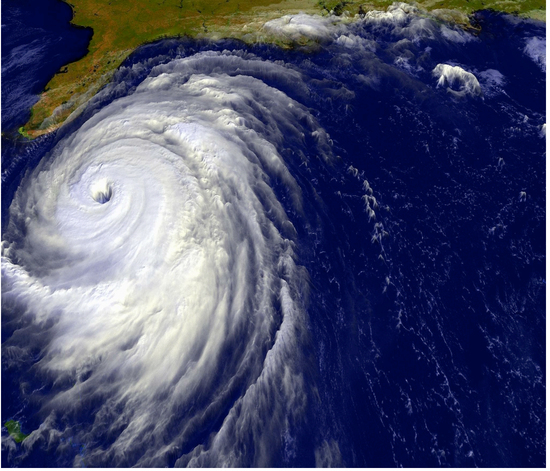
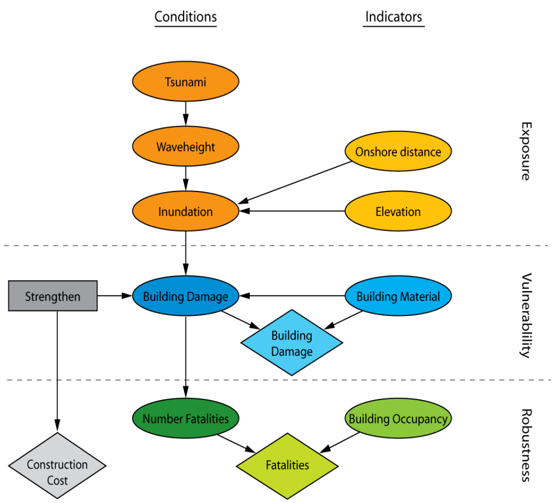




JCSS
Joint Committee on Structural Safety

Workshop on Risk Acceptance Criteria in Civil Engineering Decision Making

Trondheim, June 19-20, 2023

IABSE COMMISSION 1

Formal Criteria Derived from Bayesian Decision Analysis

Michael Havbro Faber
Aalborg University

Contents of Presentation

Motivation – which are the Issues?

Probabilistic modeling, reliability analysis and risk assessments have undergone very substantial developments over the last several decades.

By now - for most relevant situations in engineering – risk for personnel as well as monetary losses may be appropriately modeled.

Given all these efforts and successful developments - it is astonishing to find that there are significant inconsistencies in the regulation of life safety risks.

Motivation – which are the Issues?

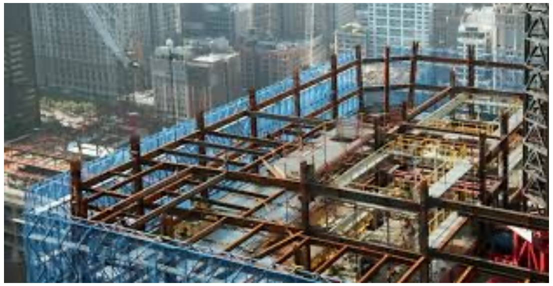
Especially the regulation of life safety risk to individuals suffer from diverting perspectives in the research community as well as in national and international best practices/Standards.

Typical inconsistencies relate to the following issues:

- Fundamental issues of logic
- Fse of different metrics in different application areas
- Averaging over time/space
- Averaging over technologies
- Averaging over systems (epistemic uncertainties)
- Life safety risks are addressed at the level of “known” individuals

Motivation – which are the Issues?

Life safety risks are regulated using different metrics



Per person kilometer Per working hours Annual

Different sectors have different metrics and different perspectives – some with focus on activities, some with focus on the individuals and some with focus on technologies

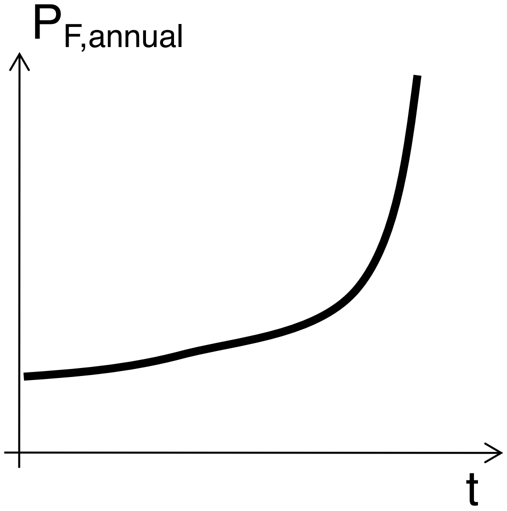
Motivation – which are the Issues?

Life safety risks are addressed at the level of “known” individuals

E.g. - typically regulations prescribe higher levels of acceptable life safety risks for sub-way and metro systems personnel than for the passengers

Motivation – which are the Issues?

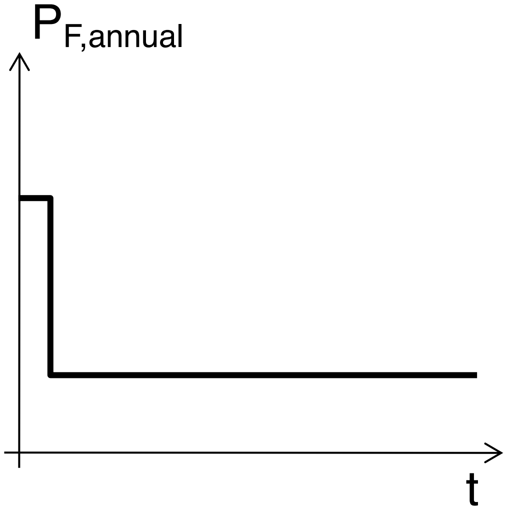
Life safety risks are averaged over time



High risks towards/after the end service life are often averaged out with low or moderate risks up to the end of service life

Motivation – which are the Issues?

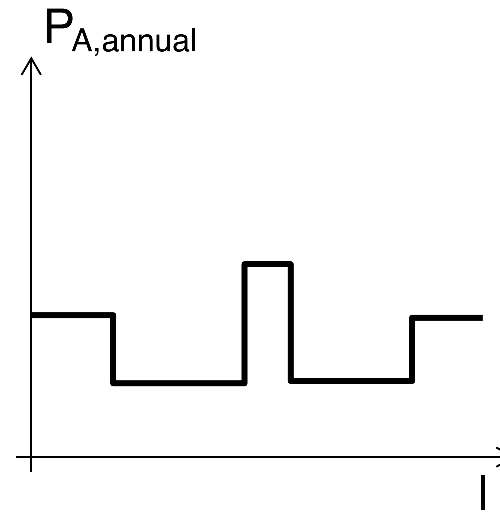
Life safety risks are averaged over time



High risks during construction and towards/after the end service life are often averaged out with low or moderate risks during the other phases of service life

Motivation – which are the Issues?

Life safety risks are averaged over space



High risks in some domains are often averaged out with low or moderate risks in other domains

Motivation – which are the Issues?

But also the fundamental question remains:

What risks can consciously be exposed to third parties?

Many different approaches to treat this question have been followed – a common perspective is to take basis in observed preferences – what risks do people actually buy into?

E.g. the PLANAT (2004) approach where acceptable risks are assessed based on degree of control and degree of voluntariness

Motivation – which are the Issues?

Basic values, however, say we are not allowed consciously to take the life of other persons -

This implies that we are also not allowed consciously to take the life of an unknown person out of a group of persons –

This fact renders the whole discussion on acceptable life safety risks MEANINGLESS!

It is necessary to take another perspective !

Life safety as a tradeoff DM problem

Bayesian decision analysis lends itself as a theoretical framework to support decisions in pursuit of safe, resilient and sustainable developments.

Fischhoff (2015), points out - given that adequate models are available to:

i) represent the preferences of the decision maker through a utility function and
ii) to select and map decision alternatives into expected value of utility

decision analysis is reduced to an exercise of systematic and consistent information management.

Fischhoff, B. (2015). The realities of risk-cost-benefit analysis, *Science* Vol. 350, Issue 6260, aaa6516.

Life safety as a tradeoff DM problem

Tversky and Kahnemenn (1981), point out that the representation of preferences is associated with a substantial ethical problem.

The framing of decision problems strongly affects the:

- Preferences of decision makers and stakeholders
- Identification and selection of relevant decision alternatives
- The valuation of the possible outcomes associated with these

Tversky A, Kahneman D. (1981). The framing of decisions and the psychology of choice. Science 211:453–58

Life safety as a tradeoff DM problem

Sen (1985) introduces the concepts of "functionings" and "capability" for individuals, and underlines that not solely revealed preferences but rather the process of informing preferences is of central importance.

The perspective is taken that the preferences must be identified successively in an informed and transparent process.

- Directions on resilient societal developments must be based on preferences and available knowledge, but preferences and knowledge should be continuously assessed and directions adapted accordingly.
- This process is best supported by knowledge consistent assessments on how possible decision alternatives, including policies, affect resilience, sustainability and welfare.

Sen, A. (1985). Commodities and capabilities. Amsterdam New York New York, N.Y., U.S.A: North-Holland Sole distributors for the U.S.A. and Canada, Elsevier Science Pub. Co. ISBN 9780444877307.95.

