Symposium on Risk, Resilience and Disaster Management - Launching the World Bosai Forum/ IDRC Sendai 2019

Managing Technical Risks
Matrisk

Sustainability and Resilience of Engineered Systems

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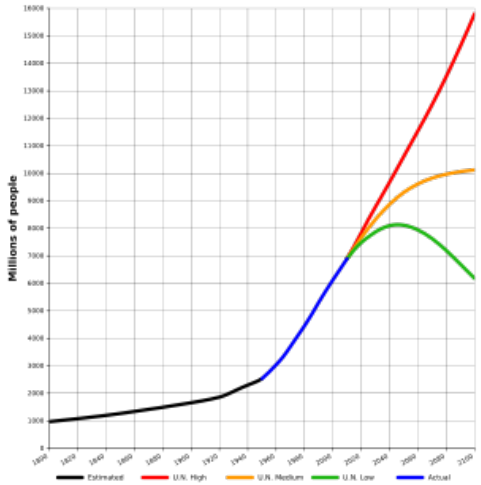
Aalborg University, Denmark

Risk
Reliabiliy
Resilience
Sustainability
Built
Environment

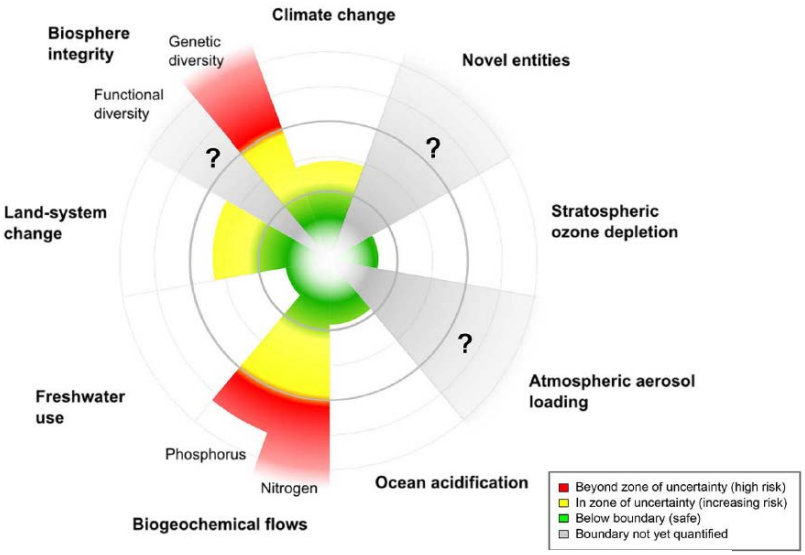
Setting the Scene

Pressing boundaries for societal developments:

At local and global scales it is increasingly appreciated that societal developments are approaching the limits of the capacities of the ecological systems and the Earth life support system



Population growth, Wikepedia, UN

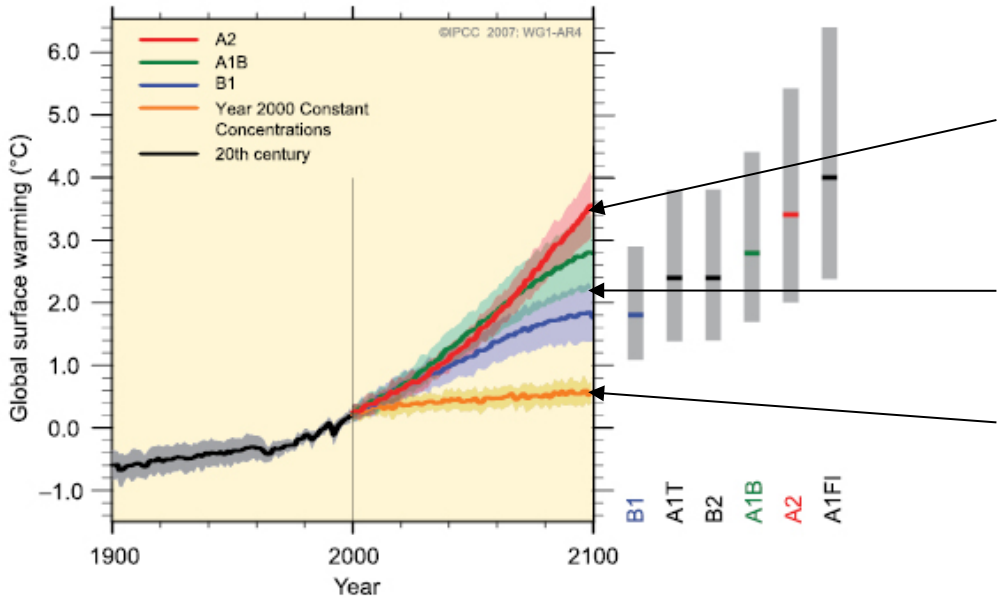


Planetary boundaries, Steffen *et al*. 2015[1]

Setting the Scene

Pressing boundaries for societal developments:

Significant signs of the back-coupling between civilizations and living conditions for civilization are observable



Scenario A2 – heterogeneous world

Scenario B1 – convergent world

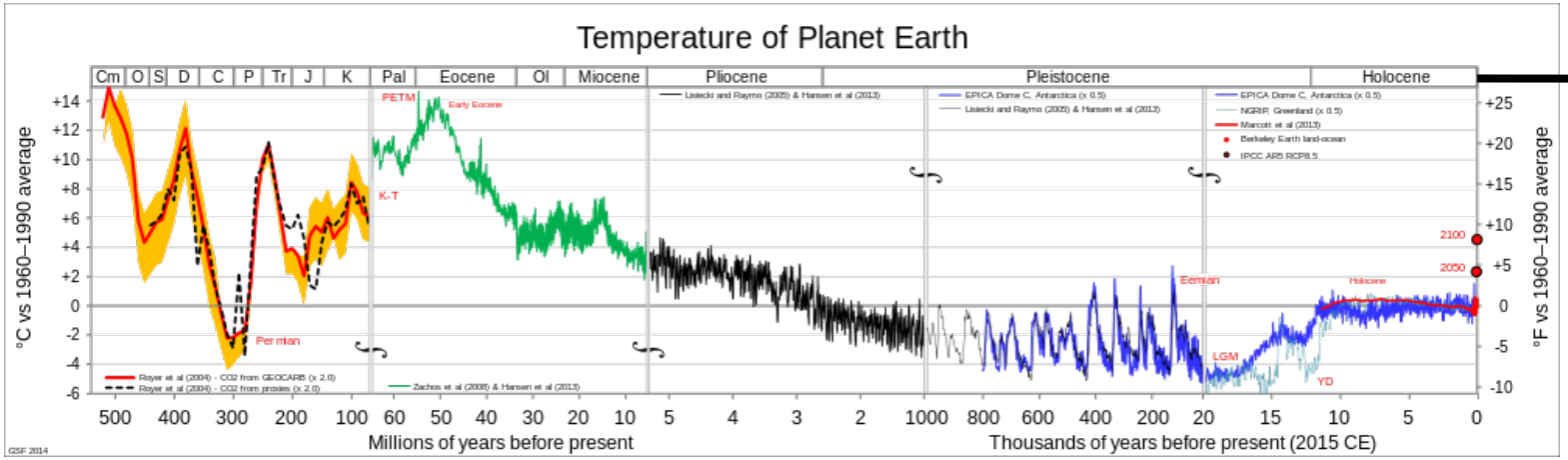
CO2 emissions constant at 2000 level

IPCC homepage

Setting the Scene

Pressing boundaries for societal developments:

Significant signs of the back coupling between civilizations and living conditions for civilization are observable



Wikepedia

Anthropocene

Setting the Scene

Infrastructures accommodating 7.5 billion people

Cities in the world (+1 million inhabitants)	~ 500
Bridges in the USA	~ 600.000
Global road network	> 13 million km
Global rail network	> 1 million km
Airports	~ 50.000
Offshore platforms in the world	~ 6.500
Dams in the world	~ 45.000
Nuclear (civil) reactors in the world	~ 440

.....

.....

Setting the Scene

Built environment alone

Contributes with ~10% of GDP in Europe

Responsible for 50% of global energy consumption

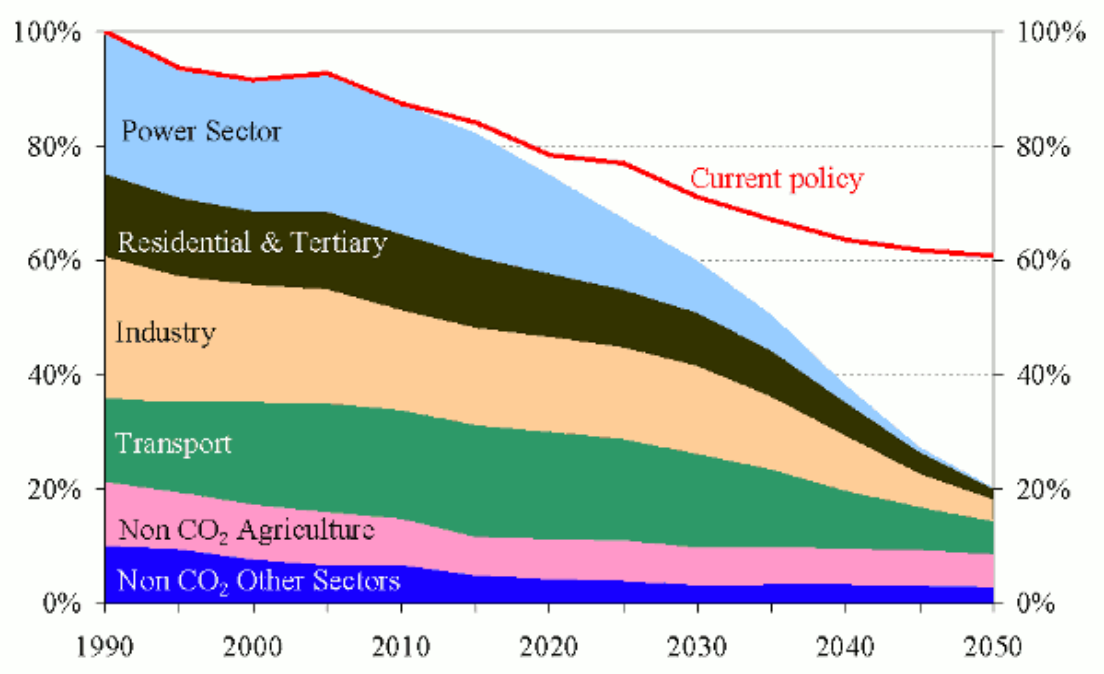
Concrete responsible for ~8% of global CO2 emissions

