Building scientific research perspectives: infrastructures of tomorrow for energy transition

IFSTTAR - December 4th 2018 Amphithéâtre Coriolis
Cité Descartes - Champs sur Marne

On Resilience Informed Decision Support for the Management of Systems

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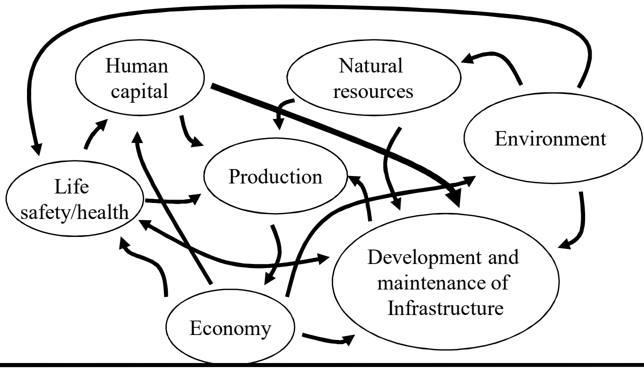
Risk
Reliabiliy
Resilience
Sustainability
Built
Environment

Setting the Scene

Infrastructure as part of society

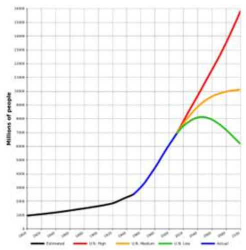
Infrastructures as part of the built environment play a crusial role for the existence and development of society



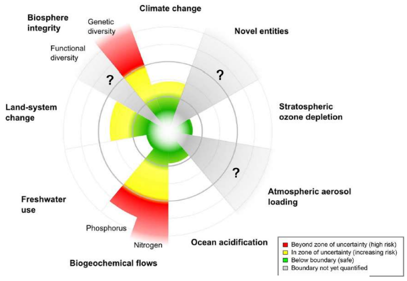
Setting the Scene

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

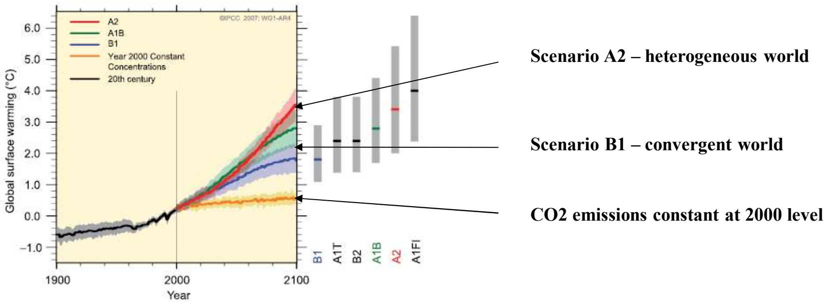


Planetary boundaries, Steffen *et al.* 2015[1]

Setting the Scene

Pressing boundaries for societal developments:

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

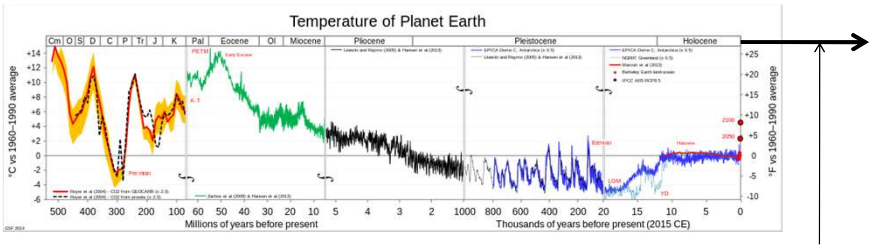


IPCC homepage

Setting the Scene

Pressing boundaries for societal developments:

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



Wikepedia

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

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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

Climate change/sustainability

McKinsey and Co Ltd

Contents of Presentation

Resilience/sustainability – some Definitions and Insights

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*

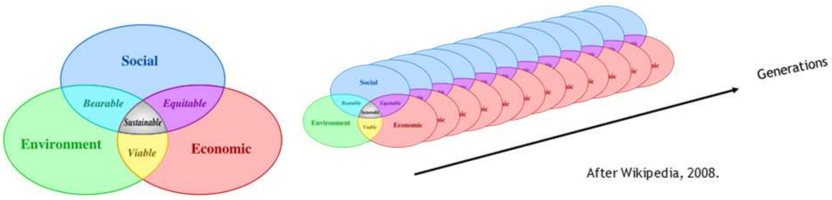
National Academy of Science (NAS, USA) - *Resilience….a systems ability to plan for, recover from and adapt to adverse events over time*

Resilience/sustainability – some Definitions and Insights

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*"



Resilience/sustainability – some Definitions and Insights

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.