Life safety as a tradeoff DM problem

Societal preferences for welfare

Life safety, resilience and sustainability is addressed jointly

Mainstream academic measures of sustainability include:

- Ecological footprint accounting
- Environmental Life Cycle Assessment
- Social Life Cycle Assessment

More widespread measures include:

- Human Development Index
- Environmental Sustainability Index
- Environmental Performance Index
- Genuine Progress Indicator
- Happy Planet Index
- Inclusive Growth and Wealth Index

Life safety as a tradeoff DM problem

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- Environmental Performance Index
- Genuine Progress Indicator
- Happy Planet Index
- Inclusive Growth and Wealth Index

stated societal preferences at policy level

No evidence of their "true" existence

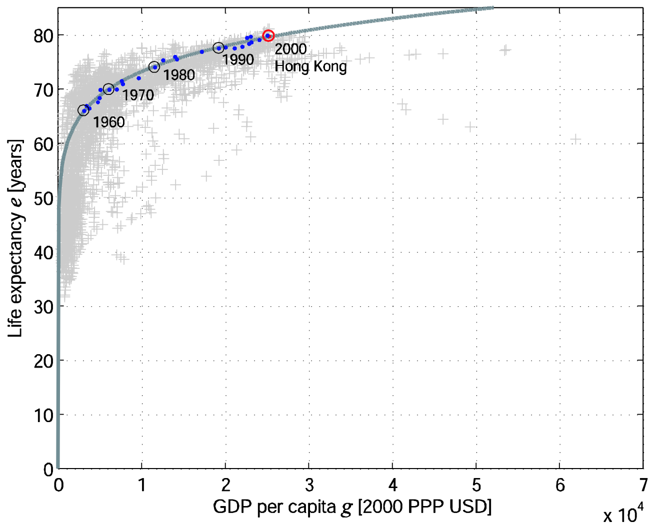
Life safety as a tradeoff DM problem

Societal preferences for welfare

As a measure of welfare we choose the Life Quality Index by Nathwani, Lind and Pandey (1997)

Emperically verified by Rackwitz (2002)

Shown to cover 70% of global population by Faber and Virguez-Rodriguez (2011)



Nathwani, J.S., Lind, N.C. and Pandey. M.D. (1997). Affordable Safety by Choice: The Life Quality Method. Institute of Risk Research, University of Waterloo, Ontario, Canada, 1997.

Faber, M. H. and Virguez-Rodriguez, E. (2011). Supporting decisions on global health and life safety investments, in Proceedings of the 11th International Conference on Applications of Statistics and Probability in Civil Engineering, pp. 434-443

Rackwitz, R. (2002). Optimization and risk acceptability based on the life quality index Struct Saf, 24 (2002), pp. 297-331

Life safety as a tradeoff DM problem

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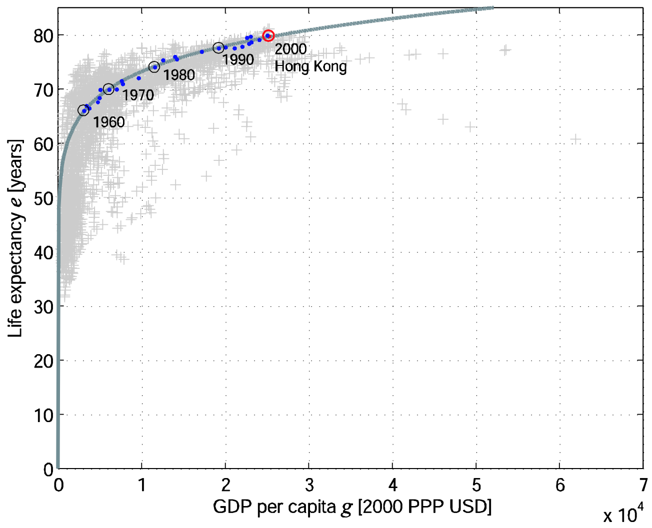
Revealed preference



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Life safety as a tradeoff DM problem

Probabilistic system representation

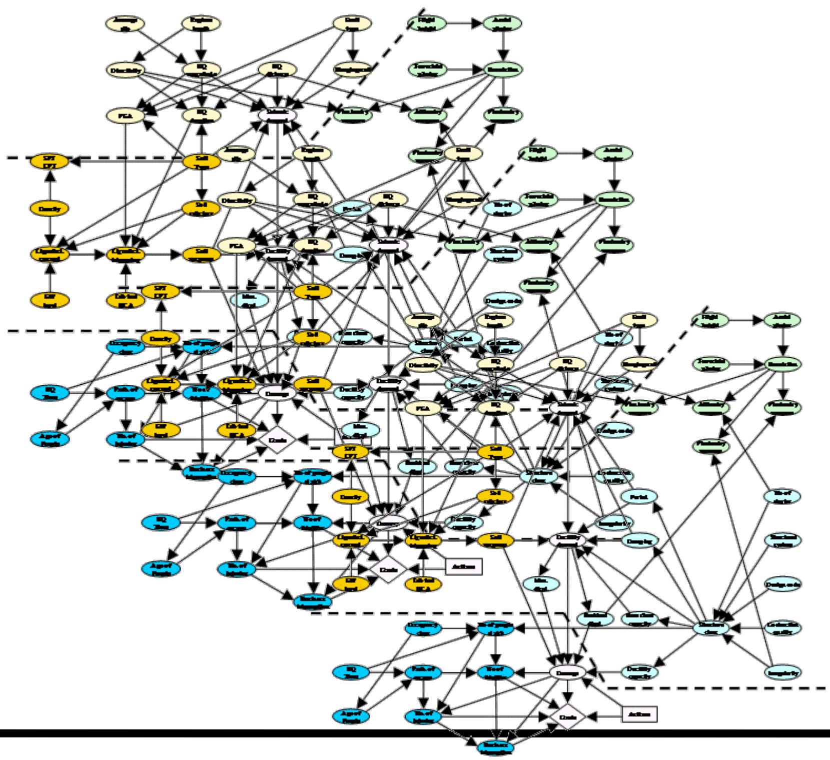
System model $\mathbf{M}(\mathbf{a}) = (\Sigma(\mathbf{a}), \mathrm{C}(\mathbf{a}), \mathbf{X}(\mathbf{a}))^{\mathrm{T}}$

Graph model $\Sigma(\mathbf{a})$

Constituents model $\mathrm{C}(\mathbf{a})$

Probabilistic model $\mathbf{X}(\mathbf{a})$

Decision alternatives $\mathbf{a}$

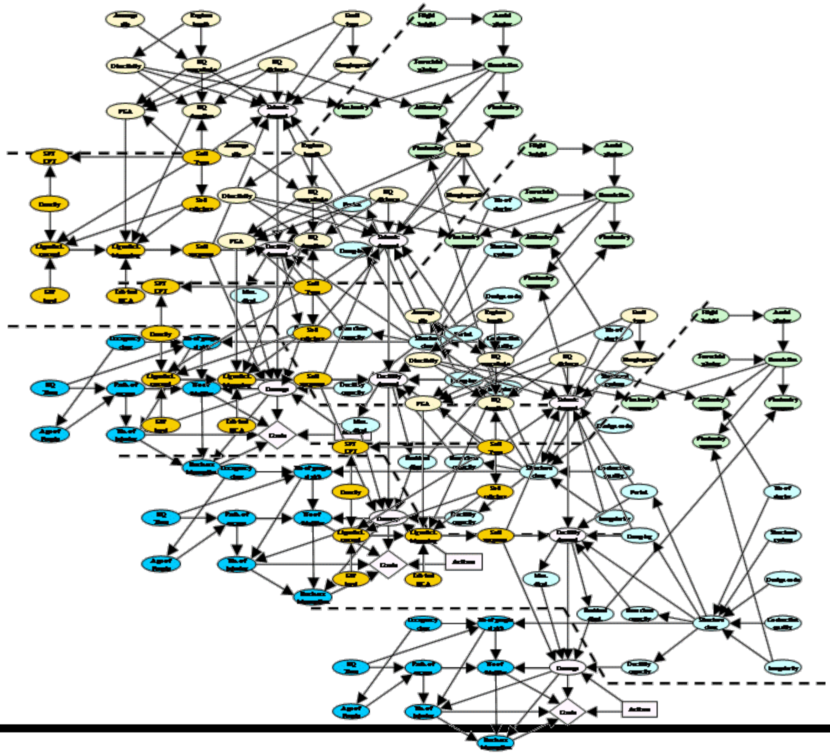


Life safety as a tradeoff DM problem

System representation

$$\mathbf{M}(\mathbf{a}) = (\Sigma(\mathbf{a}), \mathrm{C}(\mathbf{a}), \mathbf{X}(\mathbf{a}))^{\mathrm{T}}$$

- System models may be established using “bottom-up” approaches as in structural engineering or by “top-down” approaches as in data-mining
- Potentially a combination of the two approaches would be adequate
- Bayesian Networks lend themselves for system modelling in either case