Responsible for ~90% of global material consumption (weight)

Setting the Scene

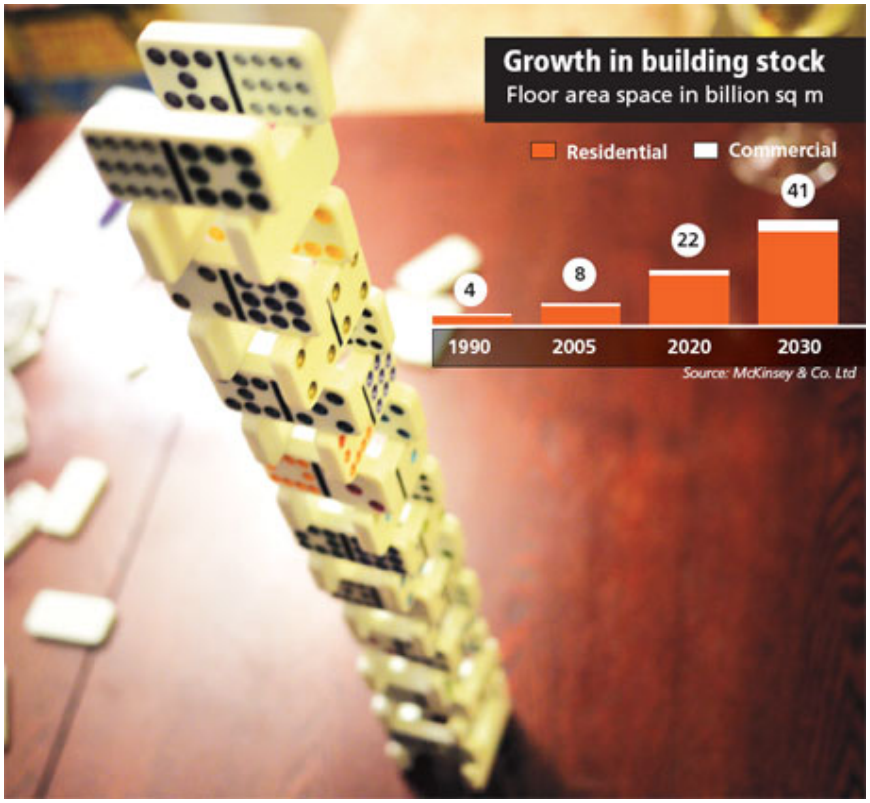
Targets for mitigation of climate change

EU aims to cut CO2 emissions by 40% in 2030 and 80% in 2050 relative to 1990 levels



Setting the Scene

Climate change / sustainability



McKinsey and Co Ltd

Contents of Presentation

Sustainability and resilience – a view across the sciences

Decision Support Framework

Probabilistic systems representation
- Robustness of systems
- Resilience of systems
- Consequences to health and environment
- Sustainability of systems

Principal example

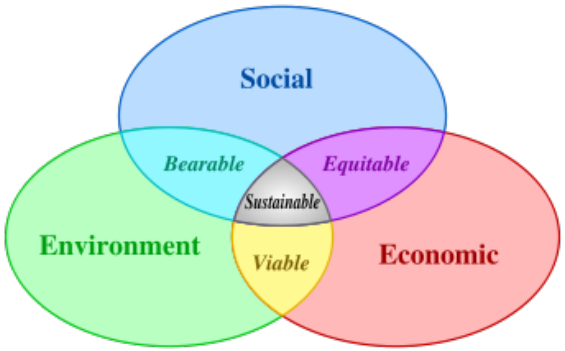
Conclusions and outlook

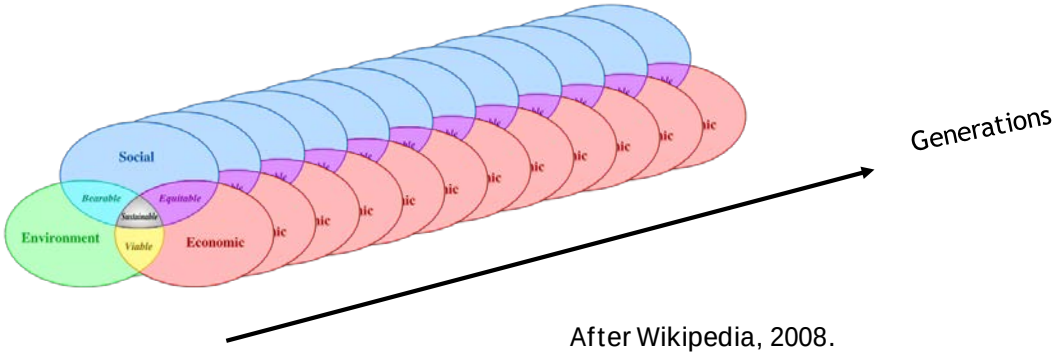
Sustainability and Resilience – a View Across the Sciences

Sustainability:

Gro Harlin Bruntland report (1987) – Our Common Future

"Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"





After Wikipedia, 2008.

Sustainability and Resilience – a View Across the Sciences

Sustainability (economy):

Strong sustainability assumes that exhaustible resources and human capital are strictly complimentary

Weak sustainability assumes that exhaustible resources and human capital are exchangeable

Solow (1974) studies equity from the perspective of weak sustainability and concludes that **exhaustible resources shall be used – optimally** - according to the same principles as reproducible resources
"Earlier generations may "draw down" exhaustible resources as long as they use them optimally and exchange them optimally with reproducible resources"

Solow (1991) proposes that gains from exploitation of **exhaustible resources are transferred unreduced** to future generations in terms of investments

Sustainability and Resilience – a View Across the Sciences

Sustainability (environment):

Kates et al.(2001) recommends to explore and assess the relation between resilience and sustainability and propose to **utilize decision support** systems as a means to identify sustainable paths of societal developments

Steffen et al. (2015) introduce the concept of **Planetary Boundaries** as a concept for representing the capacities of the Earth System (Earth Life Support System - ELSS)

Hauschild (2015) suggests to utilize **quantitative sustainability assessments** to assess the aggregate impacts of human activities at global level with respect to the main parameters controlling safe operating conditions (ELSS) for the planetary system.

Sustainability and Resilience – a View Across the Sciences

Resilience (definitions):

Pimm (1984) - *Resilience….the time it takes till a system which has been subjected to a disturbance returns to its original mode and level of functionality*

Holling (1996) - *Resilience….the measure of disturbance which can be sustained by a system before it shifts from one equilibrium to another*

Cutter (2010) - *Resilience…. capacity of a community to recover from disturbances by their own means*

Bruneau (2009) – *Resilience…. a quality inherent in the infrastructure and built environment; by means of redundancy, robustness, resourcefulness and rapidity*

National Academy of Science (NAS, USA) - *Resilience….a systems ability to plan for, recover from and adapt to adverse events over time*

Sustainability and Resilience – a View Across the Sciences

Insights

Sustainability is an organizing principle and a process

Sustainability as well as resilience at any scale necessitate preservation of stable living conditions – Earth Life Support System (ELSS) functions

Resilience at global scale is equivalent to sustainability

At smaller scales there is a tradeoff between sustainability/efficiency and resilience

Infrastructures have a very significant environmental foot print and must be designed, operated and managed optimally with due consideration of the environment, safety and health and economy

