Optimizing monitoring: application to assessment of roof snow load

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What are the risks related to use of structure?
What analyses shall be performed?
What type of inspections and monitoring?
What type of measures shall be taken?

OUTLINE

1. Framework/Introduction
2. Normative references
3. Asset information
4. Structural Performance (member, system)
5. Monitoring strategies
6. Intervention actions
7. Decision analysis
   Life cycle costs
8. Conclusions

1. FRAMEWORK (background requirements)

- Case study of practical and structural importance
- Easy to read and understand
- Representative for a wide range of experienced cases
- Reflecting output of WG1 to WG3 results
- Consistent to WG5 guideline
- Identifying VoI of SHM
- Aimed at practicing engineers
- Generally valid conclusions

- **Ref: SEI paper March 2018 Optimizing monitoring: standards, reliability basis and application to assessment of roof snow load risks by Diamantidis et al.**

2. NORMATIVE REFERENCES

EN 1990 Eurocode Basis of structural design, 2002
EN 1991-1-3. Eurocode 1: Actions on structures - Part 1-3: General actions; Snow loads, 2003.

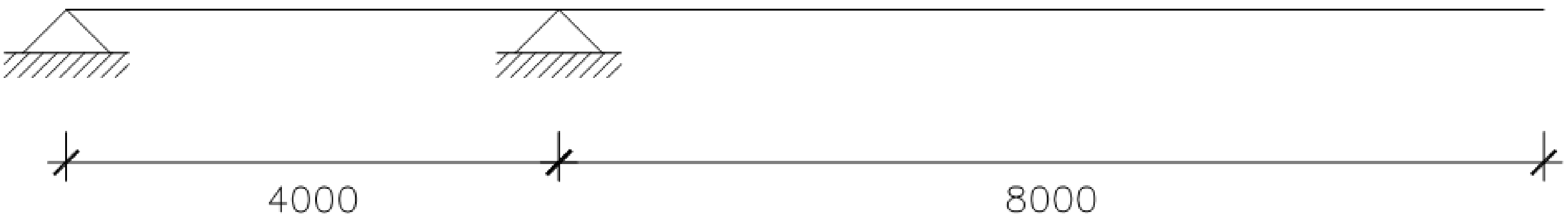
D.M. 12.02.82. Criteri generali per la verifica di sicurezza delle costruzioni, dei carichi e dei sovraccarichi. Italy: ISO; 1982.

D.M. 14.01. Nuove Norme Tecniche per le Costruzioni (in Italian). Italy; 2008.
ISO 2394. General Principles on Reliability for Structures. 4th ed. Geneve, Switzerland: ISO; 2015.
ISO 13822. Bases for design of structures - Assessment of existing structures. Geneve, Switzerland: ISO TC98/SC2; 2010.
VDI 6200. Standsicherheit von Bauwerken - Regelmäßige Überprüfung. VDI; 2010.
RVS 13.03.01. Monitoring von Brücken und anderen Ingenieurbauwerken. Wien: FSV; 2012.
ISIS Canada. Guidelines for structural health monitoring (Design manual, no. 2.). Winnipeg: ISIS Canada; 2001.
UNI/TR 11634:2016. Linee guida per il monitoraggio strutturale. Italy: UNI; 2016.

JCSS. JCSS Probabilistic Model Code (periodically updated, online publication). Joint Committee on Structural Safety; 2001.
JCSS. Probabilistic Assessment of Existing Structures (edited by D. Diamantidis). Joint Committee on Structural Safety, RILEM Publications S.A.R.L.; 2001.

3. ASSET INFORMATION

- Stadium constructed in the beginning of 1990s
- Located in Northern Italy, altitude - 190 m
- Capacity: 4000 spectators - CC3 structure
- Structural system:
  - member: cantilever steel beam IPE450
  - system: spacing between adjacent beams - 5 m with stiffening members
- Design requirements:
  - snow loads: old code D.M. 12.02: 0.9 kN/m^2, EC1-3: 1.25 kN/m^2
  - design requirements: ***resistance of the roof is about 90% of that required by the Eurocodes (in terms of design values)***