Life safety as a tradeoff DM problem

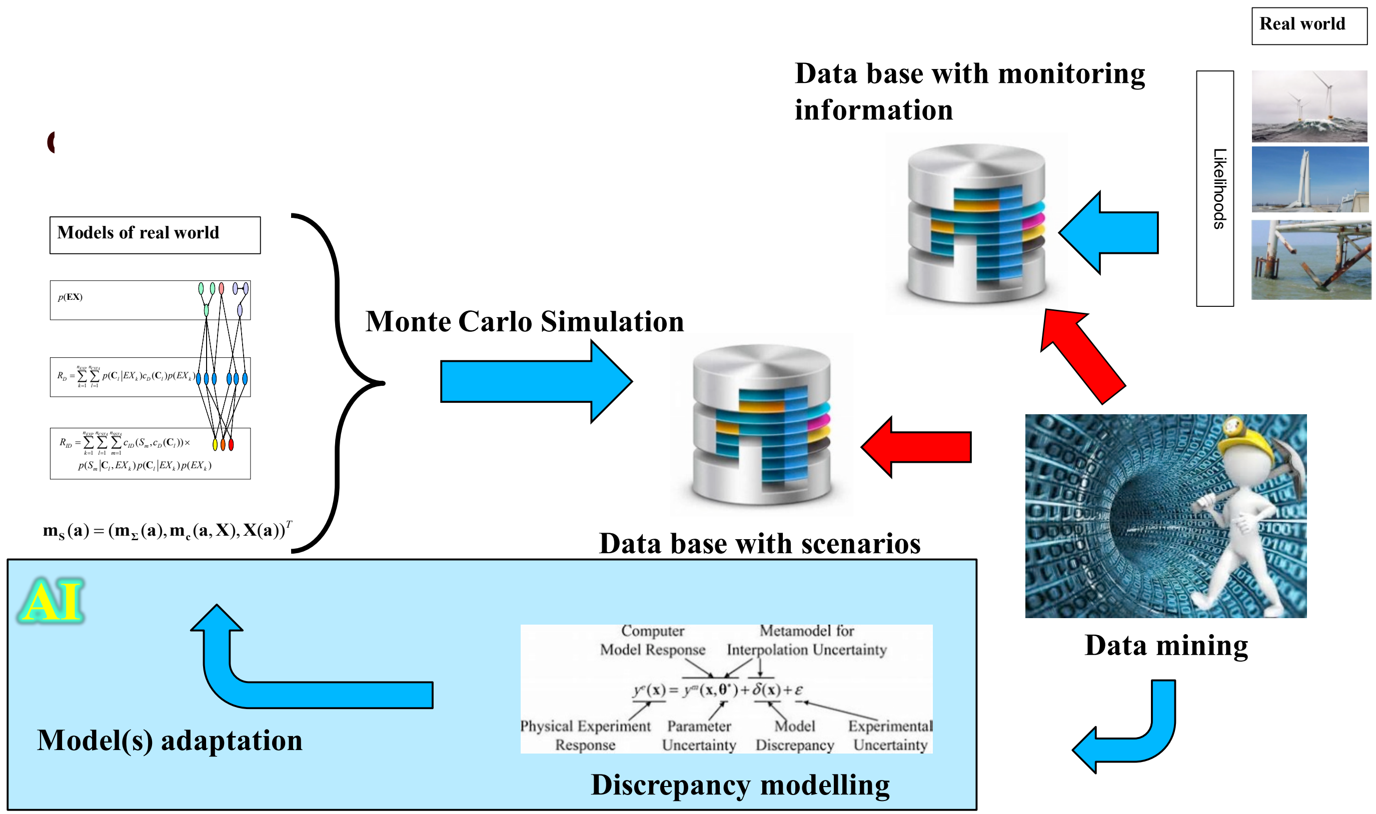
Systems representation

Top-down models – or data driven modelling approaches are usually assumed to be better that bottom-up models – ”data cannot lie”.

It is overseen that data-driven models depend entirely on the data-bases, ”experiment” plans and algorithms they take basis in – all of which are choices – and thus subjective – in the same manner as bottom-up models

Life safety as a tradeoff DM problem

Fusing (prior) Knowledge and Observations



- Glavind, S. T., Sepulveda, J. G., & Faber, M. H. (2022). On a simple scheme for systems modeling and identification using big data techniques. *Reliability Engineering & System Safety*, *220*, 108219.

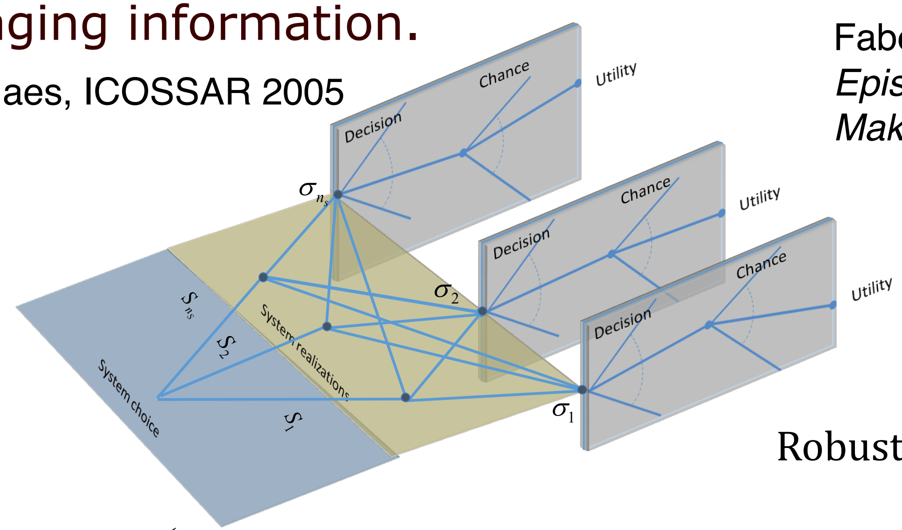
Life safety as a tradeoff DM problem

Decision optimization – multiple possible systems

Bayesian decision analysis as framework for managing information.

Faber and Maes, ICOSSAR 2005

Faber, M. H. and Maes, M. A., 2005, *Epistemic Uncertainties in Decision Making,* OMAE2005-67241.



$$\text{Robustness} = \frac{E'_{\mathbf{X}|s}(U(a^*,\mathbf{X}))}{E'_{\Sigma\backslash s}\left(E'_{X|\{\Sigma\backslash s\}}(U(a^*,X))\right)}$$

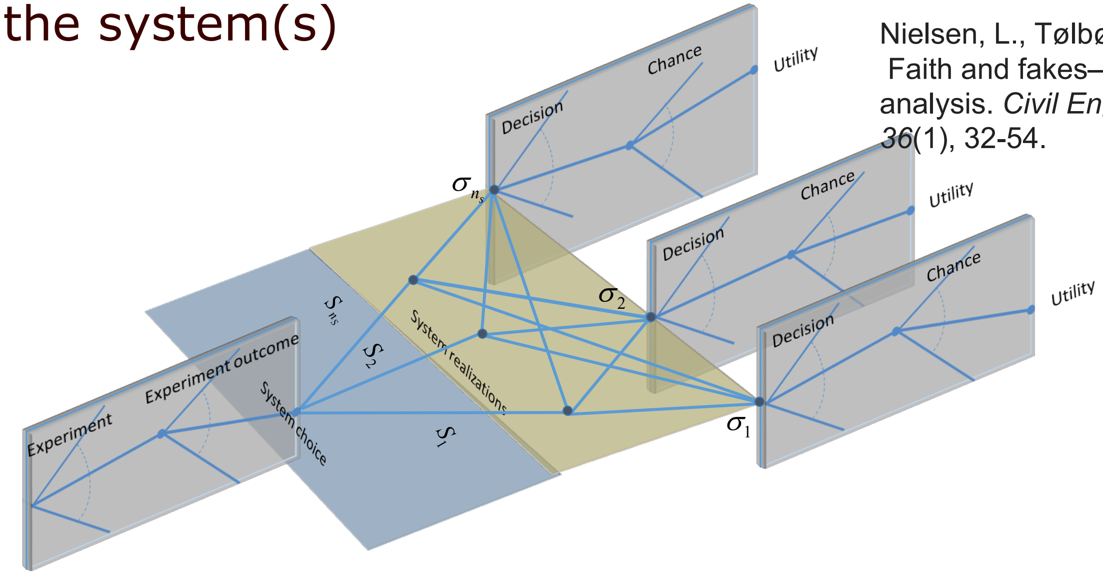
$$(s^*,a^*) = \max_s \left(P'(\Sigma = s)\max_a\left(E'_{\mathbf{X}|a}\left[U(a,\mathbf{X})\right]\right) + E'_{\Sigma\backslash s}\left[E'_{\mathbf{X}|\{\Sigma\backslash s\}}\left[U(a^*,\mathbf{X})\right]\right]\right)$$

When new information is available prior probability assignments may be updated and the importance of the different possible systems will change – as well as the probability assignments within the different possible systems

Life safety as a tradeoff DM problem

Decision optimization – multiple possible systems

Pre-posterior decision analyses to identify how additional information most efficiently contributes to the management of the system(s)



Nielsen, L., Tølbøll Glavind, S., Qin, J., & Faber, M. H. (2019). Faith and fakes–dealing with critical information in decision analysis. *Civil Engineering and Environmental Systems*, *36*(1), 32-54.

$$(e^*, s^*, a^*) = \max_e E'_{\mathbf{Z}}\left[\max_s\left(P''(\Sigma = s|\mathbf{z})\max_a\left(E''_{\mathbf{X}|a}\left[U(a,\mathbf{X})\right]\right) + E''_{\Sigma\backslash s}\left[E''_{\mathbf{X}|\{\Sigma\backslash s\}}\left[U(a^*,\mathbf{X})\right]\right]\right)\right]$$

Life safety as a tradeoff DM problem

Taking basis in the philosophical insight that the basic asset individuals have is time – Nathwani, Pandey and Lind developed the ***Life Quality Index (LQI).***

This is a preference model which at a societal level acts as a revealed preference on how we weigh money against lifetime and time for private activities.

$$L(g,\ell) = g^q \ell$$

g : is the part of the GDP available for investment into life safety

ℓ : is the life expectancy at birth

w : is the part of life spent for work

$$q = \frac{1}{\beta}\frac{w}{1-w}$$

β : is a factor which takes into account that only a part of the GDP is based on human labour