Sustainability and Resilience – a View Across the Sciences

Strategies for sustainable and resilient systems

Efficiency/optimality

Diversity

Redundancy

Temporally optimized solutions

Planned and smart renewals

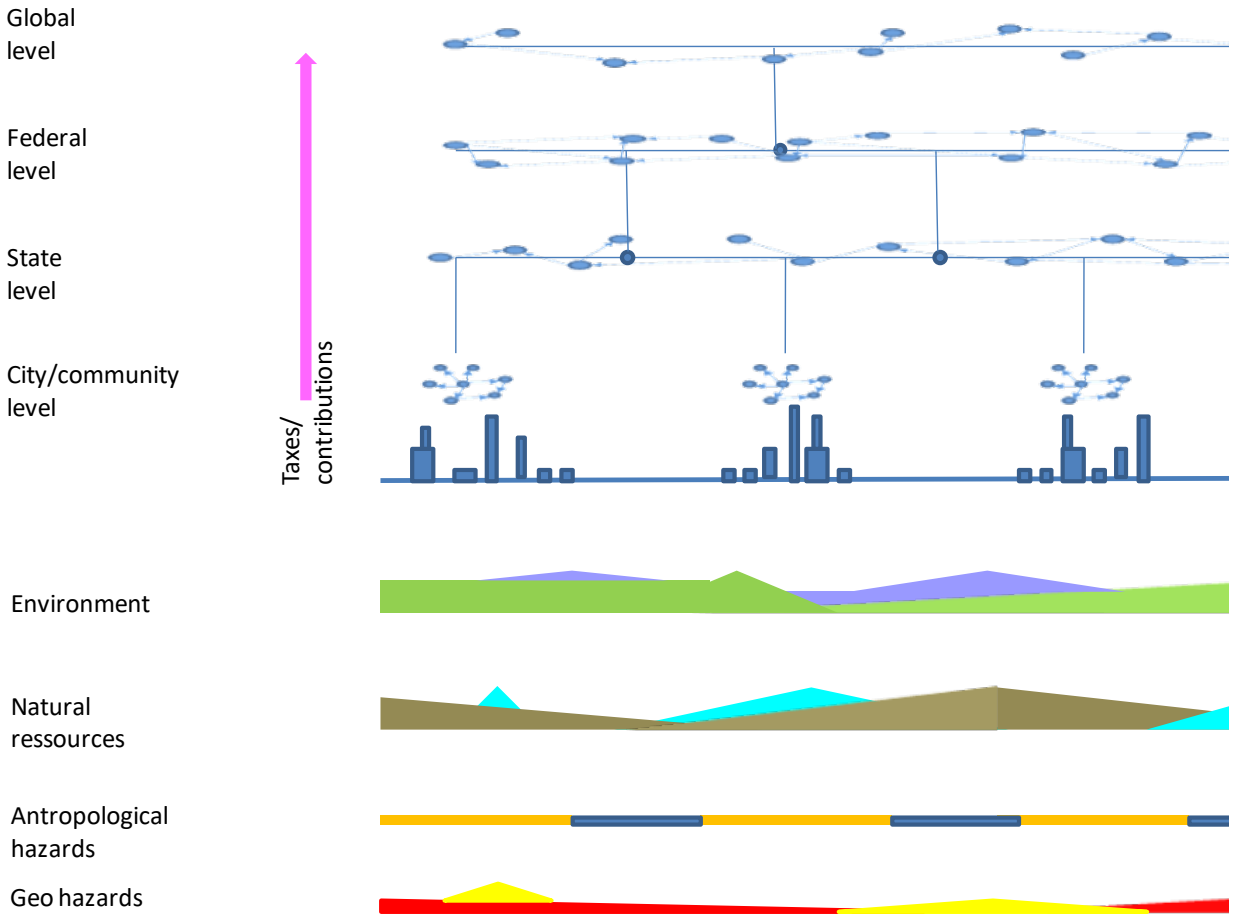
Optimal balance between sustainability/efficiency and resilience

Calibration of and fulfillment of performance criteria with respect to environmental impacts, Planetary Boundaries, safety and economy

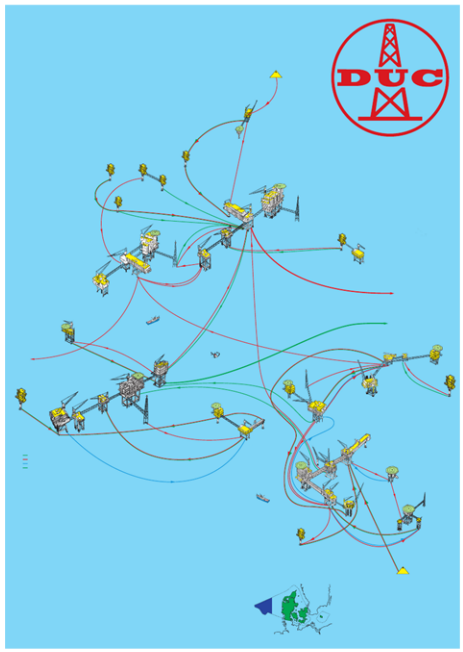
Options for buying information and changing strategies

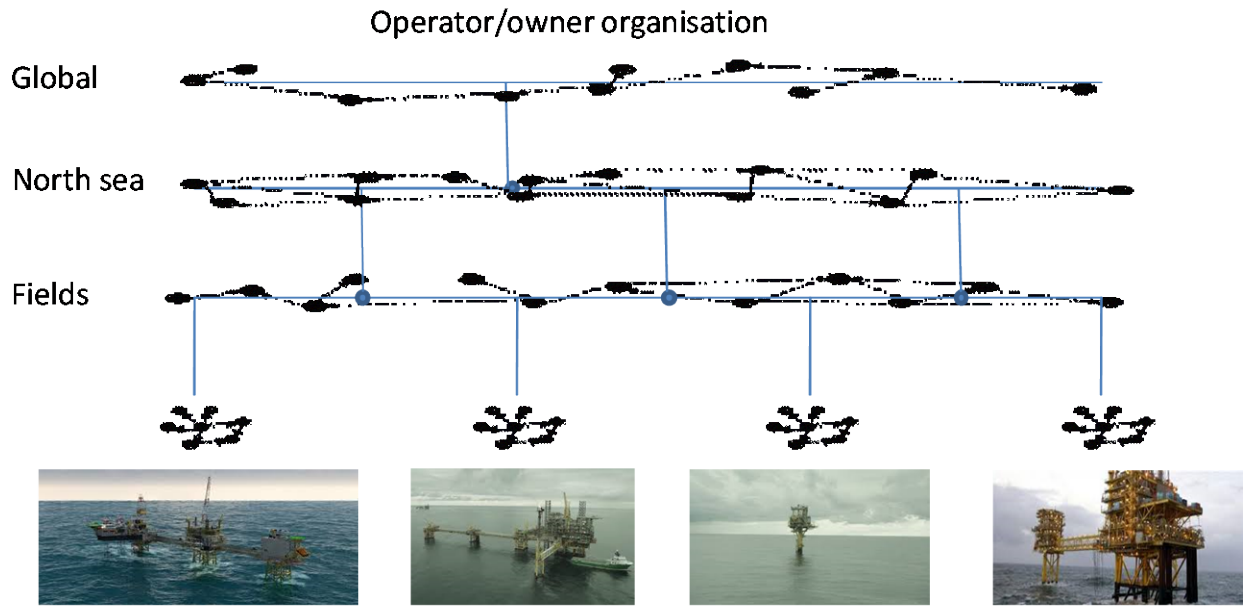
Additional data collection, monitoring and control