Resilience/sustainability – some Definitions and Insights

Insights

Resilience at global scale is equivalent to sustainability

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

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

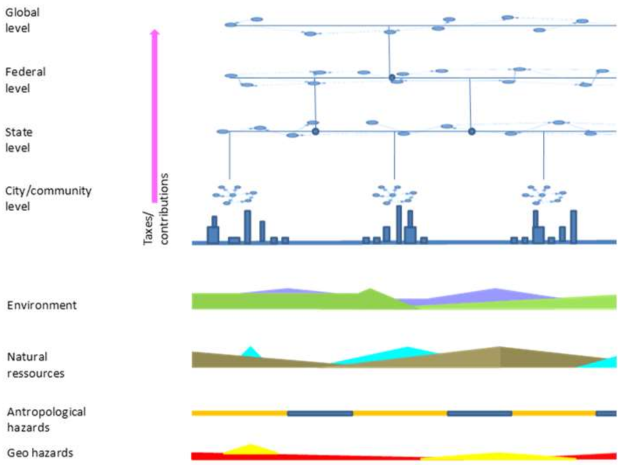
Infrastructures have a very significant environmental foot print and must be designed, operated and managed optimally with due consideration of the environment, safety and health and economy

Resilience/sustainability – some Definitions and Insights

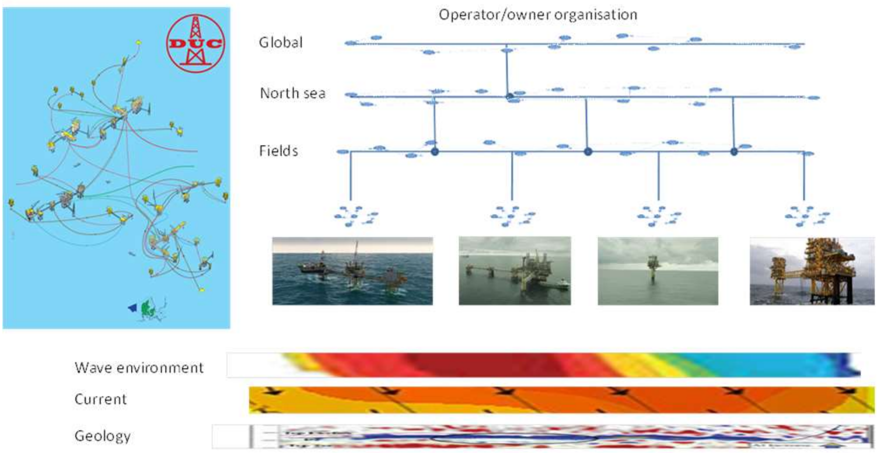
Strategies for sustainable and resilient systems

- Efficiency/optimality
- Diversity
- Redundancy
- Robustness
- Temporally optimized solutions
- Planned and smart renewals
- Optimal balance between 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