THE NEED FOR MONITORING

- The roof ***does not comply*** with the requirements in EN 1990
- The ***snow load dominates*** structural reliability → continuous monitoring of snow loads will help
- When a specified limiting value of the monitored parameter is exceeded, either snow on the roof can be ***removed*** or the stadium can be temporarily ***closed***.
- In full agreement with the concept of a safety plan provided in ISO 2394:
  “*the performance objectives, the scenarios to be considered for the structure, and all present and future measures (design, construction, or operation, - e.g. monitoring) to ensure the safety of the structure.*”

4. STRUCTURAL PERFORMANCE (limit states)

Failure through limit state of bending

$$Z(\boldsymbol{X}) = \vartheta_R W_{pl} f_y - \vartheta_E L^2/2 \, [\gamma_{steel} \cdot A_s + g_{roof} \, b + \mu_i \times \gamma_{snow}(d) \times b \times d]$$

main random variables

- *f_y yielding stress*
- *ϑ_R and ϑ_E model uncertainties for R and E*
- *μ_i shape factor*
- *$\gamma_{snow}(d)$ x d: snow load*

System behavior simplified as a series system - correlations amongst components:

- *full*: resistance and load model uncertianty, steel density, weight of roofing, annual maxima of ground snow load
- *significant*: yield strength, shape factor

4. STRUCTURAL PERFORMANCE (snow loads)

Table 3. Models of basic variables.

Basic variable	Dist.	Mean	CoV	Note
Shape factor, μ_i: A: no monitoring on the roof B: monitoring on the roof	N	A: 0.8 B: 1	A: 0.15 B: 0.05	A: Conversion ground to roof loads, JCSS. B: Deviation from uniform distribution.
Annual maxima of ground snow load, S_g	Gumbel max.	0.55 kN/m^2	0.6	Based on data from a nearest meteorological station.
Maximum observed ground snow load, $S_{g,sur}$	N	1.35 kN/m^2	See note.	Maximum load observed by a nearest meteorological station since the time when the roof has been completed; ≈ 90% of the characteristic value of the ground snow load.
Measured ground snow load (monitoring M1), $S_{g,mon}$	N	measured value	See note.	As for $S_{g,sur}$ – measurement uncertainty described by standard deviation of 0.05 kN/m^2.
Snow depth (M2), d	N	measured value, in m	See note.	Measurement uncertainty.
Snow density (M2), γ_{snow}	LN	1.09d + 2.4; in kN/m^3 for d in m	0.2	The mean is an average of estimates obtained by the snow density models provided in ISO 4355 [31] and JRC report [32] for the location of the stadium. CoV is obtained by comparing outcomes of the ISO 4355 models.
Snow load measurement $S_{r,mon}$ (M3)	N	measured value in kN/m^2	See note	Measurement uncertainty defined by the producer.
Snow load predicted for next three days, ΔS	LN	provided by meteorologists, in kN/m^2	See note.	Uncertainty in prediction is estimated to be slightly larger than for measurements by the sensors and thus standard deviation of 0.15 kN/m^2 is taken into account.

DET = deterministic; LN = lognormal; N = normal.