Decision Support Framework

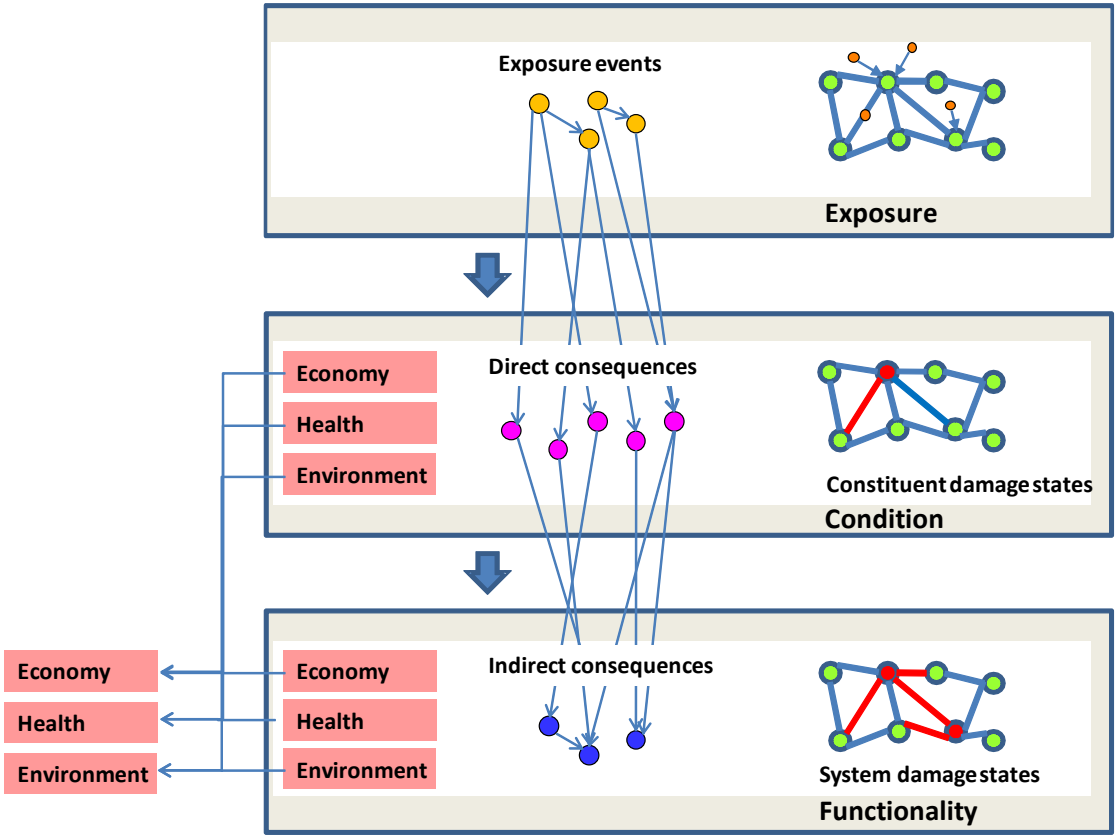


Decision Support Framework

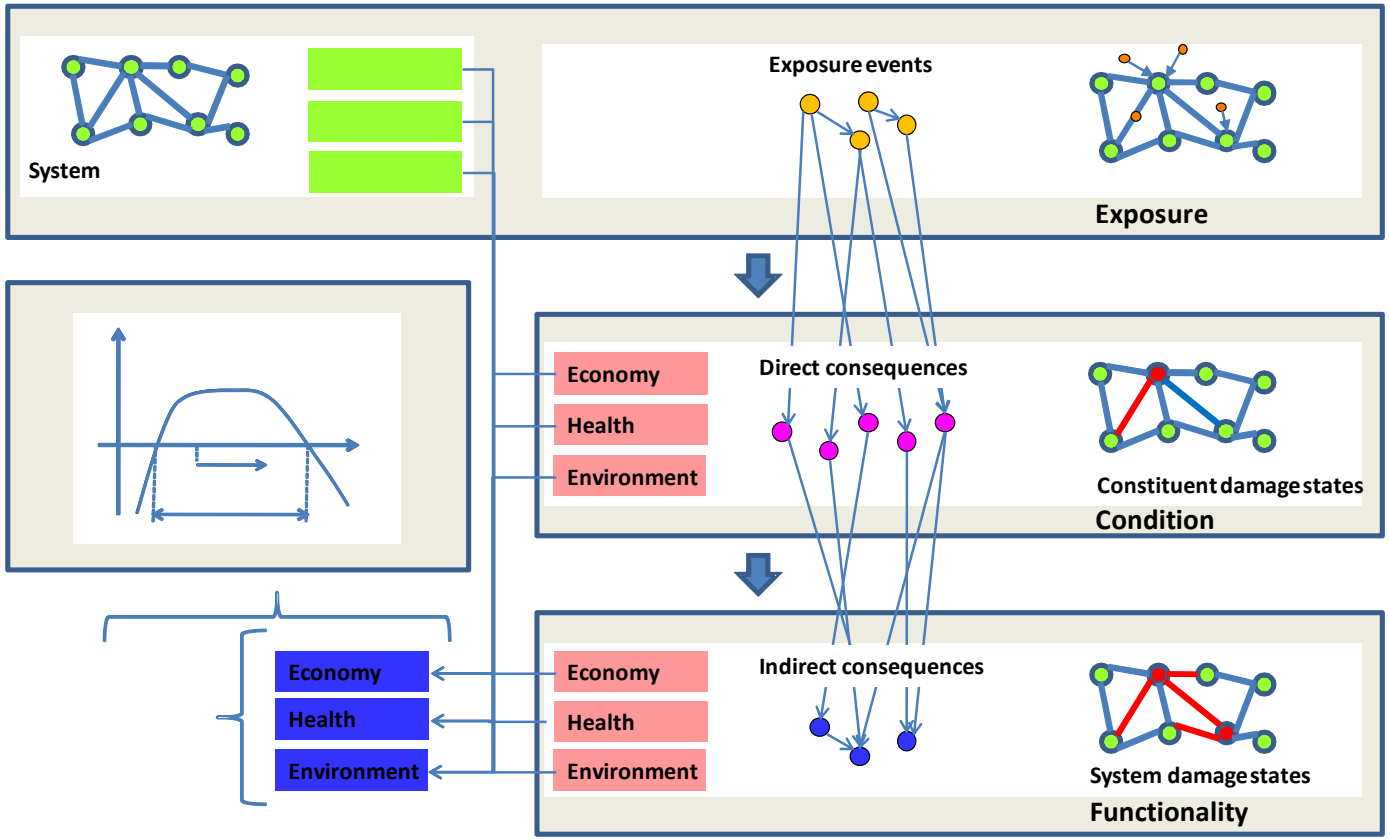




Decision Support Framework

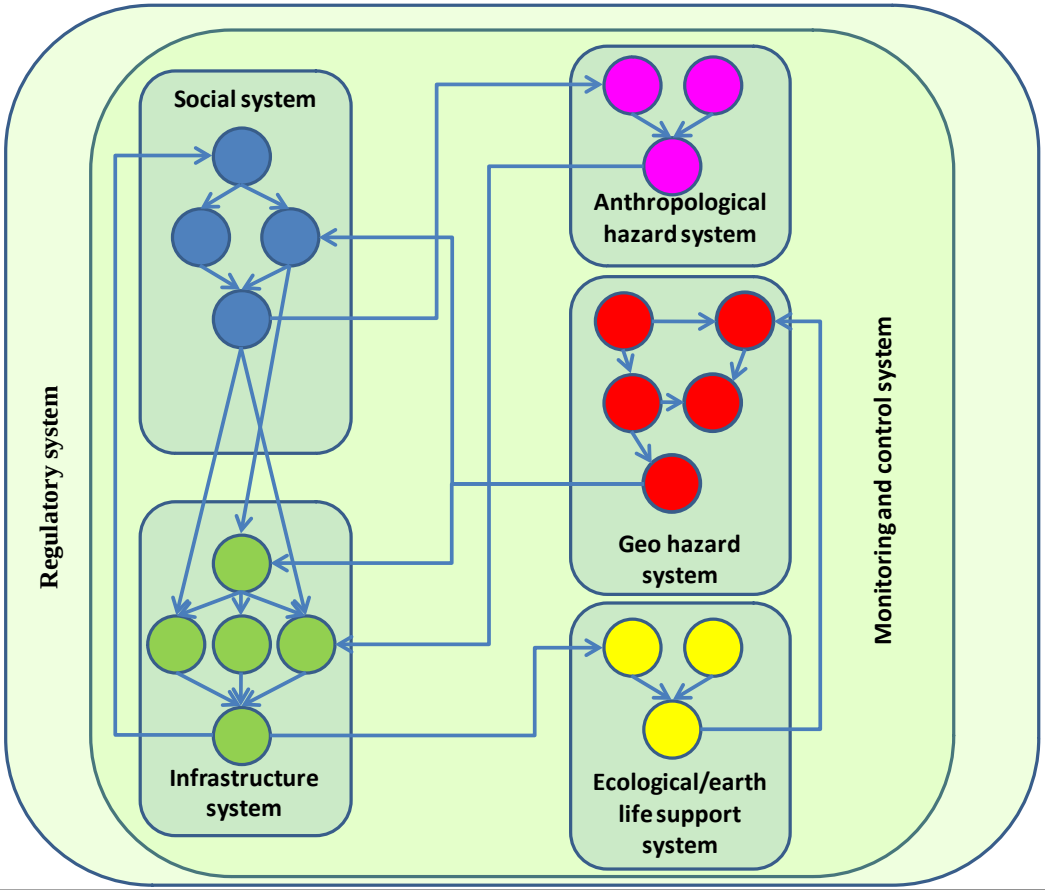


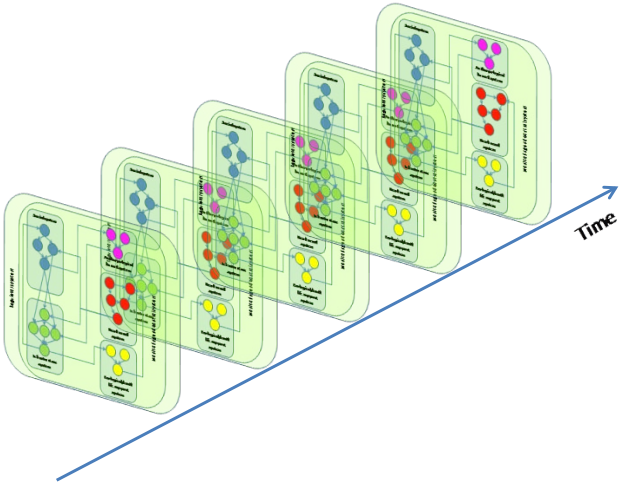
Decision Support Framework



Probabilistic System Representation

Interlinked systems





Probabilistic System Representation

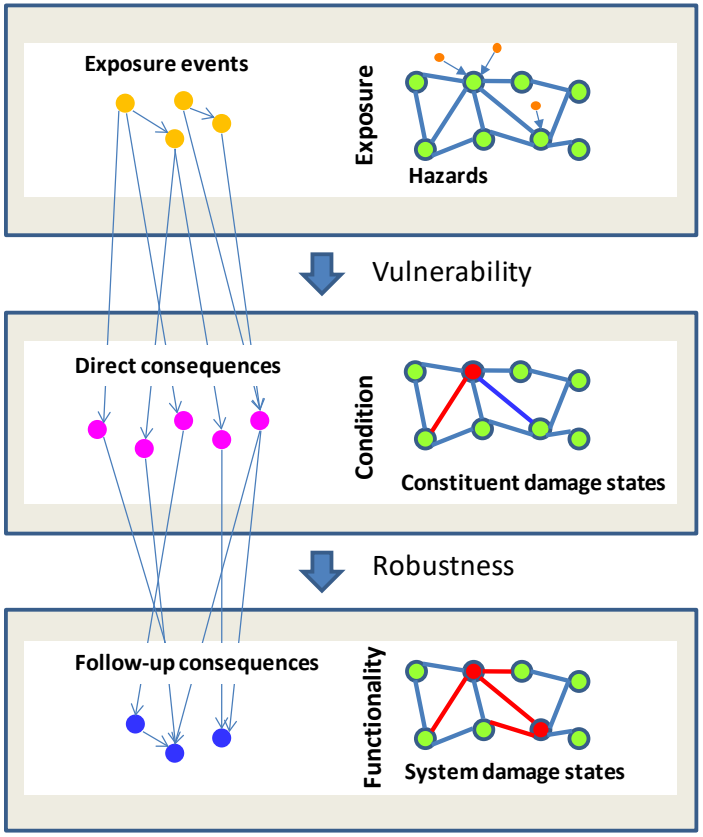
Hazards and disturbances

Type 1: “Large scale averaging events”
- low probability/high consequences

Type 2: “Seepage events”
- high probability/low consequences

Type 3: “Non-averaging events”
- low probability/extreme consequences

Type 4: ”Fake news events”
- as for Type 1-3

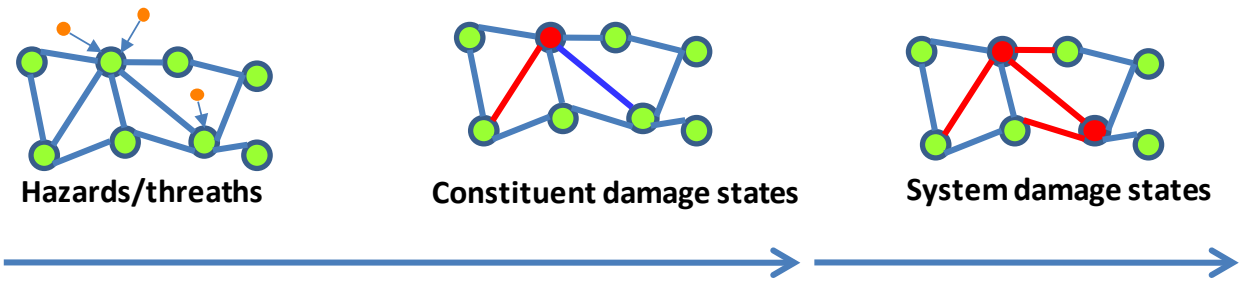


Probabilistic System Representation

Direct and indirect consequences

Phase 1
