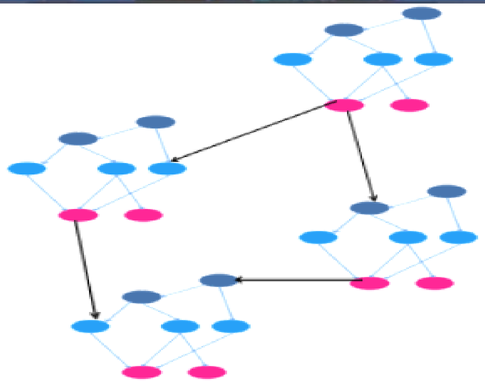
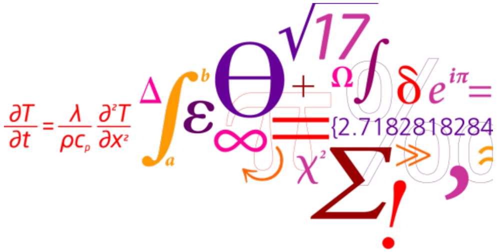


Value of Information in SHM – Considerations on the Theoretical Framework



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Contents of Presentation

- **Motivation**
- **Structural Health Monitoring**
- **Engineering decision making**
- **Decision and VoI analysis**
- **Basic Principle of VoI analysis**
- **Recent Works in the Field**
- **Conclusions and future directions**

Motivation

Potential of pre-posterior decision analysis in SHM

Rational decision making in structural engineering was recognized as a main objective already in early works by Freudenthal.

Theoretical and methodical developments on Bayesian decision analysis by e.g. Raiffa and Schlaifer were recognized and advocated by e.g. Benjamin and Cornell as a strong framework for providing rational decision support.

Despite these insights and efforts, applied decision analysis has not gained the impact it could have.

Especially the potential of the pre-posterior and Value of Information (VoI) analysis has not been realized/exploited.

Motivation

Use of decision analysis in SHM

The aim of this presentation is to :

- Point at different classes of engineering decision problems which may be addressed by decision analysis.

- Highlight that management of structural safety may be seen as an information management problem.

- Show that the prior, posterior and pre-posterior decision analysis may be applied to quantify the benefit associated with information from SHE.

- Illustrate the use of Value of Information analysis

Structural Health Monitoring

SHM for risk management

- Prototype development
- Code making and code calibration for the design and assessment of structures
- In optimizing warning measures
- For the optimization of maintenance strategies

Structural Health Monitoring

Prototype development

Health monitoring of new structural concepts intended for larger productions, facilitates concept optimization with respect to life-cycle benefit, before the initiation of a series production.

By instrumentation and subsequent monitoring and analysis of monitoring results it is possible to gather knowledge on important (model) uncertainties associated with the response and performance of the prototype.

Such information may be utilized for the purpose of optimizing design decisions which in turn can be related to the service life benefit.

Can be formulated as a decision problem!

Structural Health Monitoring

Code making and code calibration for the design and assessment of structures

Systematic and strategically undertaken monitoring of structures may facilitate that design basis for the considered category/type of structure is modified or adapted in accordance with the information collected.

Monitoring could e.g. focus on information concerning the model uncertainties associated with codified design equations, reflecting uncertainty in the relevant load-response transfer functions.

The value of monitoring would be realized through the improved design rationale facilitating that material and costs are minimized and risk, safety and reliability are controlled at adequate acceptable and affordable levels.

Structural Health Monitoring

In optimizing warning measures

Monitoring may adequately facilitate that indications of possible adverse performances or damages of structures in operation can be observed, and utilized as trigger for remediate actions.

The information collected from monitoring could relate to changes in stiffness properties monitored e.g. in terms of dynamic and static responses.

The value of monitoring would relate to the possibility of loss reduction by shutting down the function or reducing the loading of the structure, before human lives, environment and structure are lost and/or damaged further.

Structural Health Monitoring

For the optimization of maintenance strategies

Collection of information concerning the performance of a structure may facilitate improved decision basis for optimizing inspection and maintenance activities.

The monitoring may provide information of relevance for improving the understanding of the performance and response of the structure and this improved understanding may in turn be utilized during the life of the structure to adapt inspection and maintenance activities accordingly.

