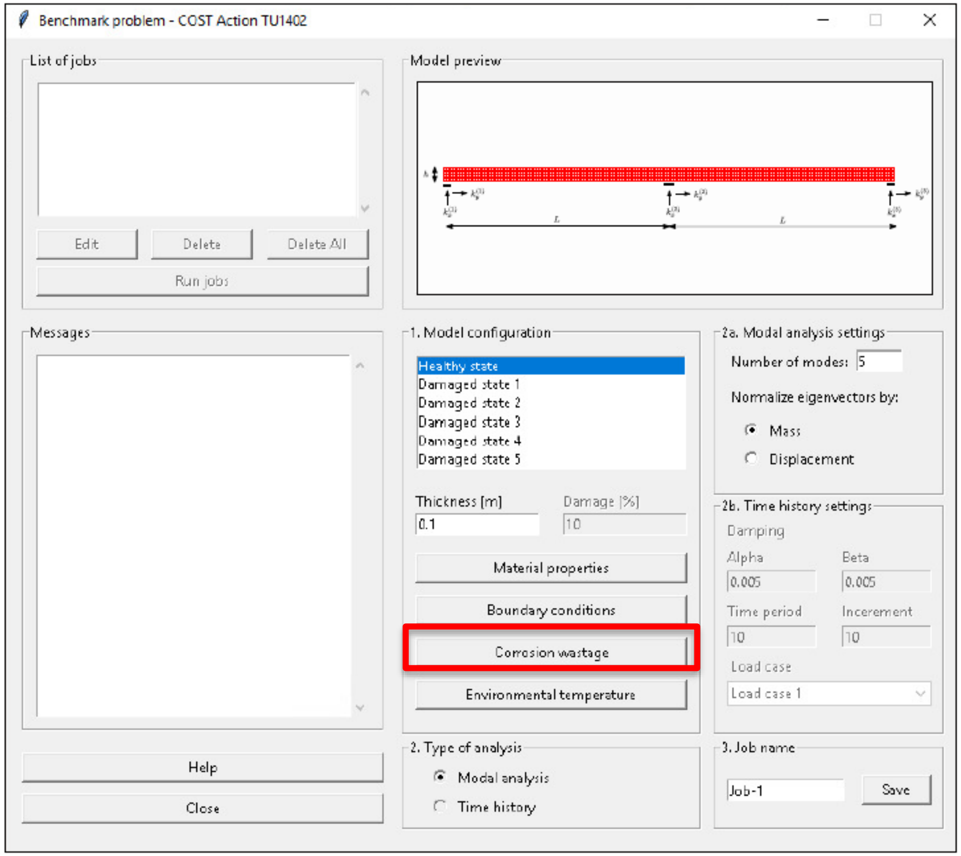


Figure 3: Graphical user interface for generation of simulated data.

Lessons learnt

- A multitude of methods is requried for a VoI analysis
- Methods exist for all individual tasks involved in the VoI (as reflected in our factsheets)
- The appropriate combination of methods is application specific
- The challenge in real applications lies mostly in the modeling – which must consider the limits of existing methods and tools
- Heuristics are an approriate tool for addressing the exponential or polynomical complexity of the decision process
- Incorporating system reliability into a VoI analysis remains a challenge
- Finding a common vocabulary among different fields of research remains a challenge

Conclusions

- VoI analysis can only be performed by combining models, methods and tools from multiple disciplines
- WG 3 has provided a collection of methods and tools (and the associated vocabulary) from different disciplines
- Participants of WG 3 have further developed methods and tools and have developed a benchmark

Thank you for your attention

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