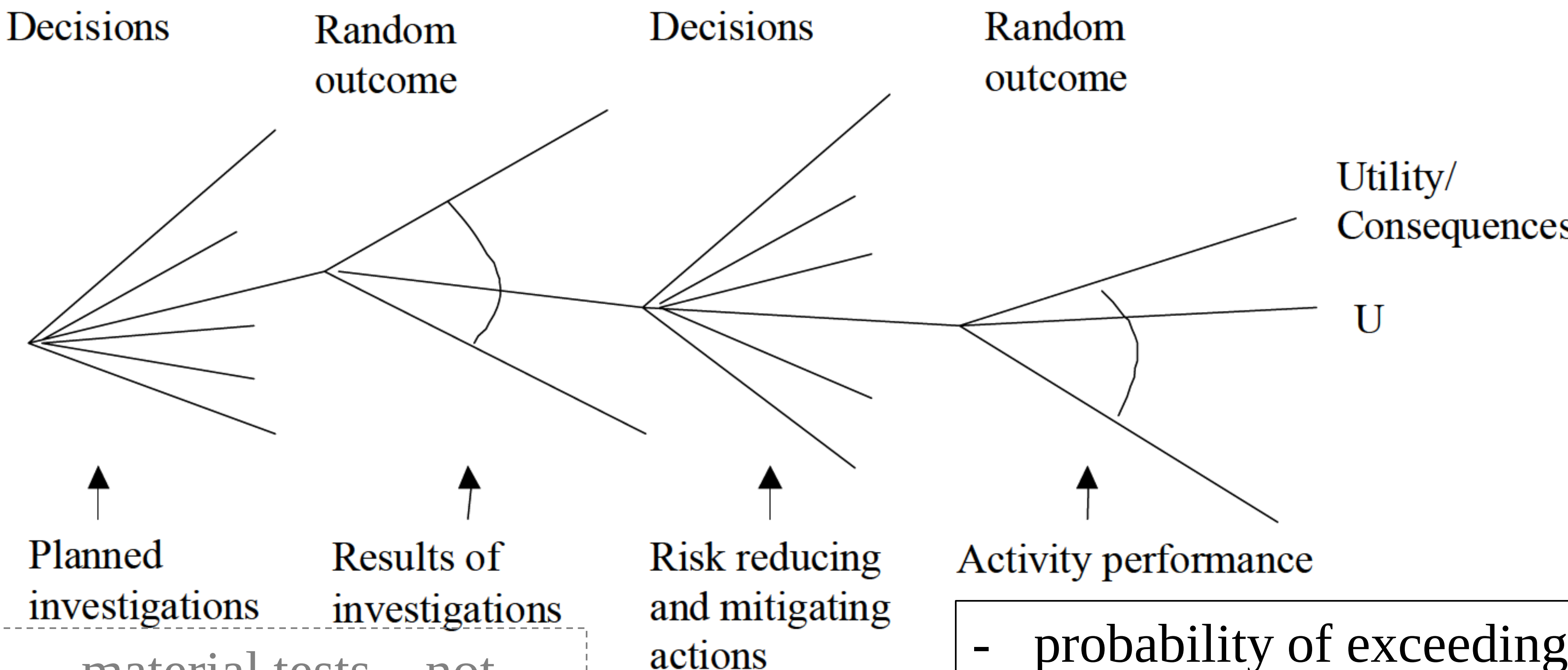
4. STRUCTURAL PERFORMANCE (reliability analyses)

a) prior information (uncertainties based on JCSS PMC)

- **$\boldsymbol{\beta}_{\mathbf{comp}}$ = 3.85 < 5.2** given in EN 1990 for CC3 (annual values)
- β_{sys} = 3.55 (lower bound estimate as horizontal stiffening members and other secondary beams will likely provide some redundancy)

b) updating (survival of a high load equal to 1.35kN/m^2) - *no significant improvement*

DECISION TREE FOR PRE-POSTERIOR ANALYSIS



- material tests – not applied in case study – less important uncertainties in steel properties, code compatibility check

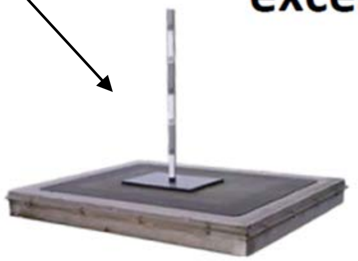
- alternatives M1-M3

- probability of exceeding threshold
- safety measures

5. MONITORING STRATEGY

Alternative	Cost	Uncertainty
M1: meteorological station snow depth on ground	negligible	very high
M2: snow depth on the roof	C_I= 7000 Euro C_O = 800 Euro /year	high (snow density)
M3: snow load on the roof	C_I= 14000 Euro C_O = 800 Euro /year	reduced (direct measurement)