Structural Health Monitoring

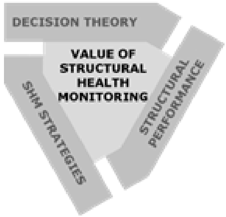
The fundamental logic of SHM is:

Monitoring may provide information concerning variables which have a significant influence on the service life performance of a structure

The information can be collected at a cost and with a given precision which depends on the technique and thereby also depends on the costs

The information collected through monitoring facilitates that adaptive actions are taken to reduce service life costs or increase service life benefits

Structural Health Monitoring



The fundamental logic of SHM is:

If the collected information is not correct or biased the actions will not be optimal and may even cause basis for adaptive actions which increase the service life costs

When assessing the benefit or value of different monitoring schemes and corresponding optimal strategies for adaptive actions the only basis for the modeling of the not yet collected information is the a-priori available data and models concerning the variables of interest.

The benefit of health monitoring cannot be assessed through one or a few anticipated monitoring results

Structural Health Monitoring

Structural Health Monitoring (SHM) is applied at very broad scale

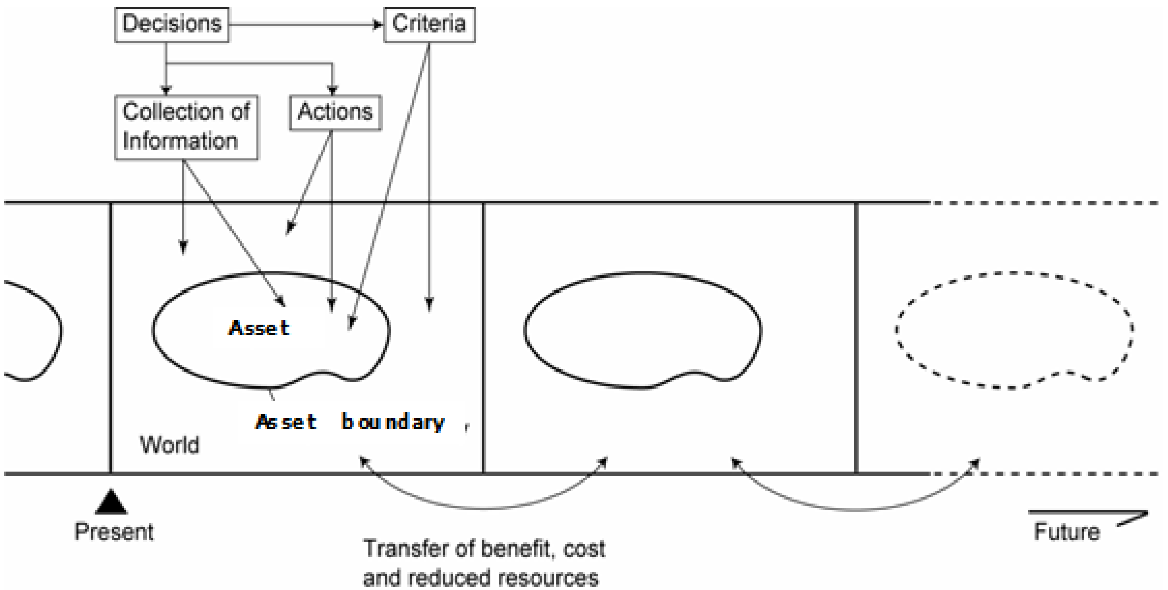
There is no doubt that SHM provides valuable information and supports decisions

But so far very little effort has been devoted on the formal and quantitative assessment of the value of SHM

There is good reason to doubt whether present best practices on SHM are economically efficient or even in some cases relevant

Engineering Decision Making

Structural safety and information management



Structural integrity may be managed through changes of the physics of the system/constituents or through improvement of knowledge and changes of the constituents/system

Engineering Decision Making

Structural safety and information management

Models of real world

Exposures/loads

Vulnerability / direct con.

Robustness / indirect con.