Life safety as a tradeoff DM problem

Based on the LQI – the consideration that every investment into life safety should lead to an increase in life-expectancy results in a risk acceptance criterion:

$$\frac{dg}{g} + \frac{1}{q}\frac{d\ell}{\ell} \geq 0$$

which leads to the important ***Societal Willingness To Pay (SWTP)*** criterion:

$$SWTP = dg = -\frac{g}{q}\frac{d\ell}{\ell}$$

GDP	59451 SFr
l	80.4 years
w	0.112
β	0.722
g	35931 SFr
q	0.175

Life safety as a tradeoff DM problem

The SWTP criterion is readily applied for the purpose of determining acceptable structural failure probabilities

$$\frac{d\ell}{\ell} \approx C_x d\mu = C_x kdm$$

where

C_x is a demographical constant

k is the probability of dying in case of structural failure

m is the failure rate of a considered structural system

Life safety as a tradeoff DM problem

The SWTP criterion is readily applied for the purpose of determining acceptable structural failure probabilities

$$dC_y(p) \geq -\frac{g}{q} C_x N_{PE} k dm(p)$$

where

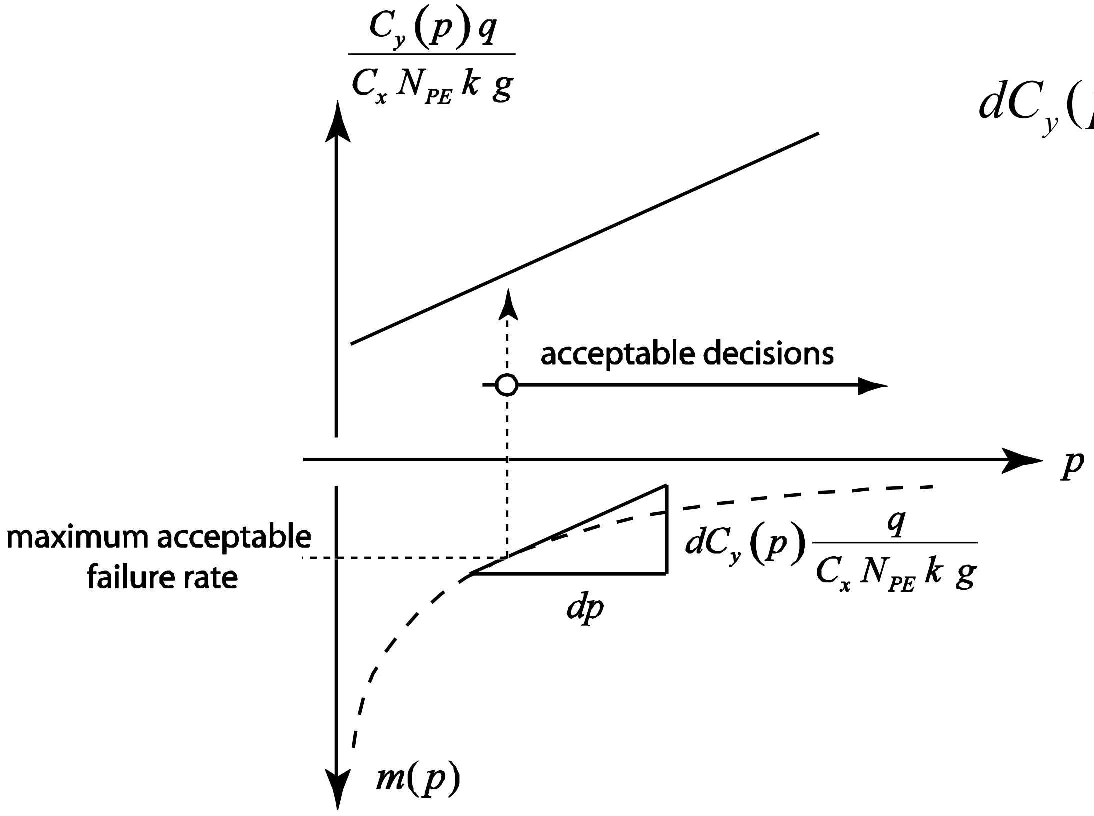
$dC_y(p)$ are the annual costs spent for risk reduction

N_{PE} is the number of people exposed to the structural failure

p is a decision alternative e.g. a structural dimension

Life safety as a tradeoff DM problem

The SWTP criterion can be visualized



$$dC_y(p) \geq -\frac{g}{q} C_x N_{PE} k dm(p)$$

Life safety as a tradeoff DM problem

Based on the LQI – also the costs of compensation for a lost life can be assessed – ***Societal Value of a Statistical Life (SVSL)***.

$$SVSL = \frac{g}{q} E$$

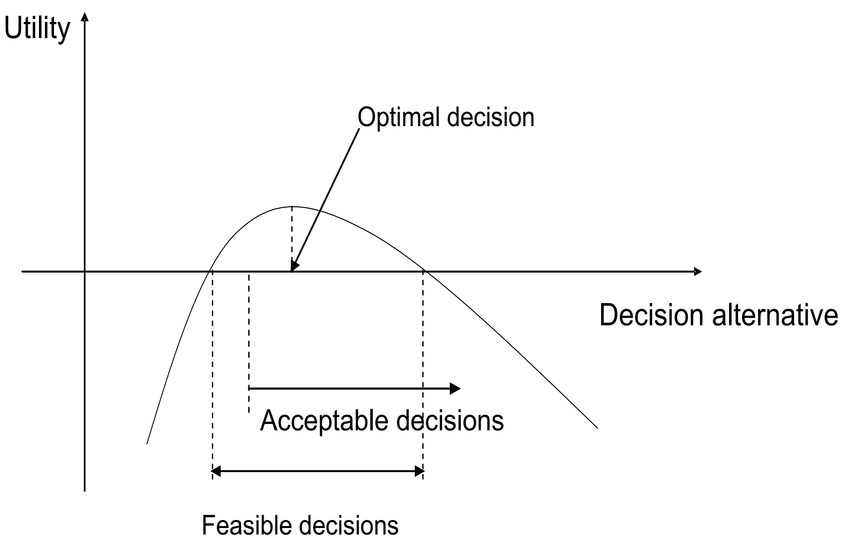
For Switzerland this amounts to about 6 million SFr

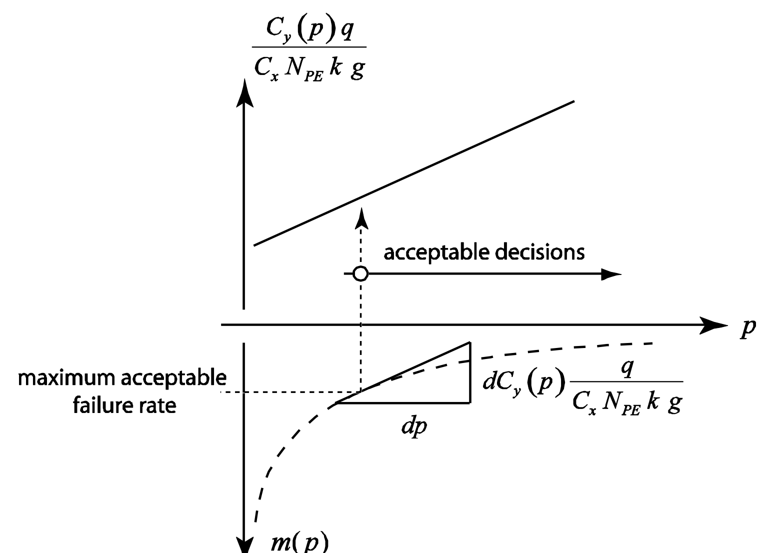
Life safety as a tradeoff DM problem

Now the optimization problem can be reassessed –

Acceptable decisions are limited by the SWTP criterion

Costs of failure include compensation – through the SVSL

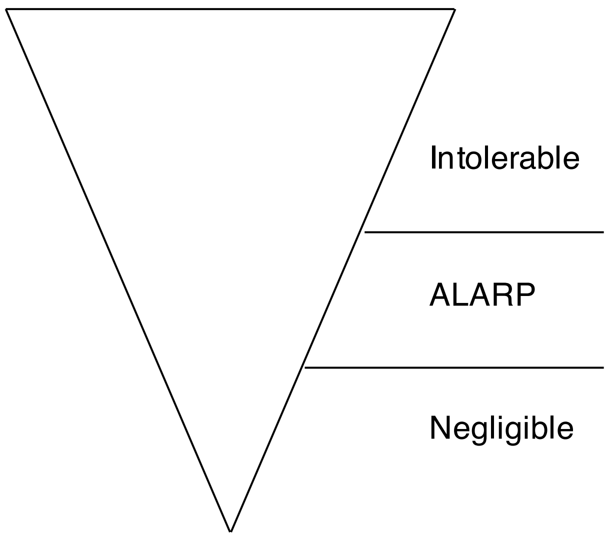




Life safety as a tradeoff DM problem

The fundamental principle for management of life safety risk is optimization (JCSS (2008), ISO 2394:2015,.....)

Fully compatible with the ALARP



Acceptability of decisions/activities are assessed through the marginal life saving costs principle using e.g. the Life Quality Index

Life safety as a tradeoff DM problem

Operational life safety risk management (i.e. for one project or activity) includes:

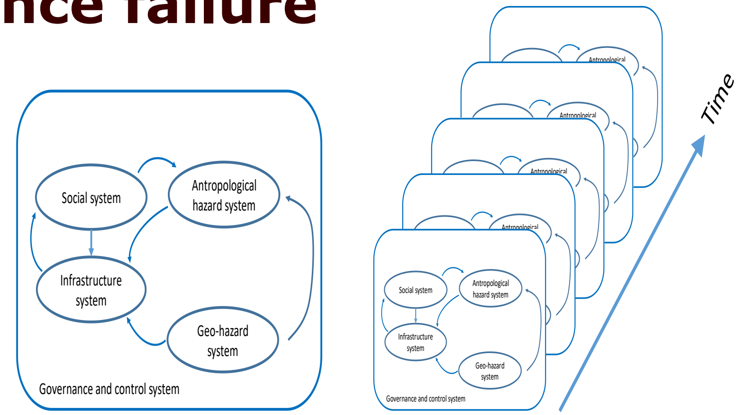
- Allocation of resources to a given project in accordance with the efficiency of relevant best practice risk reduction measures.
- Implementation of these measures.