Early warning system for excessive roof loads



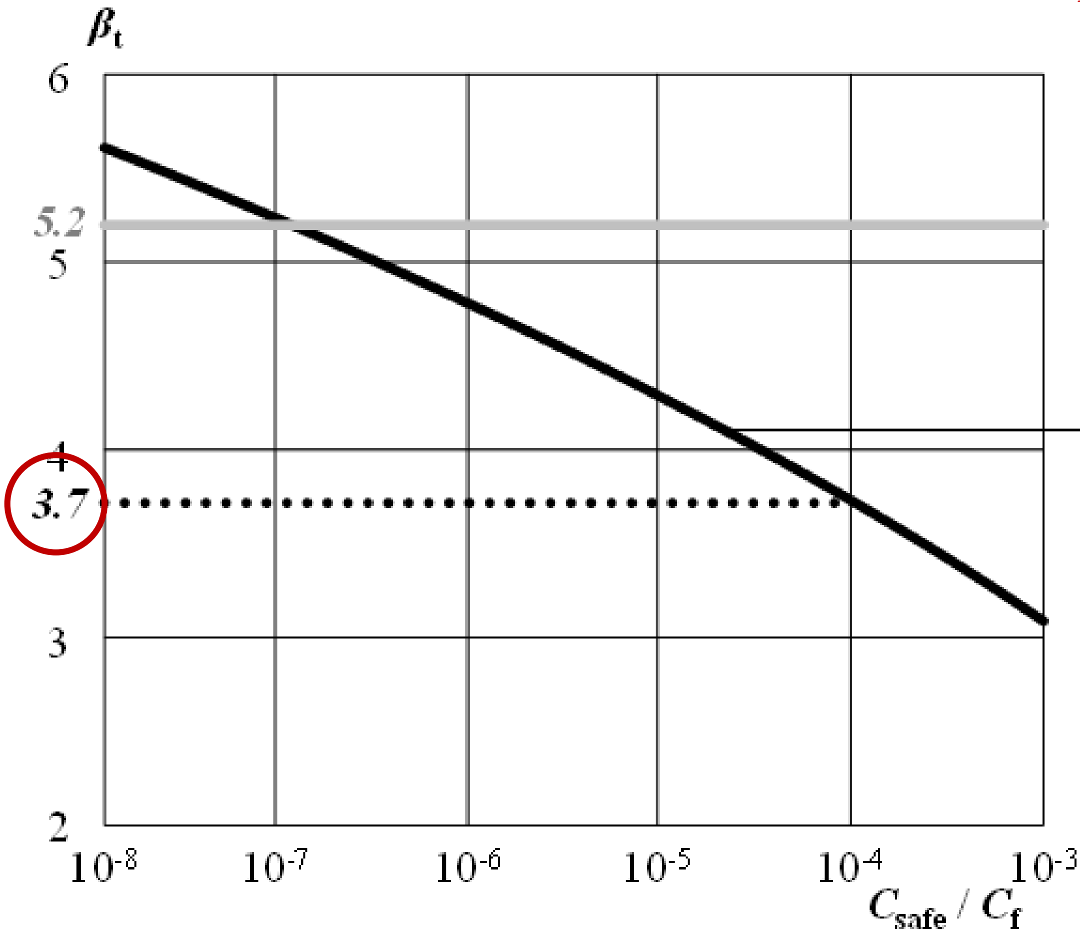
6. INTERVENTION ACTIONS/ SAFETY MEASURES

- Cleaning of the roof: $C_{\text{safe}} \approx 60$ k€ for the roof area and cleaning by specialists
- Temporary closure for one week: slightly exceeds the cleaning cost when the stadium is fully utilised.
- Do nothing