Decisions

Site investigations
Load control
Environment control
….
Materials
Component design
….
System concept
Maintenance/monitoring
Evacuation strategy
…

Observations/measurements

Real world

Safety, risk and life-cycle costs

Engineering Decision Making

Structural safety and information management

Models of real world

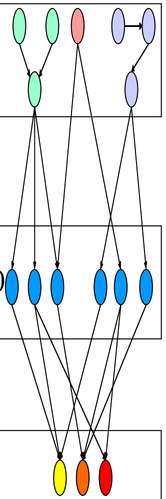
Decisions

Real world

$p(\mathbf{EX})$

$$R_D = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} p(\mathbf{C}_l | EX_k) c_D(\mathbf{C}_l) p(EX_k)$$

$$R_{ID} = \sum_{k=1}^{n_{EXP}} \sum_{l=1}^{n_{CSTA}} \sum_{m=1}^{n_{SSTA}} c_{ID}(S_m, c_D(\mathbf{C}_l)) \times p(S_m | \mathbf{C}_l, EX_k) p(\mathbf{C}_l | EX_k) p(EX_k)$$



Site investigations
Load control
Environment control
….
Materials
Component design
….
System concept
Maintenance/monitoring
Evacuation strategy
…

Likelihoods

Safety, risk and life-cycle costs

Decision and VoI analysis

Principal engineering decisions

Any design decision may be supported by the prior decision analysis

- a choice concerning structural system, materials, dimensions corresponds to a choice of the (prior) probabilistic model of $\mathbf{X}$

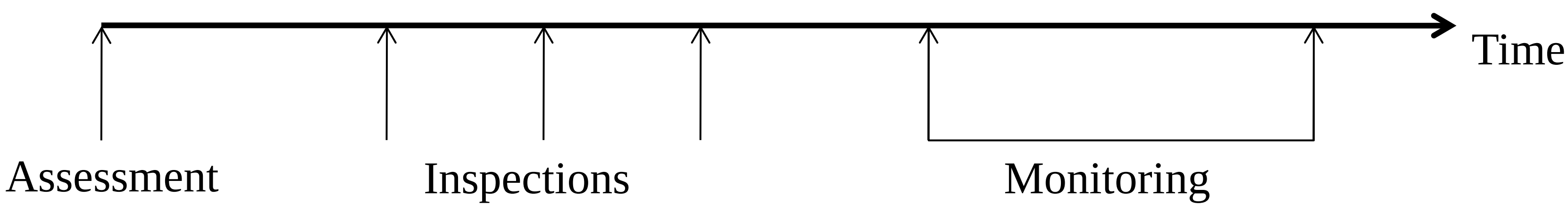
Any decision on assessments, inspections or monitoring may be supported by the pre-posterior decision analysis

- a choice concerning assessment method, inspection method and monitoring scheme will influence the (posterior) probabilistic model of $\mathbf{X}$

Decision and VoI analysis

Principal engineering decisions

In the decision analysis structure there is no principal difference between assessment, inspection and monitoring activities

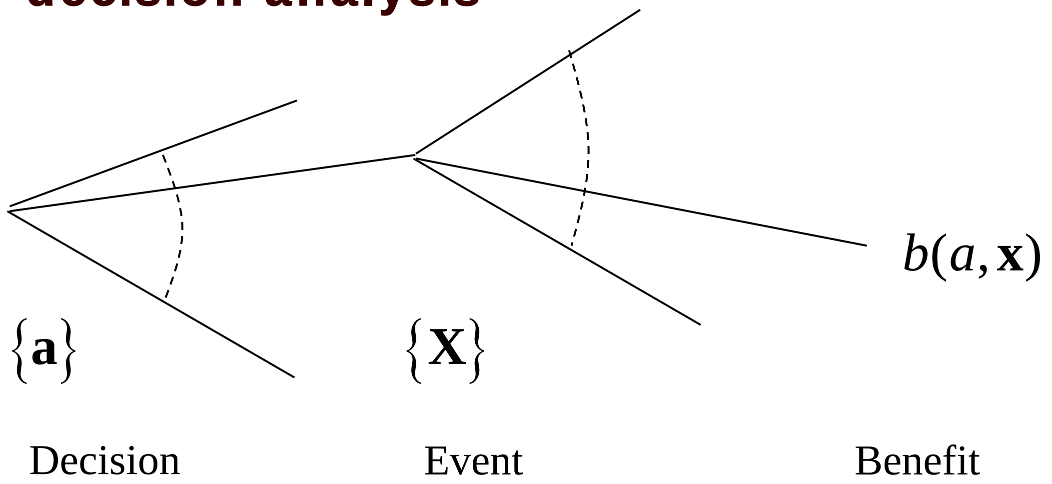


The only difference concerns the number of times at which information is collected and utilized for updating the prior probabilistic model