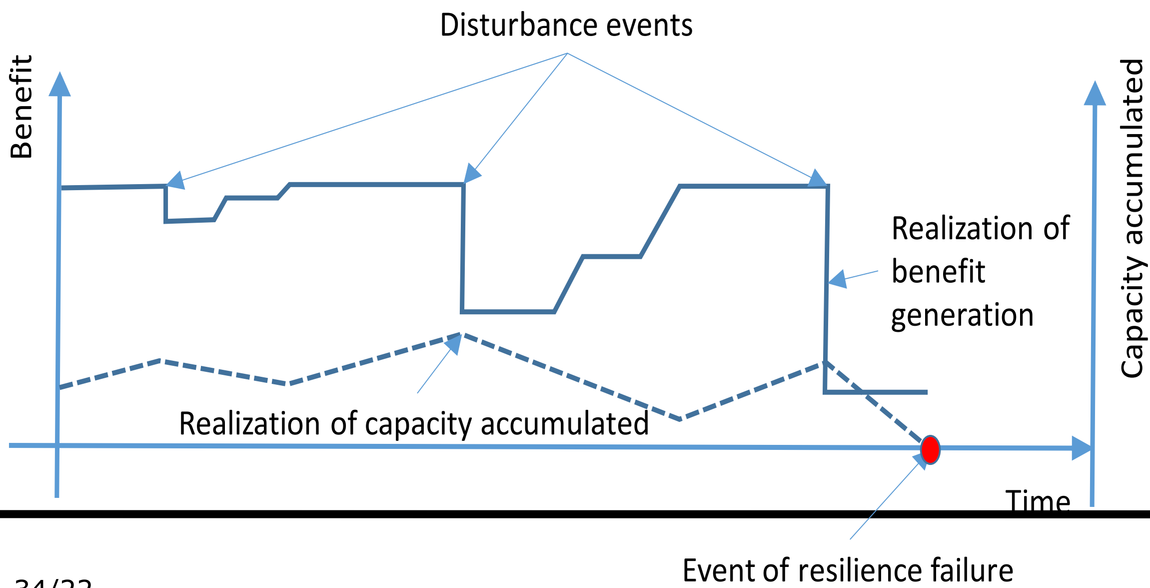
Strategic life safety risk management includes:

- Prioritization of available economical resources between projects and activities in accordance with life saving efficiency.
- Monitoring and improving best practices.

Life safety as a tradeoff DM problem

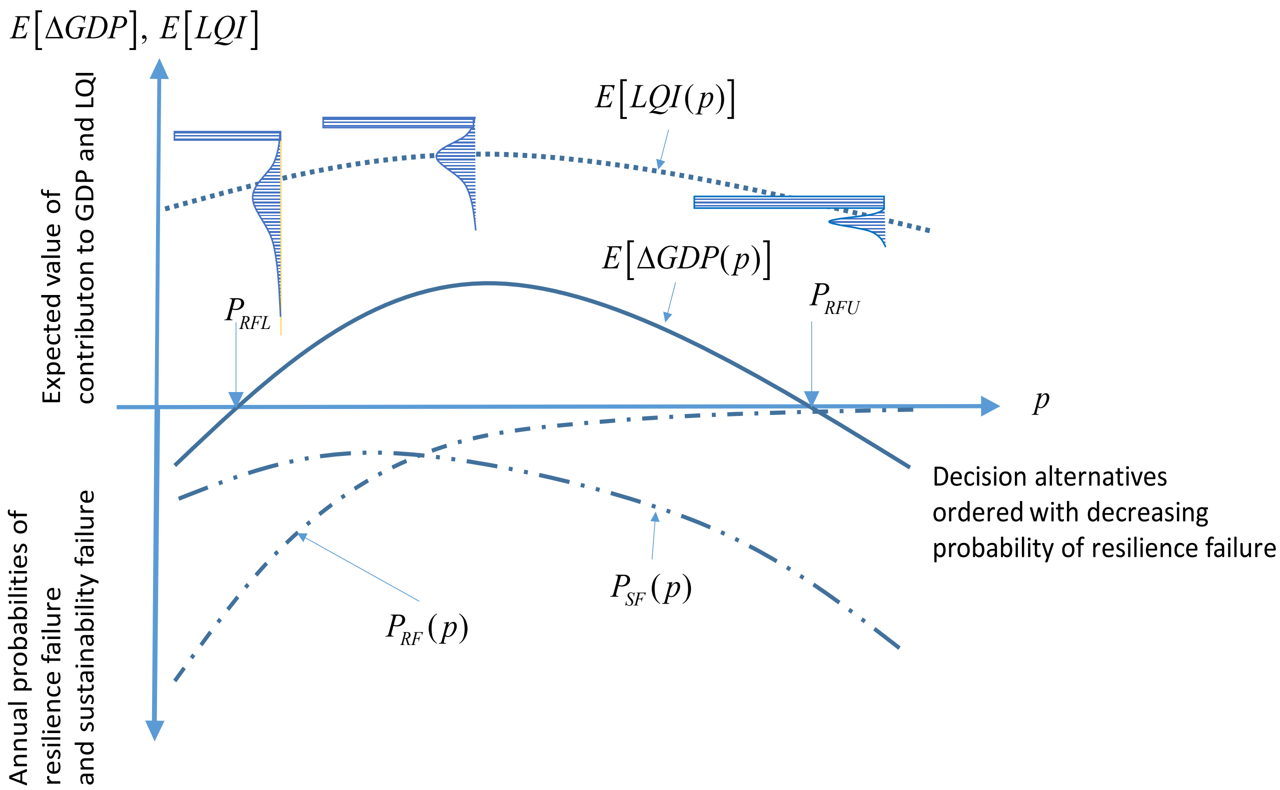
Interlinked systems and resilience failure





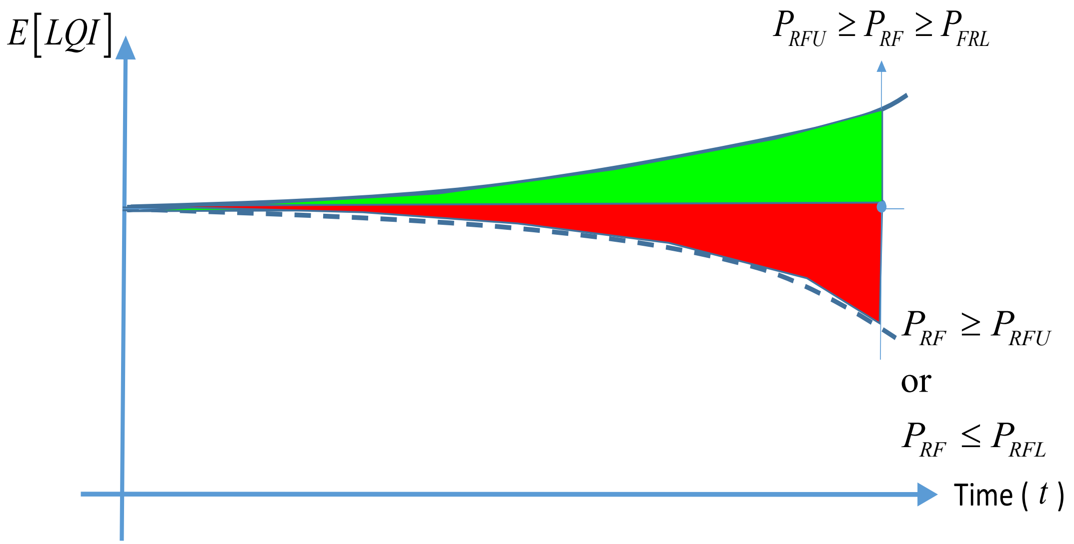
Life safety as a tradeoff DM problem

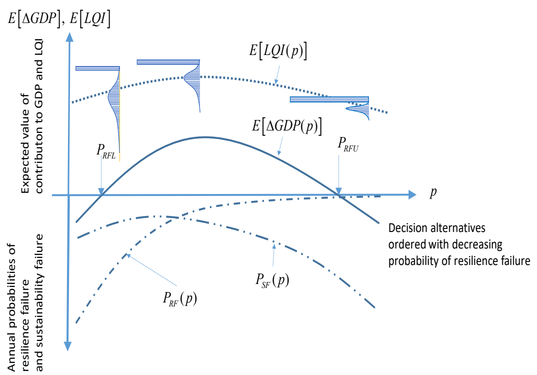
Tradeoffs in resilience and sustainability management



Life safety as a tradeoff DM problem

Tradeoffs in resilience and sustainability management





Global Life Safety Risk Management

Support by supranational organizations such as the United Nations for developing economies often directly targets improvement of life safety or improvement of infrastructure

The fundamental question has been whether it is correct to apply the preferences for investments into life safety from highly developed countries when deciding on the use of monetary resources in helping developing countries

Faber, M. H. and Virguez-Rodriguez, E. (2011). Supporting decisions on global health and life safety investments, in Proceedings of the 11th International Conference on Applications of Statistics and Probability in Civil Engineering, pp. 434-443

Global Life Safety Risk Management

Global health and life safety related decision problems include e.g.:

- Allocation of catastrophe aid

- Allocation of development aid

- Regulations and codes concerning:

  - nuclear energy exploitation
  - offshore oil and gas exploitation
  - international transport
  - building design
  - …
  - …

Global Life Safety Risk Management

The idea takes basis in three postulates (or assumptions):

Life safety and health related decisions are adequately supported by the principle of marginal life saving costs (Linnerooth, J., 1975)

If a marginal life saving costs coherent preference for life saving investments at national scale can be shown to be widely representative for the preferences of all the nations of the Earth then this preference is also valid at Earth scale

The Life Quality Index – LQI (Nathwani et al., 1997) is an adequate (preference) model to assess the marginal life saving costs at national scale

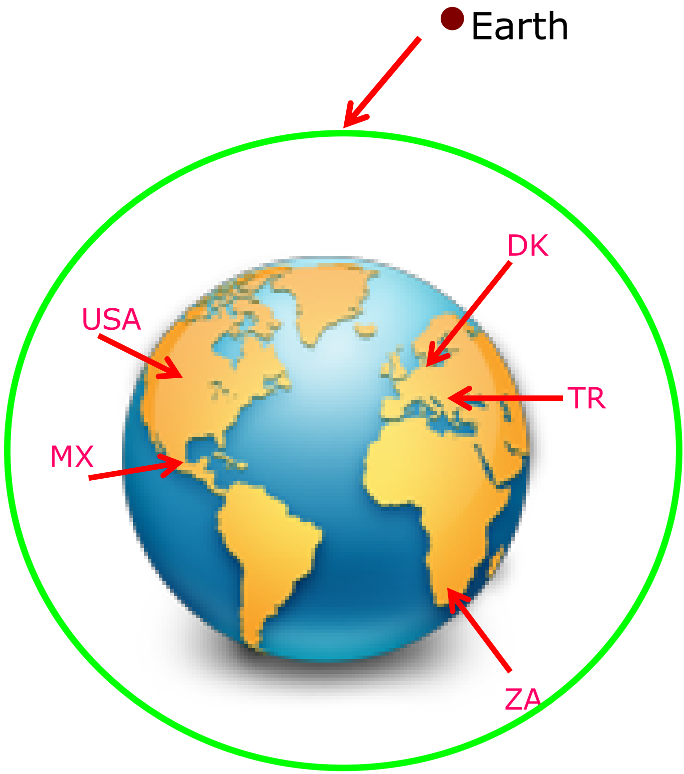
Global Life Safety Risk Management

The approach followed is to:

1) Assess demographic indicators at national scale for all nations in the world and finally also at Earth scale

2) Assess whether each individual nation of the world as well as Earth “follows” the LQI preference

3) Assess Earth marginal life saving costs (SWTP) and compensation costs (SVSL)



Global Life Safety Risk Management

Direct application of the LQI on Earth scale gives

Societal Willingness To Pay (SWTP) - π

Region	Discount Rate			
	1%	2%	3%	4%
Canada	$ 3.854	$ 3.235	$ 2.744	$ 2.357
United States	$ 3.467	$ 2.932	$ 2.503	$ 2.163
China	$ 176	$ 149	$ 127	$ 110
Brazil	$ 570	$ 473	$ 396	$ 335
Australia	$ 4.875	$ 4.070	$ 3.433	$ 2.935
Mozambique	$ 22	$ 19	$ 16	$ 14
Mali	$ 31	$ 26	$ 23	$ 20
Dem. Republic of Congo	$ 8	$ 7	$ 6	$ 5
World (World Life Table)	$ 501	$ 422	$ 359	$ 308

Global Life Safety Risk Management

Direct application of the LQI on Earth scale gives

Societal Willingness To Pay (SWTP) - Δ

Region	Discount Rate			
	1%	2%	3%	4%
Canada	\$ 5.254	\$ 4.659	\$ 4.129	\$ 3.669
United States	\$ 4.226	\$ 3.756	\$ 3.338	\$ 2.975
China	\$ 234	\$ 209	\$ 187	\$ 167
Brazil	\$ 782	\$ 693	\$ 614	\$ 546
Australia	\$ 7.270	\$ 6.436	\$ 5.694	\$ 5.050
Mozambique	\$ 26	\$ 23	\$ 20	\$ 18
Mali	\$ 40	\$ 36	\$ 32	\$ 29
D.R. of Congo	\$ 11	\$ 10	\$ 9	\$ 8
World (World Life Table)	\$ 654	\$ 582	\$ 517	\$ 462

Global Life Safety Risk Management

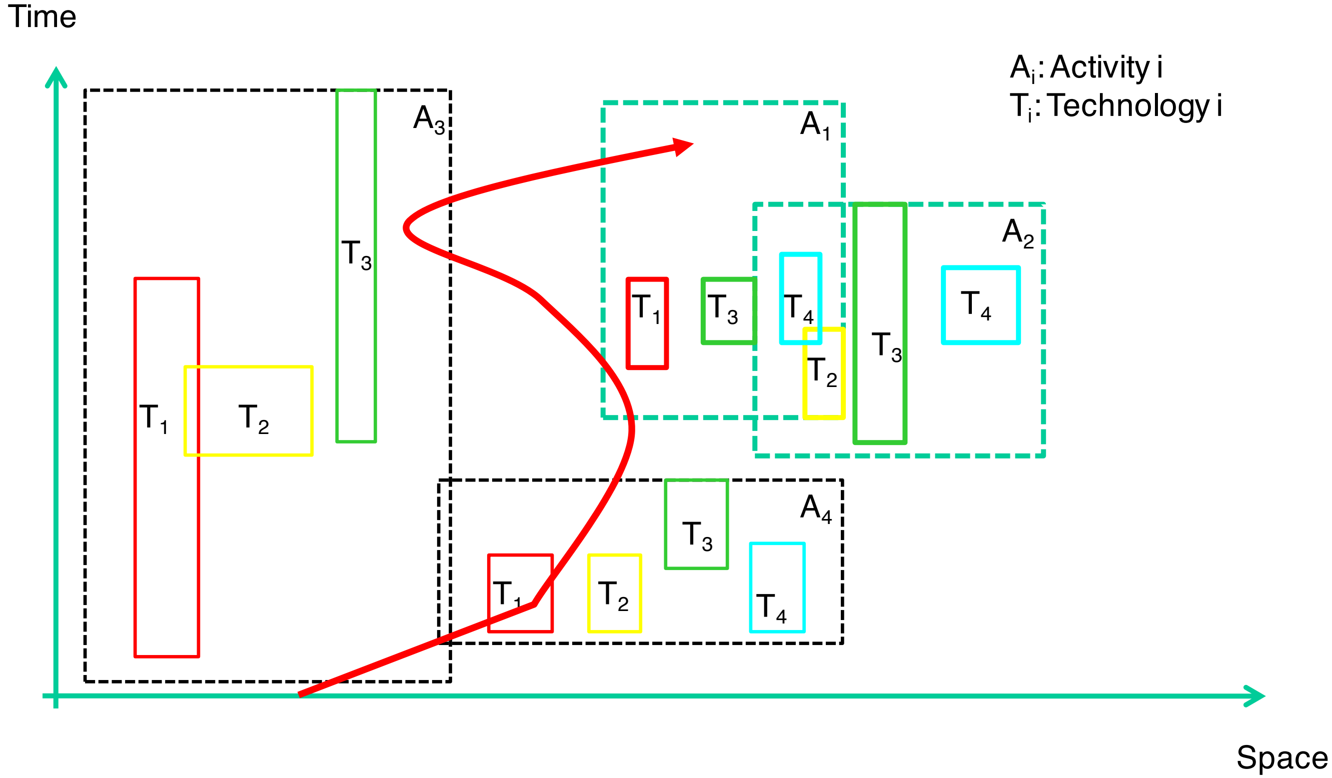
Direct application of the LQI on Earth scale gives

Societal Value of a Statistical Life

Region	Discount Rate			
	1%	2%	3%	4%
Canada	$ 8.110	$ 6.301	$ 5.064	$ 4.186
United States	$ 6.464	$ 5.060	$ 4.091	$ 3.397
China	$ 362	$ 285	$ 232	$ 193
Brazil	$ 1.186	$ 926	$ 747	$ 618
Australia	$ 11.258	$ 8.711	$ 6.977	$ 5.752
Mozambique	$ 36	$ 29	$ 24	$ 20
Mali	$ 57	$ 46	$ 38	$ 32
Dem. Republic of Congo	$ 16	$ 13	$ 10	$ 9
World (World Life Table)	$ 984	$ 775	$ 629	$ 524