6. INTERVENTION ACTIONS (background)

$$C_{safe} <> C_f \, p_f(x)$$

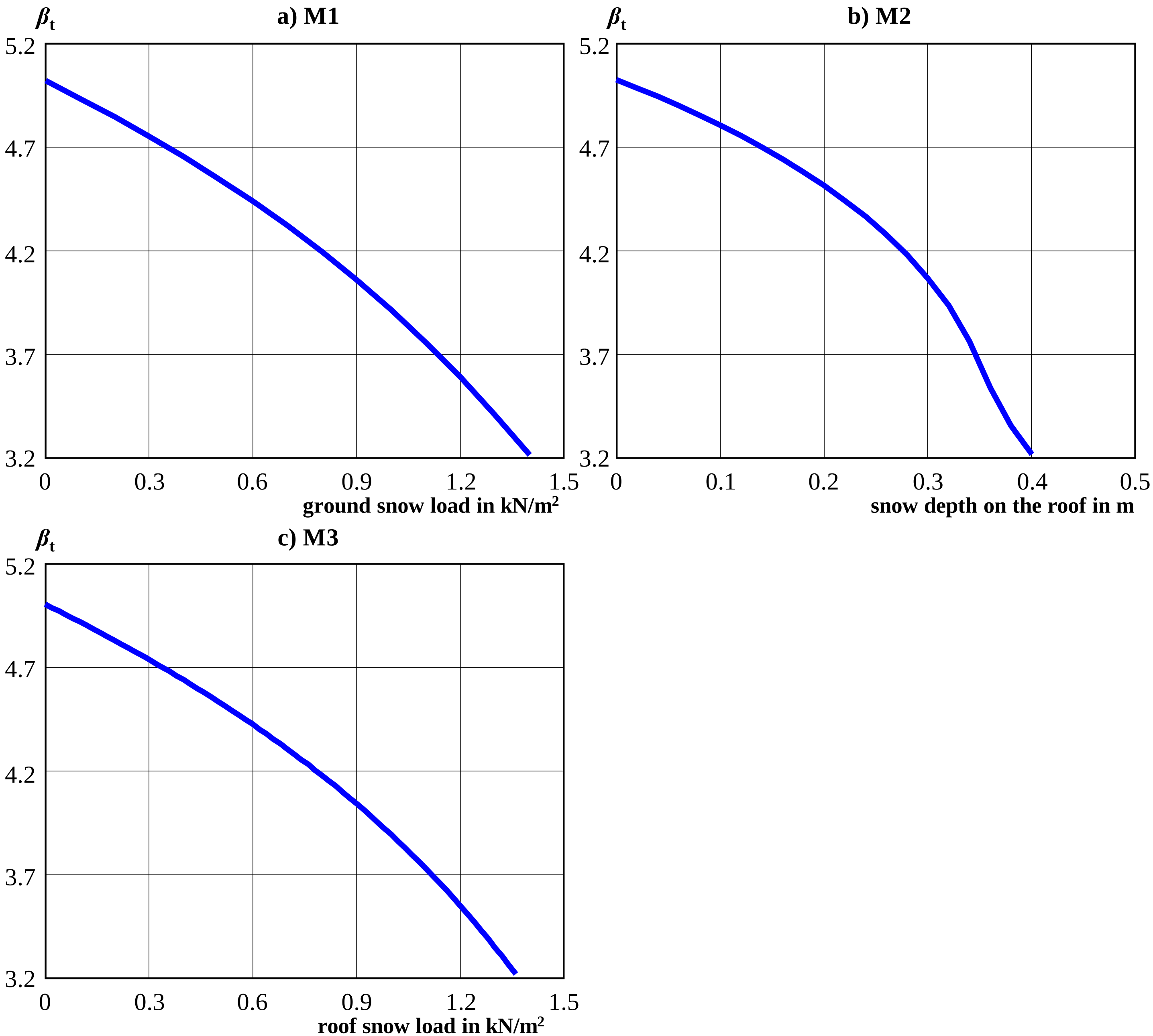
Variation of the target reliability index β_T with the ratio C_{safe} / C_f