Decision and VoI analysis

Prior decision analysis

Information is bought by choice of prior density



Optimal decision maximizes the expected value of utility (benefit)
(von Neumann & Morgenstern)

$$B_0^* = \max_a E'\left[b(a,\mathbf{X})\right] = \max_a \int b(a,\mathbf{x})\, f'_{\mathbf{X}}(\mathbf{x},a)\,d\mathbf{x}$$

Basic principle of Value of Information

Posterior decision analysis

By sampling information $\mathbf{z}$ using an experiment e we may update the probabilistic description of $\mathbf{X}$

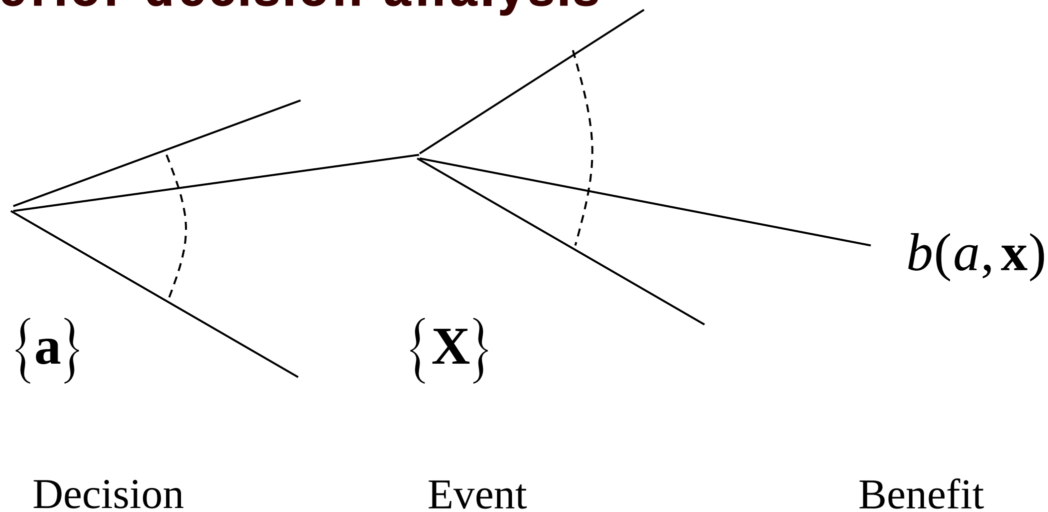
$$f''_{\mathbf{X}}(\mathbf{x}, a|\mathbf{z}) = \frac{L(\mathbf{x}|\mathbf{z})\, f'_{\mathbf{X}}(\mathbf{x}, a)}{\int L(\mathbf{x}|\mathbf{z})\, f'_{\mathbf{X}}(\mathbf{x}, a)}$$

Of course the likelihood of the sample $\mathbf{z}$ depends on the experiment e why we write