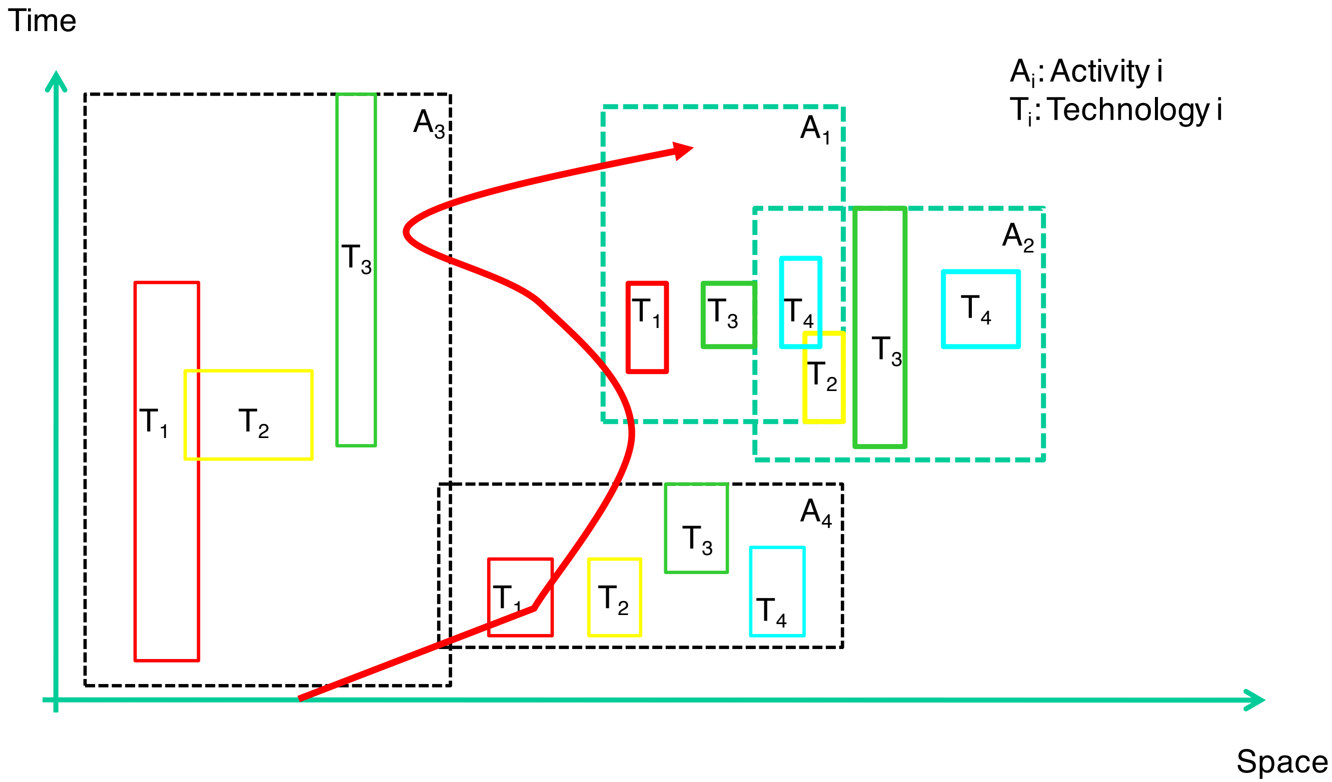
Regulation of Life Safety Risks

Activities and technologies



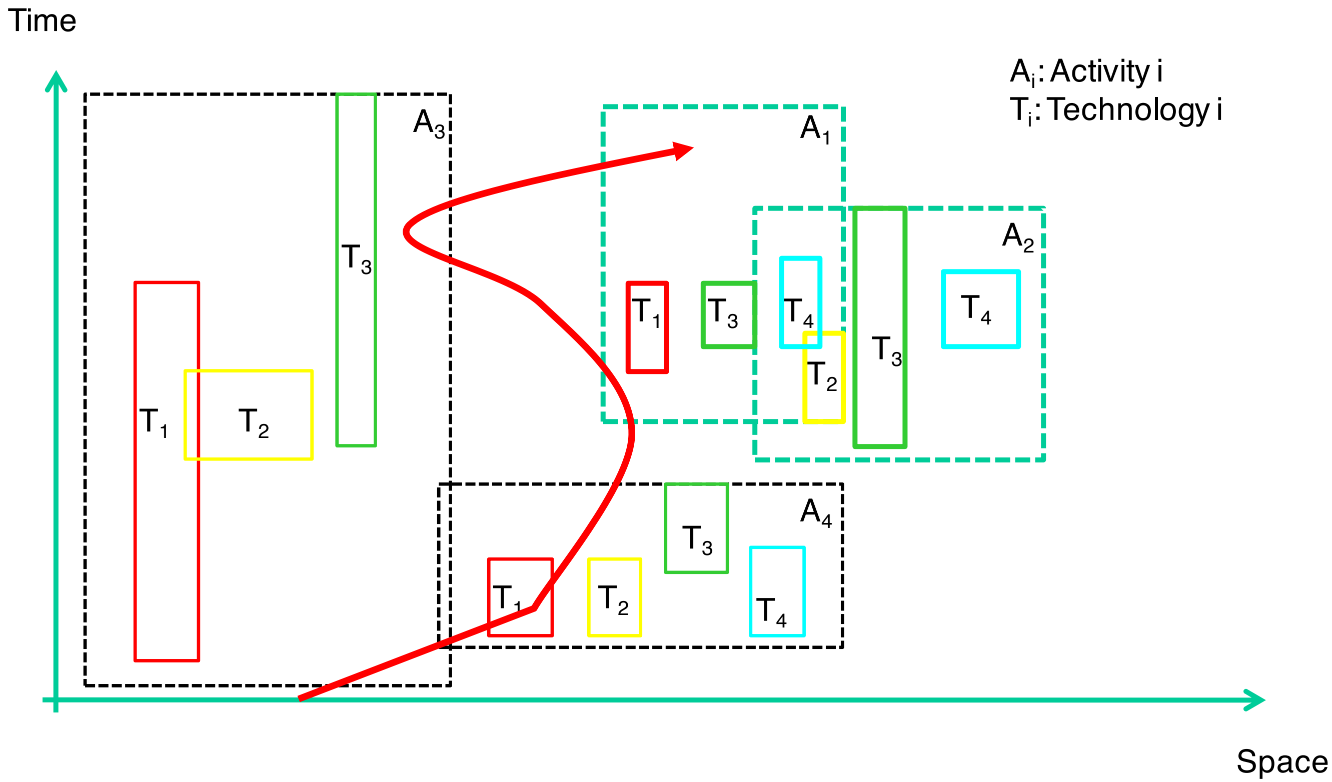
Regulation of Life Safety Risks

Activities and technologies
Overlayered with natural hazards



Regulation of Life Safety Risks

Activities and technologies
Overlayered with natural hazards
Inhomogeneous density of people



Regulation of Life Safety Risks

Which are the implications:

- Focus on the regulation of technologies and activities not individuals

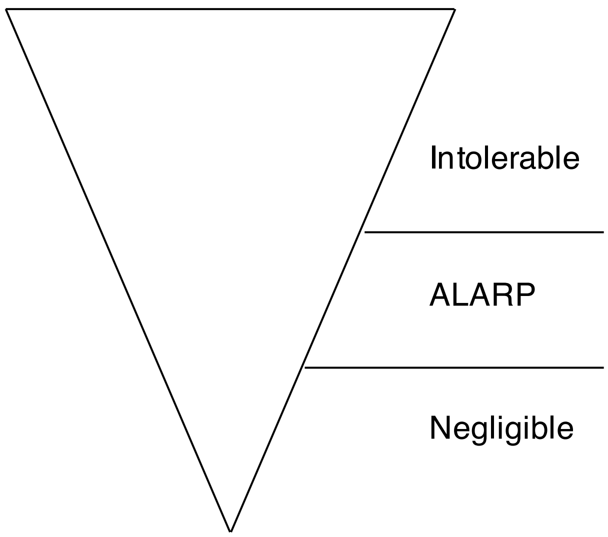
- Risk exposures from technologies and activities may be everywhere and anytime (unless otherwise regulated)

- There are no temporary activities

Regulation of Life Safety Risks

The fundamental principle for management of life safety risk is optimization (JCSS (2008), ISO 2394:2015,.....)

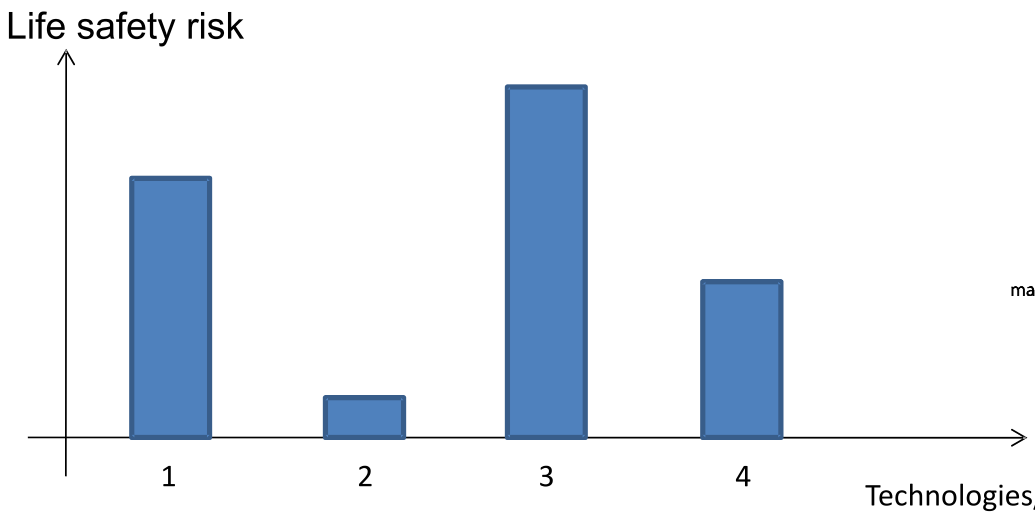
Fully compatible with the ALARP

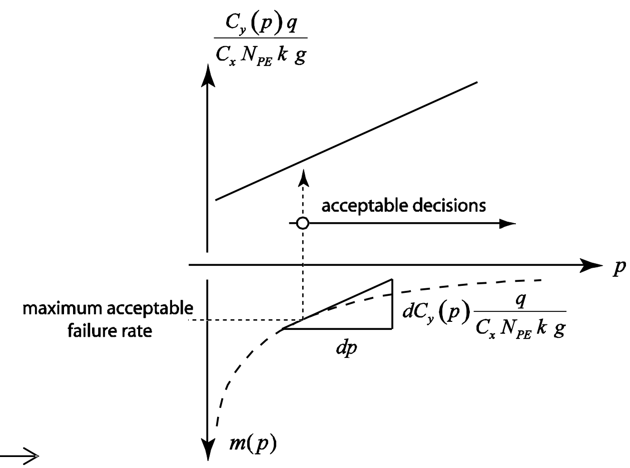


Acceptability of decisions/activities are assessed through the marginal life saving costs principle using e.g. the Life Quality Index