C_{safe}: costs of safety measure
C_f: failure costs

$$\beta_t = -\Phi^{-1}(C_{safe} / C_f)$$

7. DECISION ANALYSIS



7. DECISION ANALYSIS

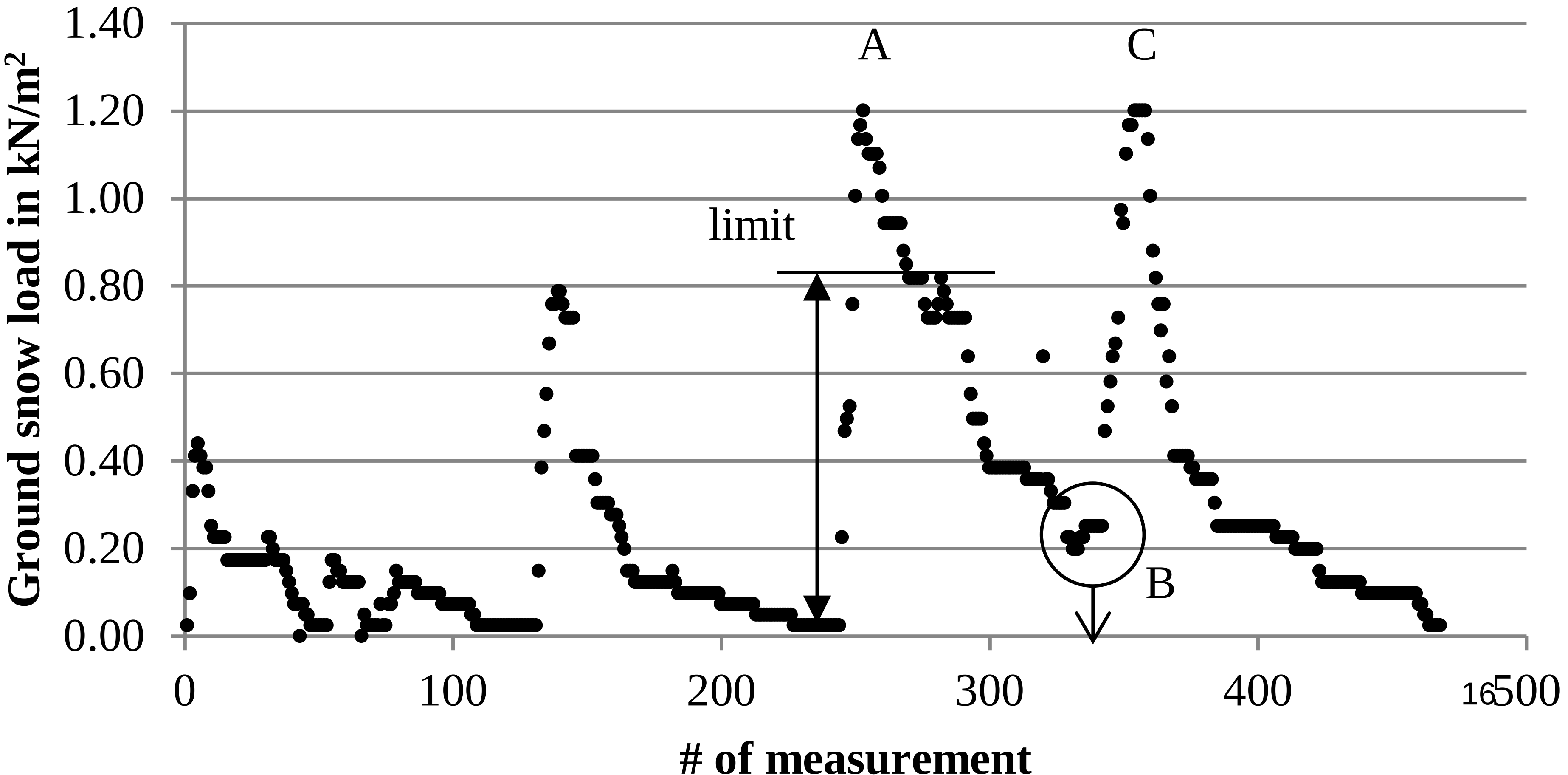
threshold values for a reduced derived safety level of $ß_T=3.7$

- M1: ground snow load $x_{lim} = 1.15$ kN/m^2
  with corresponding roof snow load of $0.8 \times 1.15 = 0.92$ kN/m^2
- M2: roof snow depth $x_{lim} = 0.35$ m,
  with corresponding roof snow load of $(1.09 \times 0.35 + 2.4) \times 0.35 = 0.97$ kN/m^2
- M3: roof snow load $x_{lim} = 1.12$ kN/m^2