Disturbance effects

Phase 2
Redistribution effects



Damages and failure caused directly by disturbances

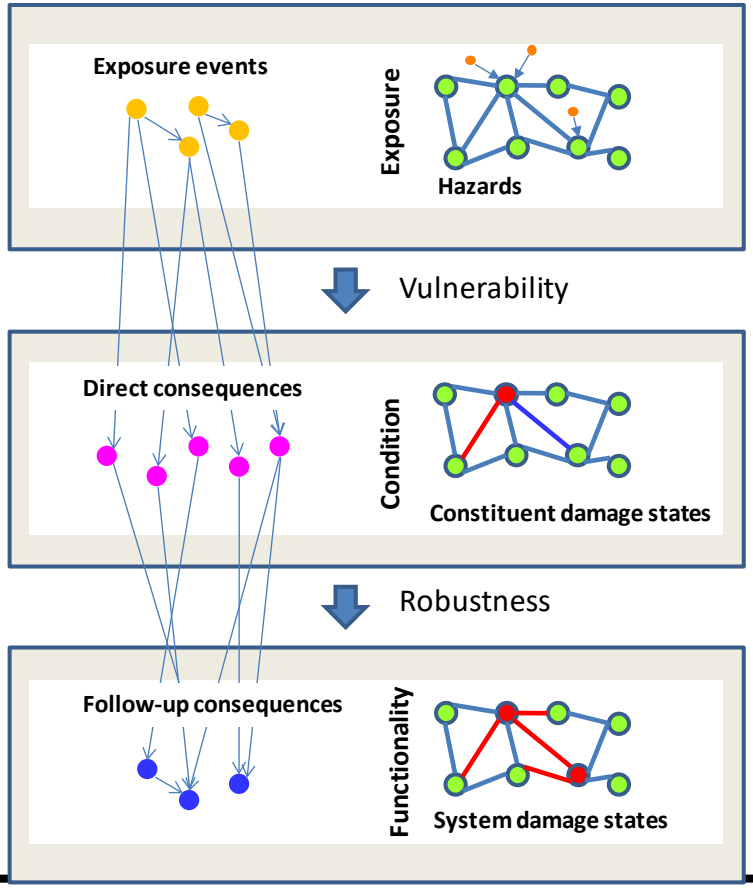
Damages and failures during internal redistribution

Direct consequences are associated with damages and failures of the constituents in phase 1 - marginally

Indirect consequences are associated with loss of functionality of the system caused by damages and failures in phase 1 and phase 2

Probabilistic System Representation

Robustness modeling



It is assumed that all relevant scenarios have been identified

$$\mathbf{S} = (i, p(i), c_{D,I}(i), c_{D,P}(i), c_{ID}(i)))$$

$$i = 1, 2, .., n_s$$

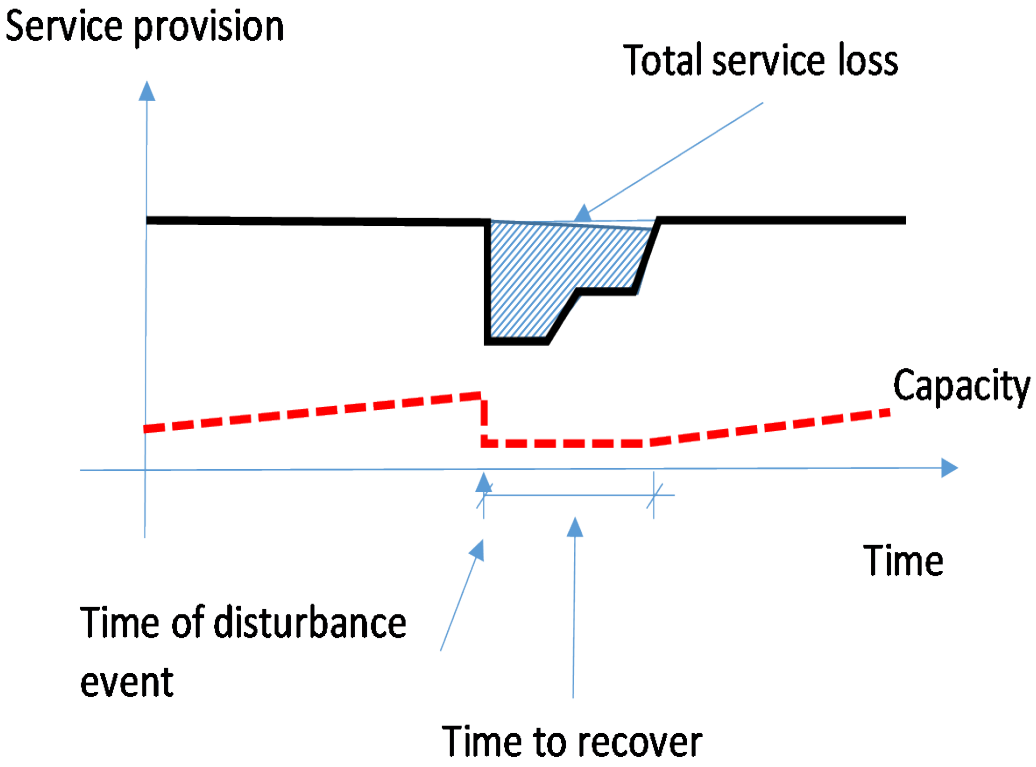
$$I_R(i) = \frac{c_D(i)}{c_T(i)}$$

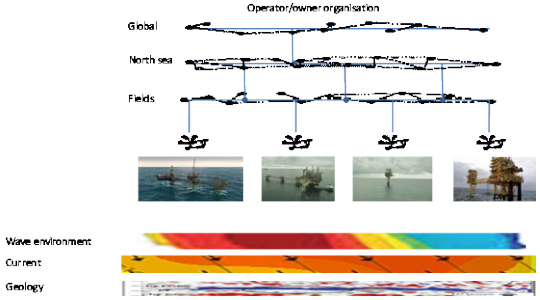
$$I_R(i) = \frac{c_{D,I}(i)}{c_{D,I}(i) + c_{D,P}(i)}$$