$$L(\mathbf{x}|\mathbf{z}) = L(\mathbf{x}|\mathbf{z}, e)$$

Basic principle of Value of Information

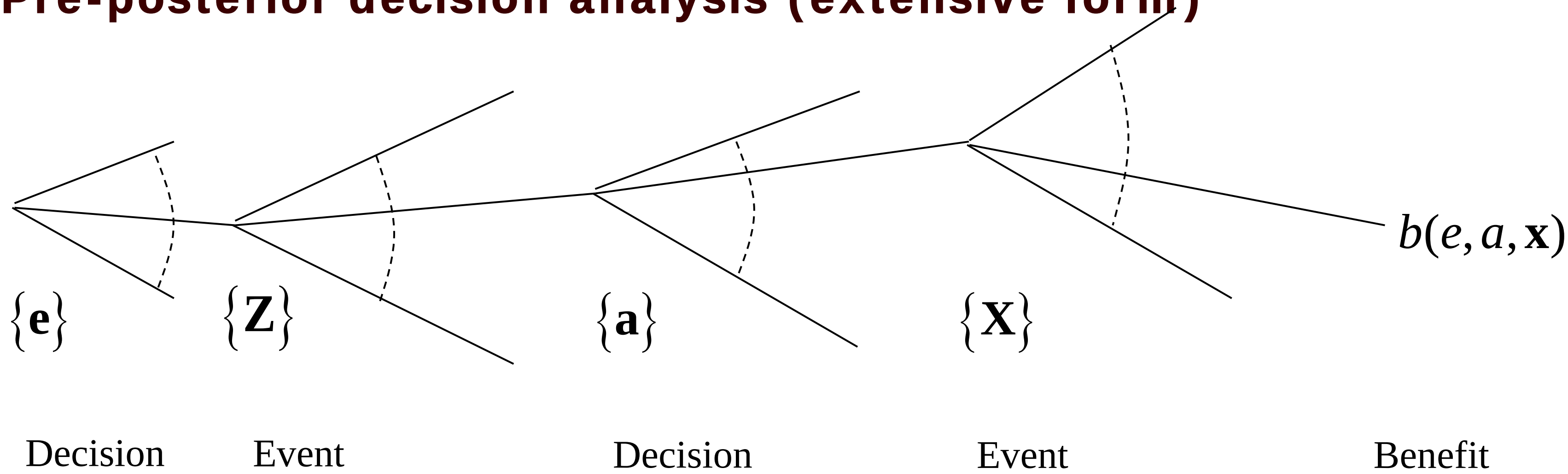
Posterior decision analysis



$$\max_{a} E''_{\mathbf{X}}\left[b(a,\mathbf{X})\right] = \max_{a} \int b(a,\mathbf{x})\, f''_{\mathbf{X}}(\mathbf{x}, a \,|\, \mathbf{z})\, d\mathbf{x}$$

Basic principle of Value of Information

Pre-posterior decision analysis (extensive form)



The optimal experiment e may be found from

Extensive form

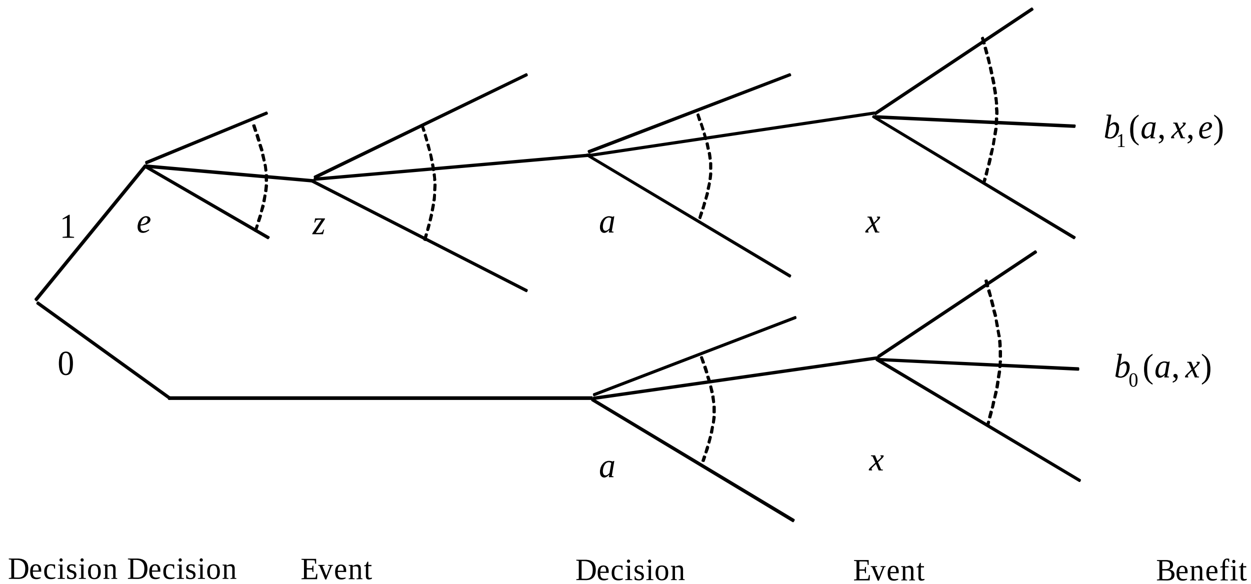
$$B_1^* = \max_e E_{\mathbf{Z}}\left[\max_a E''_{\mathbf{X}}\left[b(a,\mathbf{X})\right]\right] = \max_e E_{\mathbf{Z}}\left[\max_a \int b(e,a,\mathbf{x}) f''_{\mathbf{X}}(\mathbf{x},a\,|\,\mathbf{Z})\,d\mathbf{x}\right]$$

$$B_1^* = \max_e E_{\mathbf{X}}\left[E_{\mathbf{Z}|\mathbf{x}}\left[b_1(\mathbf{Z},d(\mathbf{Z}),\mathbf{X},e)\right]\right]$$