7. LIFECYCLE COSTS

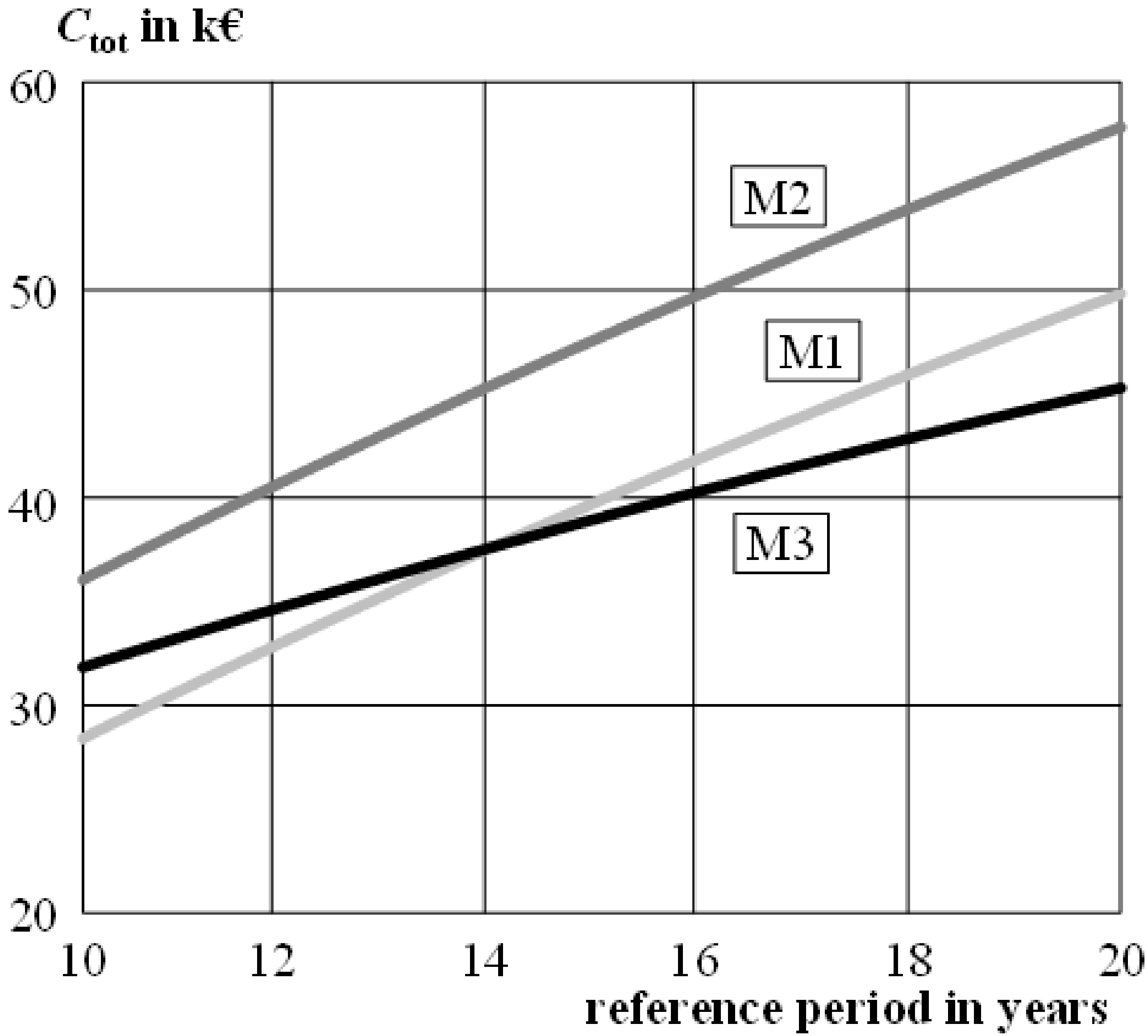
$$C_{tot} = C_{acquisition} + C_{operational}\, Q(t_{ref}, q) + C_{safe}\, Q(t_{ref}, q)\, \boldsymbol{n(x_{lim})}$$

- Expected number of exceedances per year - estimated from ground snow load data from a nearest meteorological station
- Return periods for the thresholds **~20-50 years**