Regulation of Life Safety Risks

Not all technologies/activities perform equally well





It makes sence to compare risks to benchmark technologies/activities

Regulation of Life Safety Risks

- **Acceptance criteria – Life Safety – ISO2394**

$$g = R - S$$

$$p = \frac{E[S]}{E[R]}$$

$$-\frac{dP_f(p)}{dp} \le \frac{C_1(\gamma_S + \omega)}{g/q \cdot C_x \cdot N_F} = \frac{C_1(\gamma_S + \omega)}{G_x \cdot N_F} = K_1$$

Relative life saving costs	Range for K_1 constant	LQI target reliability
Large	$10^{-3} - 10^{-2}$	$\beta = 3.1\left(P_f \approx 10^{-3}\right)$
Medium	$10^{-4} - 10^{-3}$	$\beta = 3.7\left(P_f \approx 10^{-4}\right)$
Small	$10^{-5} - 10^{-4}$	$\beta = 4.2\left(P_f \approx 10^{-5}\right)$

Regulation of Life Safety Risks

- **Acceptance criteria – Life Safety – ISO2394**

Marginal life saving costs and statistical value of life for a selection of different nations.

Country	*2008 GDP per capite*	SWTP - G_{Π}			SWTP - G_{Δ}			SVSL		
		2%	3%	4%	2%	3%	4%	2%	3%	4%
Australia	35624	3061	2614	2279	4840	4298	3843	6551	5261	4356
Brazil	9517	548	470	399	804	712	634	1074	864	724
Canada	36102	2821	2369	2038	4062	3636	3236	5494	4412	3679
China	5515	252	213	184	353	314	279	482	397	335
Colombia	8125	390	330	285	475	424	380	443	362	304
Dem. Rep. of Congo	290	11	9	8	16	14	12	20	17	14
Denmark	34005	2334	2007	1704	3842	3431	3064	3127	2549	2113
France	30595	1969	1677	1459	2935	2601	2307	2233	1820	1523
Germany	33668	2090	1785	1544	3219	2849	2527	2625	2158	1824
Hong Kong	40599	1864	1592	1384	2875	2561	2300	2243	1805	1511
India	2721	128	110	96	175	156	139	172	140	118
Japan	31464	1435	1227	1045	2286	2036	1812	1702	1404	1178
Mali	1043	40	34	29	54	48	43	70	56	47
Mozambique	774	33	28	25	40	36	32	51	42	35
Netherlands	38048	2329	1989	1700	3812	3385	3016	2967	2406	2016
Norway	49416	2794	2380	2038	3937	3500	3129	3531	2839	2348
Poland	16418	1006	846	729	1369	1218	1080	1221	989	819
Singapore	45553	2114	1799	1554	2735	2448	2191	2771	2267	1893
Sweden	33769	2249	1891	1630	2710	2406	2137	2561	2113	1743
Switzerland	37788	2943	2517	2134	4206	3727	3332	3464	2792	2332
United Kingdom	34204	2600	2178	1873	4105	3665	3270	3127	2505	2117
United States	42809	2488	2100	1822	3187	2833	2542	4293	3508	2953

A Consistent Metric for Life Safety Risk

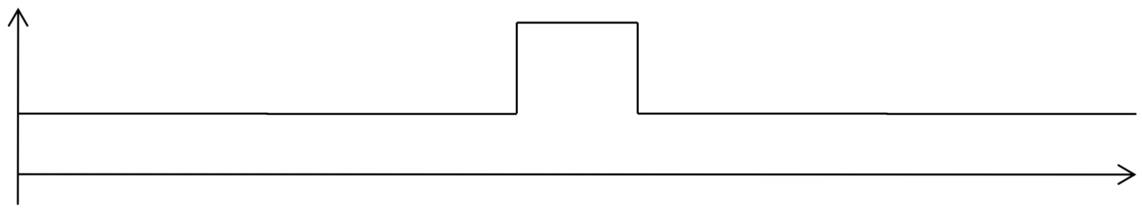
$$\gamma_{LR} = \frac{n_F}{N_L}$$ Statistical individual annual fatality rate

n_F Number of fatalities per time unit (year)

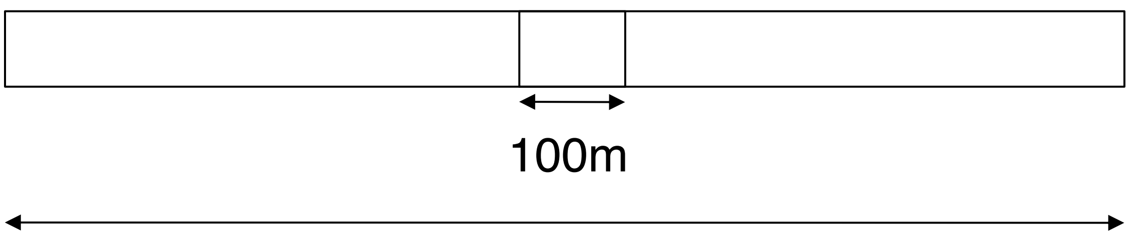
N_L Number of life years exposed per time unit (year)

A Consistent Metric for Life Safety Risk

Risk profile



Tunnel layout



50km/h
10 million persons per annum

	n_F	N_L	γ_{LR}
- middle segment	0.05	2.28	2.19×10^{-2}
- edge segments	0.05	20.55	2.43×10^{-3}
- total	0.10	22.83	4.38×10^{-3}

A Consistent Metric for Life Safety Risk

Cases	Man years of exposure per year	Fatalities per year	Fatality rate
Construction USA (2007)	2,433,820	1,204	$4.9470\ 10^{-4}$
Construction UK (2007)	481,133	72	$1.4965\ 10^{-4}$
Construction Singapore (2007)	91,688	24	$2.6176\ 10^{-4}$
Construction New York (2007)	70,120	99	$1.4120\ 10^{-3}$
Transportation and materials moving USA (2007)	2,344274	890	$3.7965\ 10^{-4}$
Transport and storage Singapore (2007)	49,806	7	$1.4055\ 10^{-4}$
Roadway traffic in Changsha City China (2007)	4,117,188	416	$1.0100\ 10^{-4}$
Gotthard road tunnel, Switzerland (1996)	408	2	$4.9000\ 10^{-3}$

Summary and Outlook

- It is proposed to optimize decisions on societal developments based on the Life Quality Index.
- Optimization based on the LQI should fulfill any policies and/or stakeholder preferences for the distribution of welfare as well as possible inconveniences over the population.
- Any decision made must conform with regulations and standards at local scales – facilitated by the proposed framework by imposing such requirements through constraints on the optimization of welfare.
- There are rather significant tradeoffs between welfare, resilience and sustainability.
- Welfare and sustainability may be at stake both if too little or too much is invested into resilience improvements.
- It is imperative that more knowledge is established to quantify and assess these tradeoffs for the enhancement of resilient and sustainable developments.

Summary and Outlook

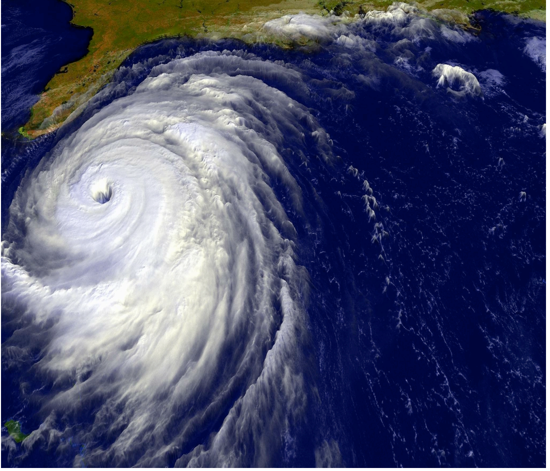
- Acceptability concerns technologies and activities (decisions)

  Unless specifically regulated – exposures of technologies and activities are everywhere and always

  There is no such thing as temporary activities/phases in life safety risk regulation

- A metric for comparison of life safety risks for statistical individuals is proposed:

  - Consistent with the marginal life saving costs principle – use of LQI criterion for assessing acceptability
  - Facilitates comparison of risks across any societal domain of regulation
  - Compares directly with risks from cohort life tables



JCSS
Joint Committee on Structural Safety

Workshop on Risk Acceptance Criteria in Civil Engineering Decision Making

Trondheim, June 19-20, 2023

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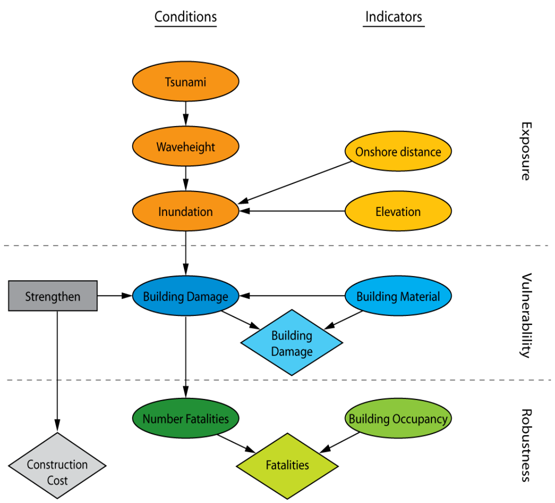

Thanks for your attention !

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