$$I_R(i) = \frac{c_{D,I}(i) + c_{D,P}(i)}{c_{D,I}(i) + c_{D,P}(i) + c_{ID}(i)}$$

Probabilistic System Representation

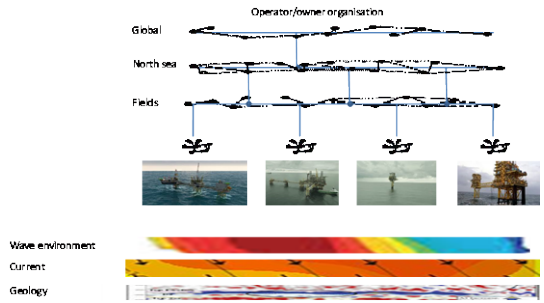
Probabilistic resilience modeling

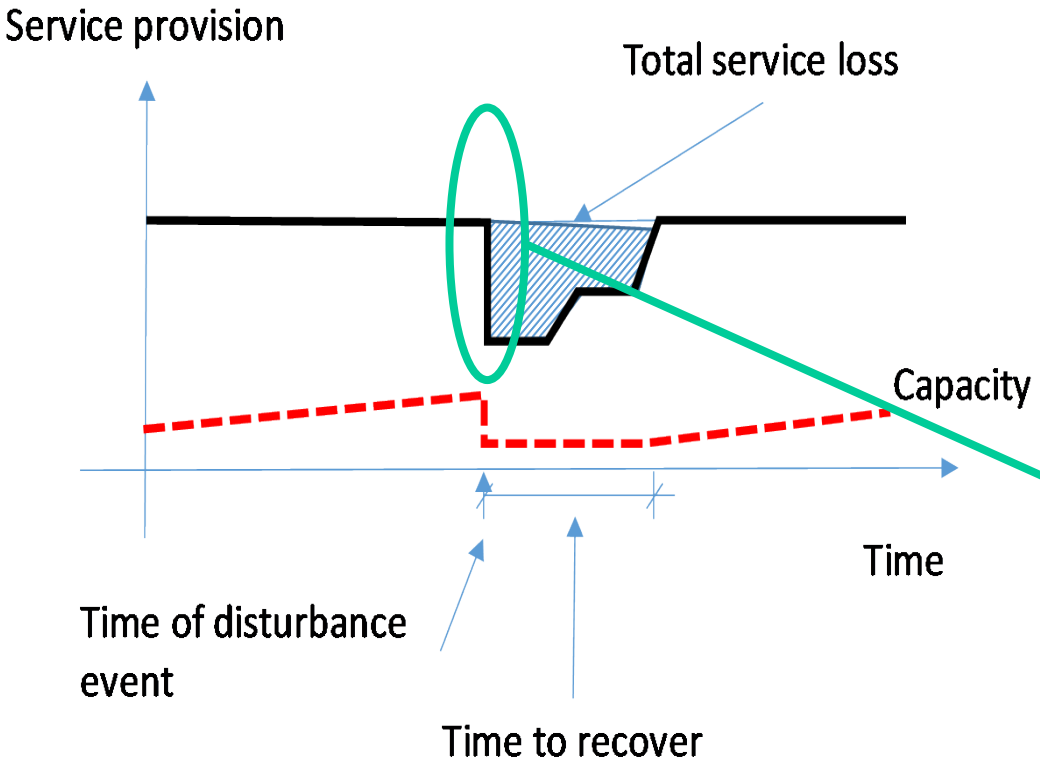




Probabilistic System Representation

Probabilistic resilience modeling

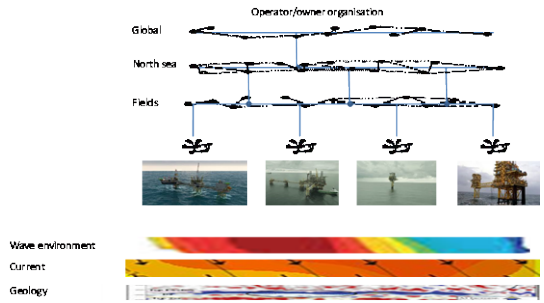


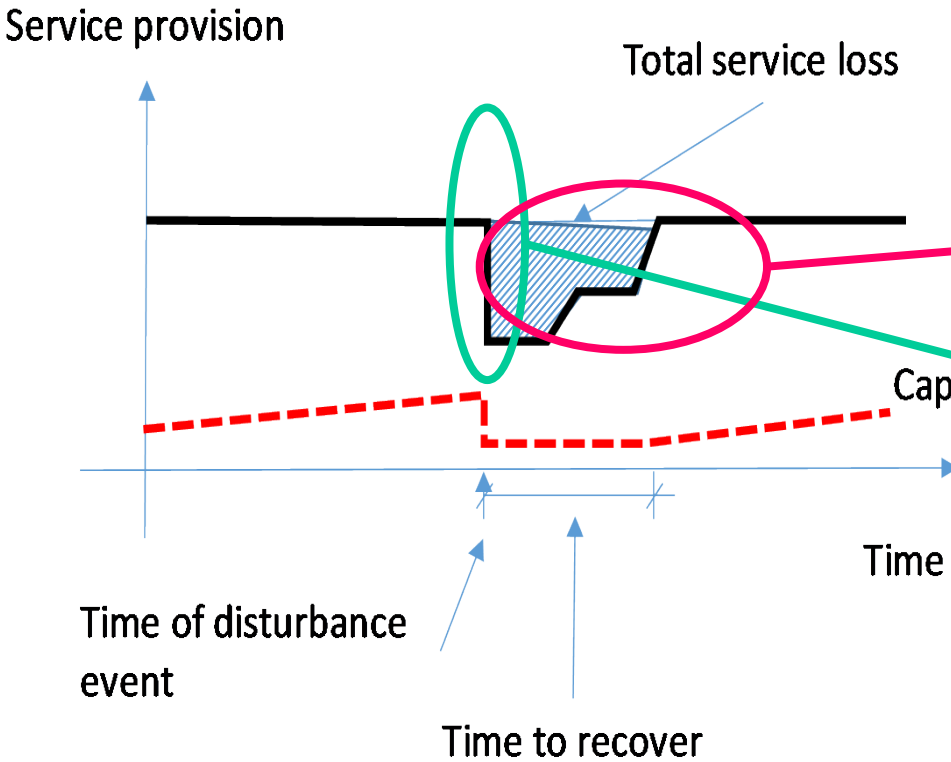


Robustness

Probabilistic System Representation

Probabilistic resilience modeling





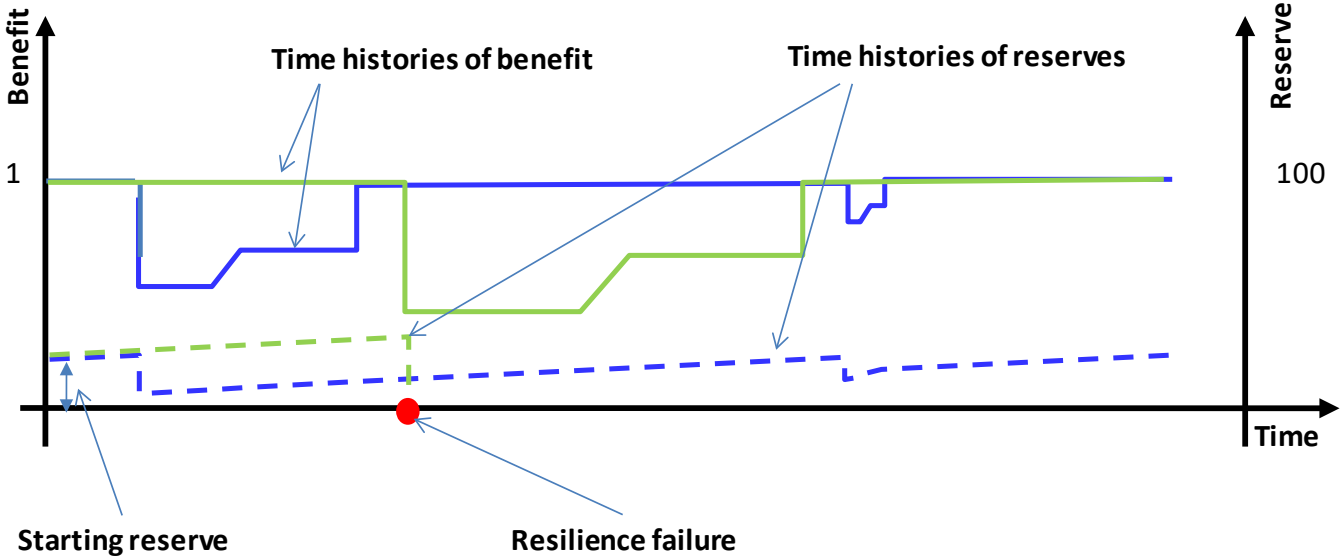
Preparedness, adaptive capasity

Robustness

Faber M. Risk Informed Structural Systems Integrity Management: A Decision Analytical Perspective. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 9: Offshore Geotechnics; Torgeir Moan Honoring Symposium ():V009T12A040. doi:10.1115/OMAE2017-62715.

Probabilistic System Representation

Resilience modeling



$$f_f(t) = \lim_{\Delta t \to 0} \frac{P(\{R(\tau) > S(\tau) \forall \tau \in [0,t[\} \cap \{R(t+\Delta t) \le S(t+\Delta t)\})}{\Delta t}$$

Probabilistic System Representation

Consequences to health, environment and economy

Impacts to health and safety are addressed through the relative utility function comprised by the Life Quality Index (LQI) (Nathwani et al, 1997)

Impacts to the environment are addressed through:
- Quantitative Life Cycle Analysis (substances/energy) (Hauschild, 2015)
- Eco-system services (space/landscape/capacities) (Constanza et al, 1997)

Impacts to the economy are addressed through:
- Monetary benefits (production functions)
- Monetary losses (production functions)

Probabilistic System Representation

Life Quality Index

The LQI can be expressed as:

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

w is the fraction of life allocated for working

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

Societal Willingness To Pay:

$$SWTP = \frac{g}{q}\frac{de_d}{e_d}$$

$$\approx \frac{g}{q} C_x dm = G_x dm$$

Societal Value of a Statistical Life:

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

Probabilistic System Representation

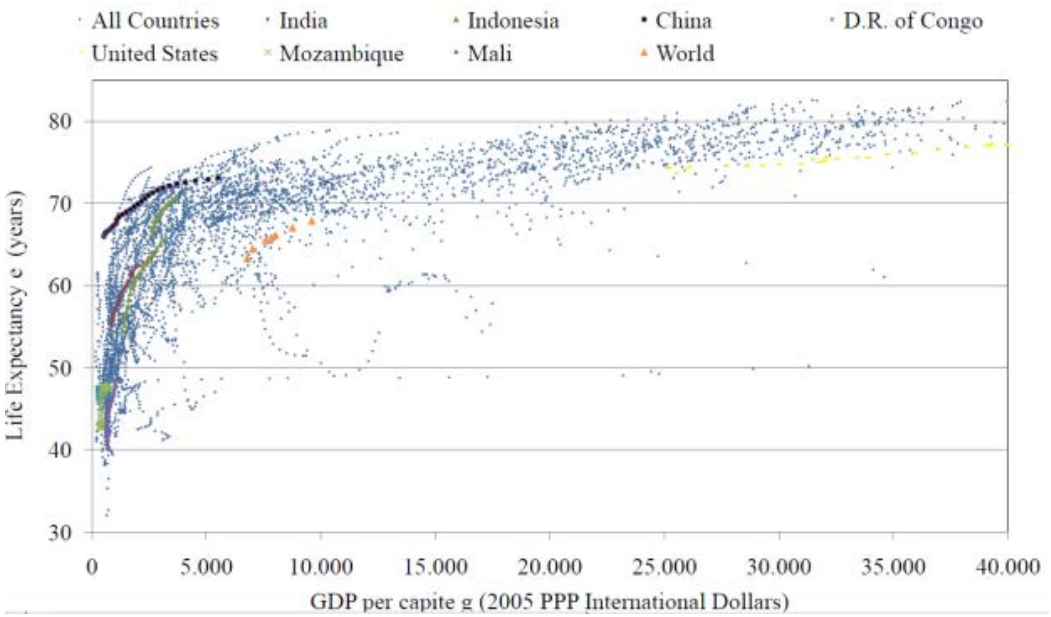
Life quality index

Coherence to the LQI principle can be assessed empirically by (Kübler and Faber (2005)):