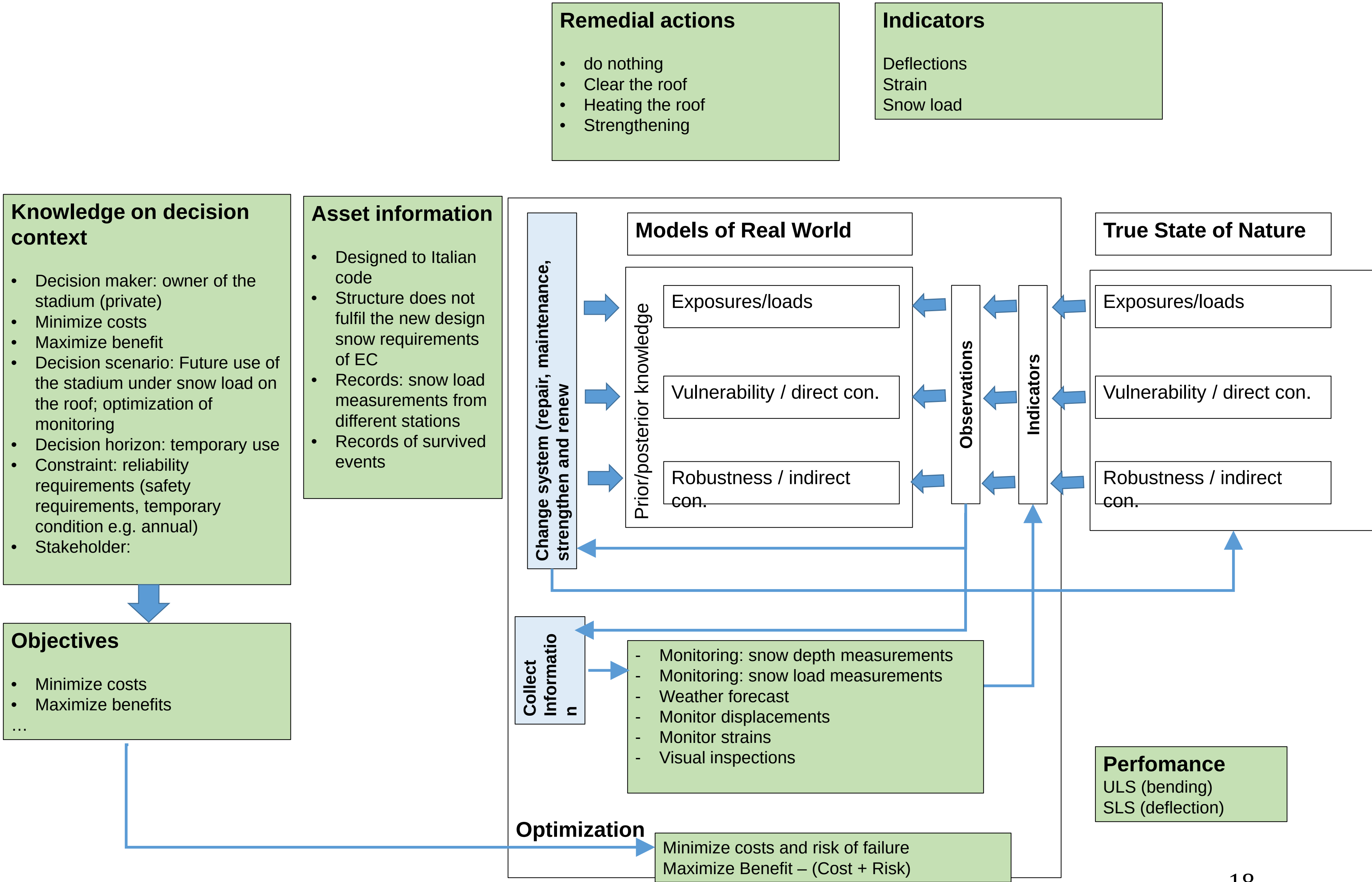


7. LIFECYCLE COSTS

representative results for M1, M2, M3 based on acquisition and operation costs



VoI flow chart



8. CONCLUSIONS

1. The ***required information*** by SHM needs to be clearly specified before the monitoring system is installed.
2. ***Design of SHM*** is a complex issue including the following steps:
   a) Component and/ or system structural reliability
   b) Identification of possible monitoring strategies
   c) Specification of threshold values for observed variables
   d) Selection of monitoring strategy based on total cost optimisation.
3. SHM systems allow for a ***real time evaluation*** and support decisions regarding safety measures
4. Other alternative to be mentioned: ***displacement measurements*** can be coupled with snow load measurements.
5. ***System representation*** may be oversimplified – FEM might reveal additional capacity, but the gain will likely be insignificant due to uniform snow load.
6. Gumbel distribution may not be appropriate – design value of snow load should be checked.

CASE STUDY BRIEF

1. Reliability of a stadium roof designed according to old Italian codes is insufficient.

2. Uncertainty in snow load dominates its reliability.

3. Monitoring of roof snow loads in combination with weather forecast proves to be efficient safety measure.

4. Once a specified snow load is exceeded, snow can be removed or the stadium temporarily closed.

Thank you for your attention