Normal form

Basic principle of Value of Information

Value of Information



The value of information *VoI* is determined from:

$$VoI = \max_{e} E_{\mathbf{Z}}\left[\max_{a}\int b(e,a,\mathbf{x})\, f''_{\mathbf{X}}(\mathbf{x},a\,|\,\mathbf{Z})d\mathbf{x}\right] - \max_{a}\int b(a,\mathbf{x})\, f'_{\mathbf{X}}(\mathbf{x},a)d\mathbf{x}$$

Shows the coupling between buying prior and pre-posterior information (design/insp. and monitoring)

Recent Works in the Field

Vast literature on RBI

Pozzi M and Kiureghian A D, Assessing the Value of Information for Long-Term Structural Health Monitoring. Health monitoring of structural and biological systems 2011. San Diego, California, United States.

Thöns, S. and M. H. Faber (2013). Assessing the Value of Structural Health Monitoring. 11th International Conference on Structural Safety & Reliability (ICOSSAR 2013). New York, USA.

Zonta, D., B. Glisic and S. Adriaenssens (2013). Value of information: impact of monitoring on decision-making. Structural Control and Health Monitoring.

Konakli, K. and M. H. Faber (2014). Value of Information Analysis in Structural Safety. Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management: 1605-1614.

Straub, D. (2014). Value of information analysis with structural reliability methods. Structural Safety 49(0): 75-85.

Roldsgaard, J. H., Georgakis C. T. and M. H. Faber (2015). On the Value of Forecasting in Cable Ice Risk Management. Structural Engineering International 1(2015).

Qin, J., S. Thöns and M. H. Faber (2015). On the Value of SHM in the Context of Service Life Integrity Management. 12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP12), Vancouver, Canada.

Conclusions and Outlook

The first systematic applications of pre-posterior analysis for SHM were actually in the context of Risk Based Inspection and Maintenance planning – already some 25 years ago

The pre-posterior decision analysis and VoI has been applied successfully for a range of different SHM problems

It appears relatively straightforward to formulate the decision problems from which the value of SHM can be quantified

A major challenge is associated with computational efforts

Decision – event trees tend to explode and informal decision analysis is necessary – simplifications and idealizations

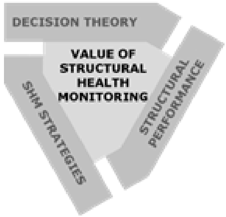
Conclusions and Outlook

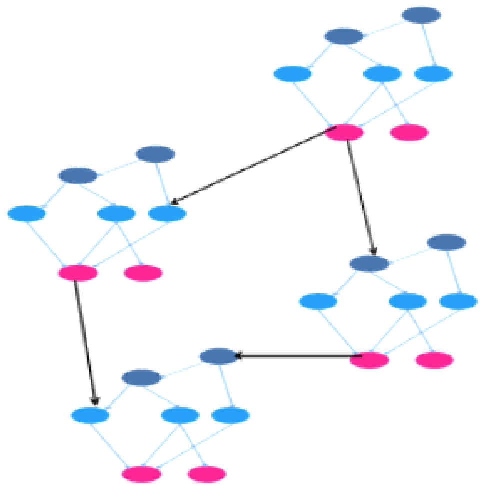
One suggestion would be to set up standard formulations for different typically occurring SHM problems – categorization

Then for each category of SMH problems to find the most efficient formulation of VoI to quantify the benefit of SHM

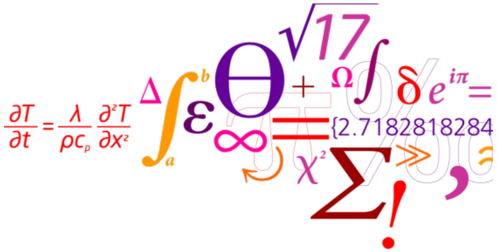
The different possibilities in terms of extensive / normal form analysis should be investigated

A thorough assessment of other fields of decision making should be undertaken – such as utilized in real options analysis





Thanks for your Attention!



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