$$I = g^{q} \boxed{g_0^{-q} I_0}$$

Regression constant

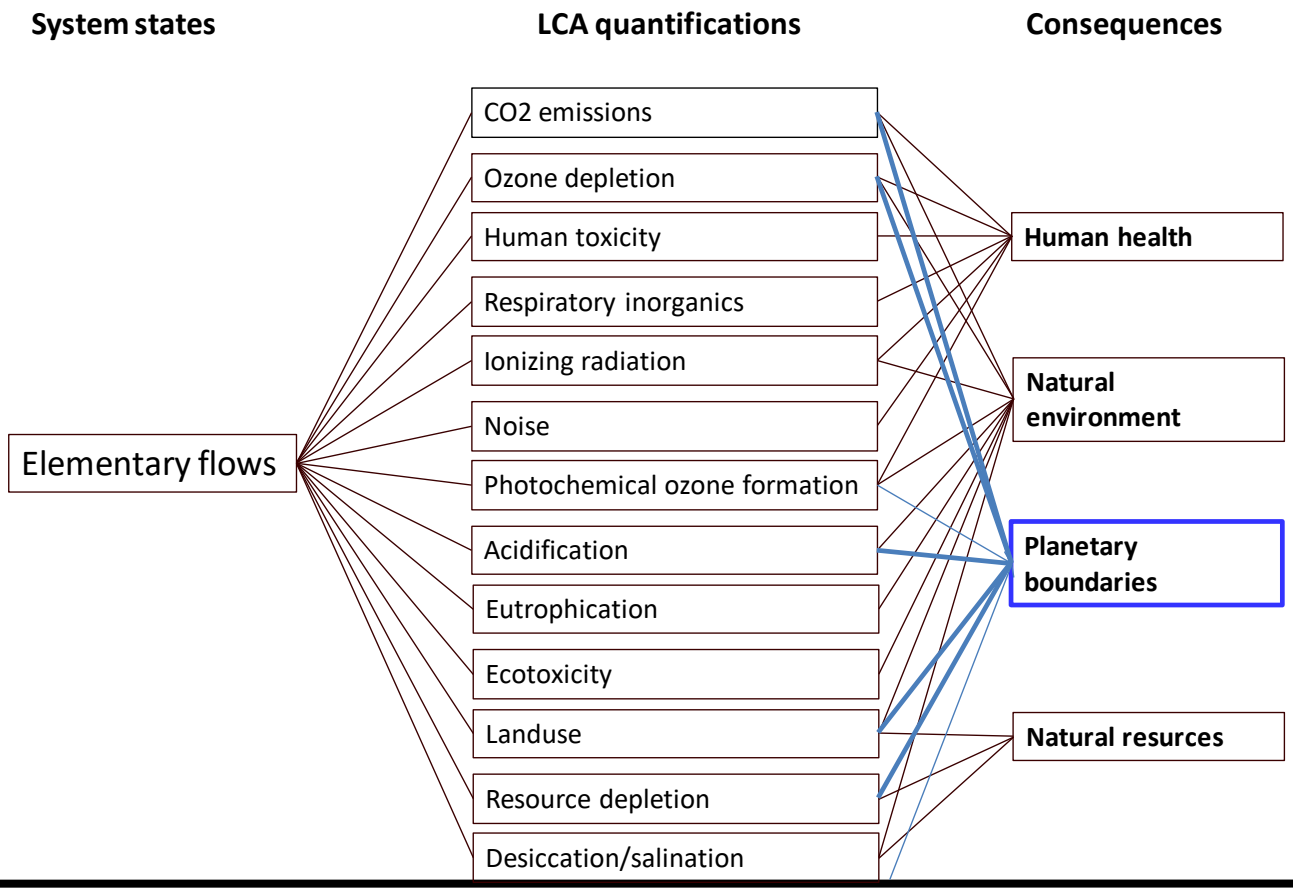
Data from 193 nations is collected and analyzed



71 nations corresponding to 70 % of the Earth's population conform with the LQI

Probabilistic System Representation

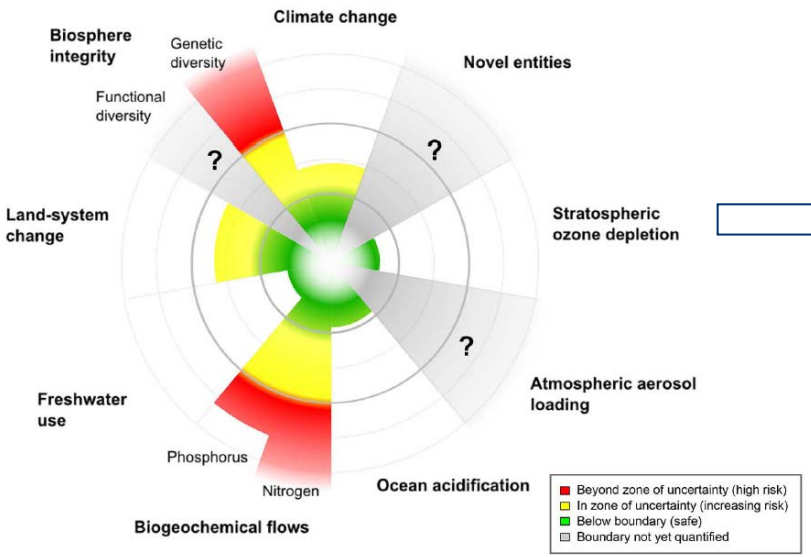
Matter book-keeping - Life Cycle Analysis (LCA)



Probabilistic System Representation

Sustainability modeling

Global Planetary Boundaries provide a means for allocating capacities to different societal activities



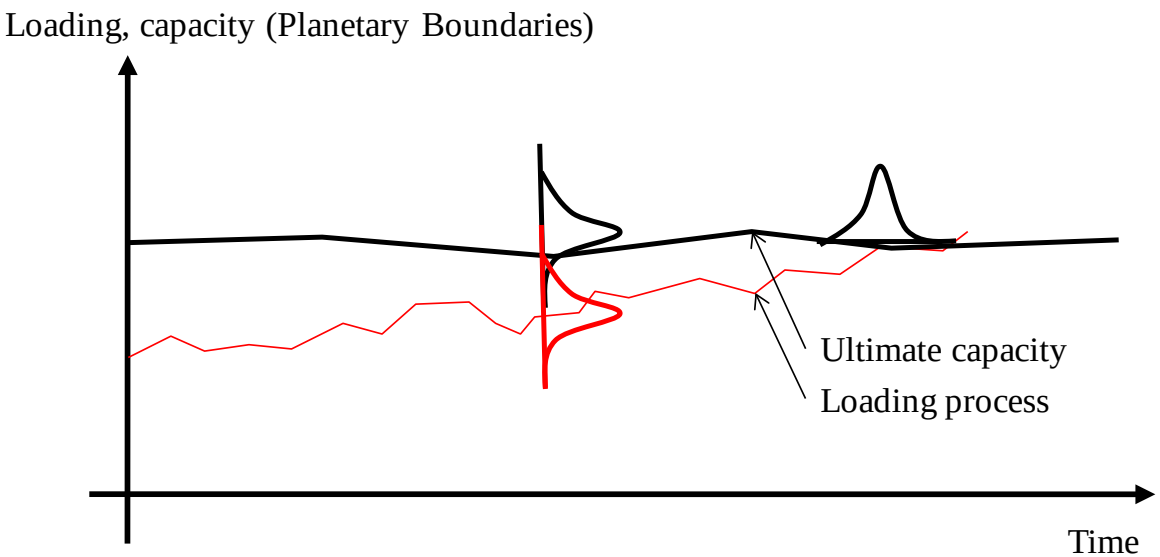
Local /national and sector wise allocation of capacities

- **Built environment**
- **Energy production and distribution**
- **Food production**
- **Transportation**
- **.....**
- **....**
- **...**
- **..**

Probabilistic System Representation

Sustainability modeling

For given sector, geographical area or project sustainability failure is expressed in terms of exceedance of Planetary Boundaries



$$f_f(t) = \lim_{\Delta t \to 0} \frac{P(\{R(\tau) > S(\tau) \forall \tau \in [0,t[\} \cap \{R(t+\Delta t) \le S(t+\Delta t)\})}{\Delta t}$$

Probabilistic System Representation

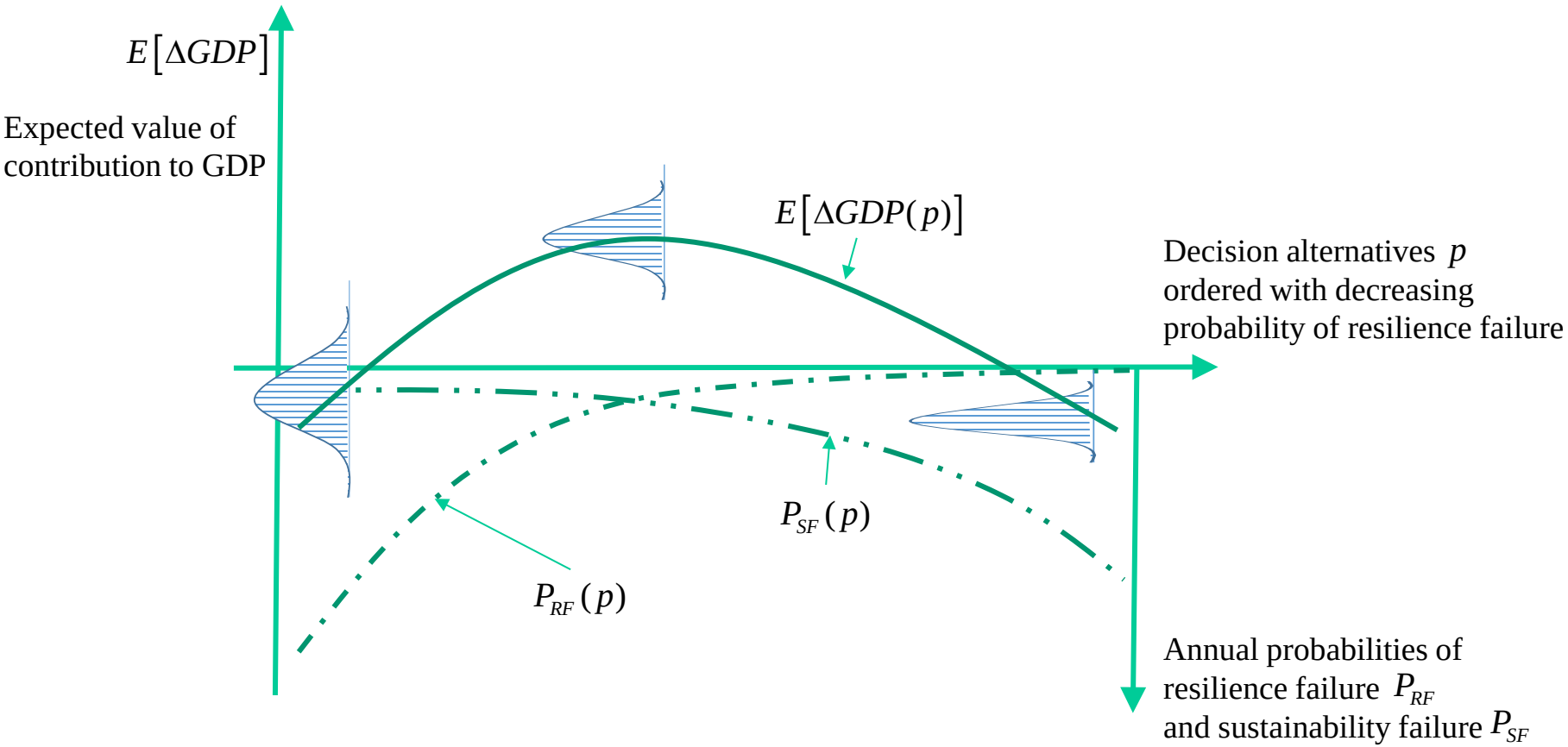
Engineered systems management

Maximize LQI

Constraints on:

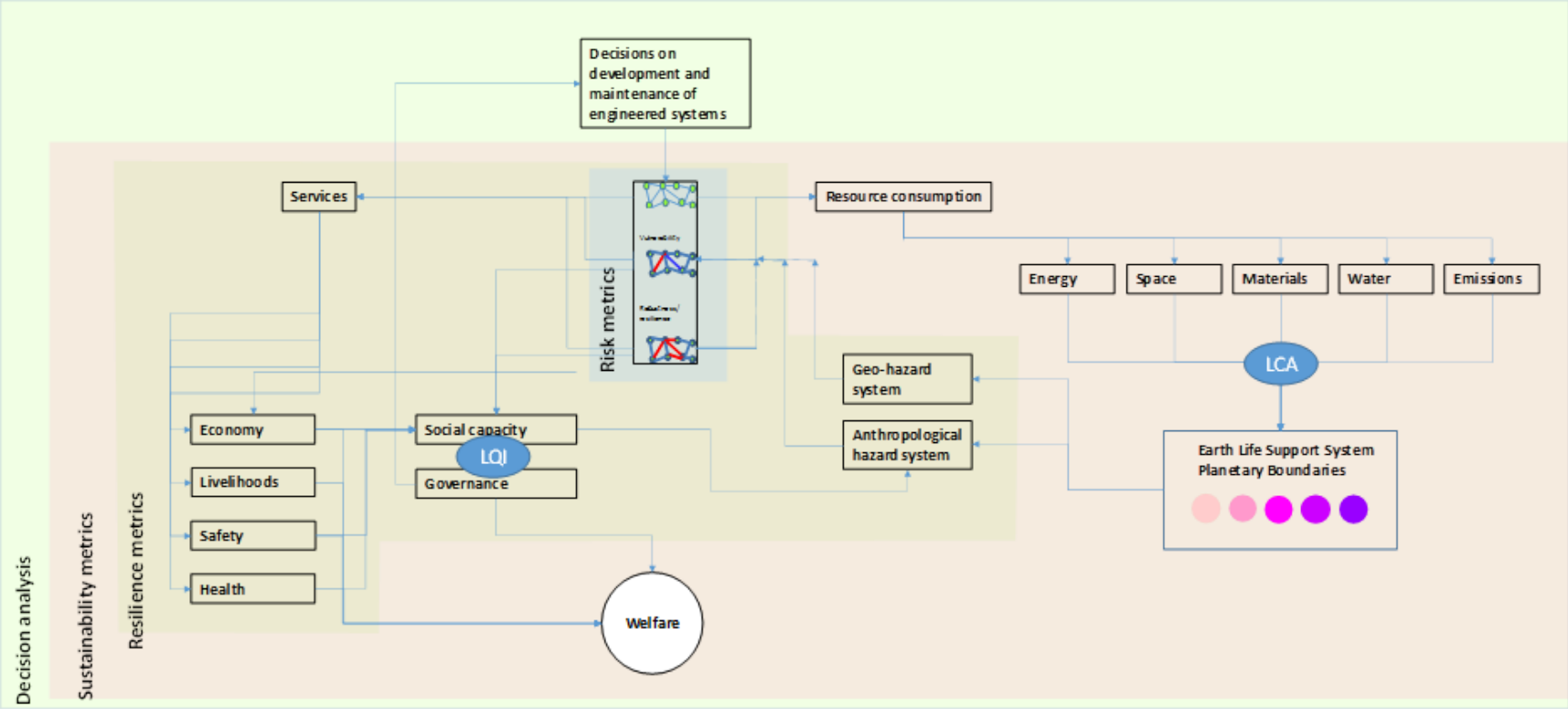
- annual resilience failure probability
- annual sustainabilty failure probability (LQI and ELSS)
- other requirements imposed wrt e.g. Inclusive Wealth Index

Probabilistic System Representation

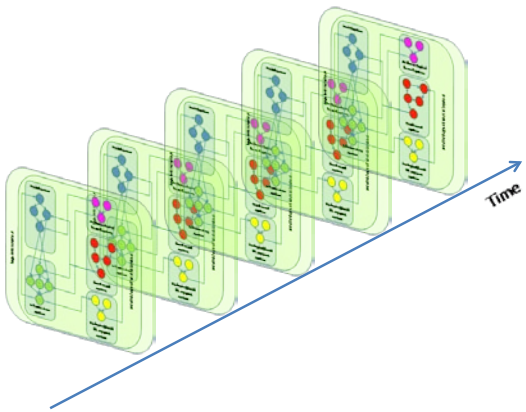


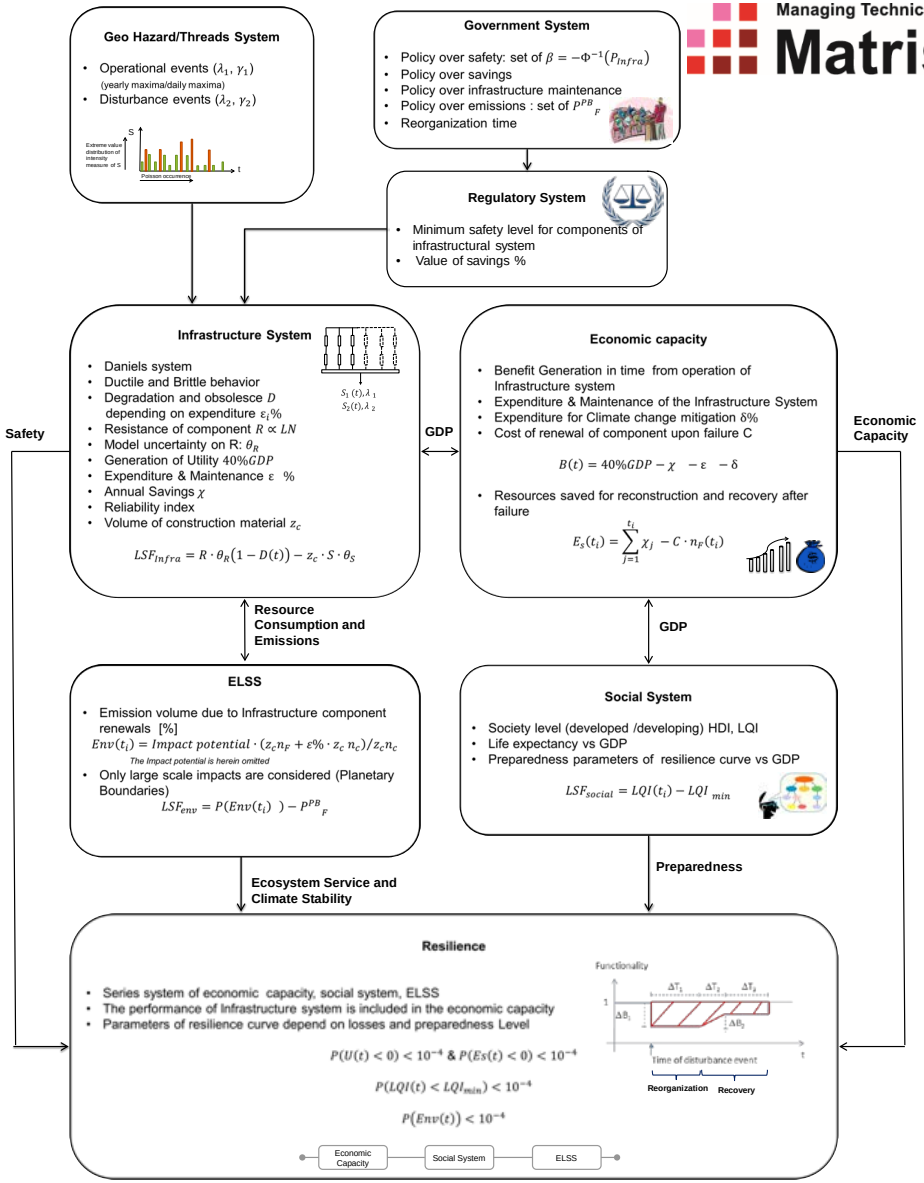
Probabilistic System Representation

Overall framework



Principal Examples





Faber, M. H., Qin, J., Miraglia, S. and Thöns, S. (2017) On the Probabilistic Characterization of Robustness and Resilience. Procedia Engineering, 2017.

Faber, MH, Miraglia, S, Qin, J and Stewart, MG Bridging Resilience and Sustainability – Decision Analysis for Design and Management of Infrastructure Systems, accepted for publication in Journal of Sustainable and Resilient Infrastructure 2017.

Conclusions and Outlook

Resilience and sustainability can be framed and quantified in the context of decision analysis

The LQI provides a strong means for representing societal preferences for “time” and societal developments

LCA and the Planetary Boundaries concept facilitate quantification of sustainability

Optimal systems management strategies can be identified accounting for political value settings (e.g. IWI)

Conclusions and Outlook

Sustainability as well as resilience at any scale necessitate preservation of stable living conditions – Earth Life Support functions

Resilience at global scale is equivalent to sustainability

Requirements to resilience and sustainability must be defined in probabilistic terms

There are quantifiable tradeoffs between sustainability/ efficiency and resilience

More research on these tradeoffs must be achieved in the nearer future to facilitate timely and informed societal decision making

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