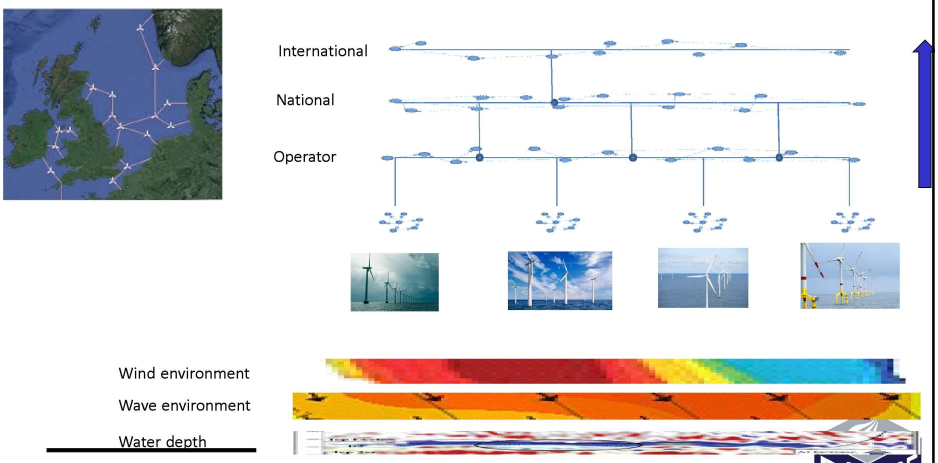


Decision Support Framework



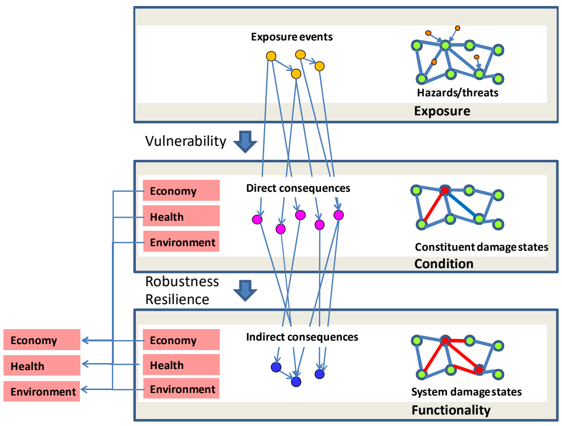
Decision Support Framework

Organizational hierarchical framework



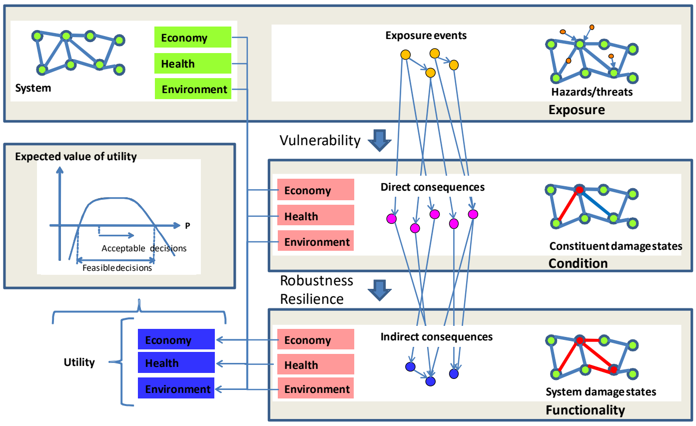
Decision Support Framework

The general framework (traditional)



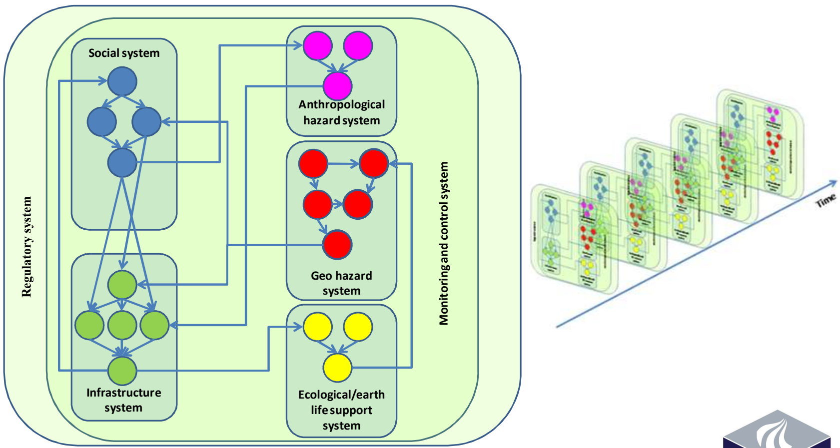
Decision Support Framework

The general framework (enhanced)



Probabilistic System Representation

Interlinked systems



Probabilistic System Representation

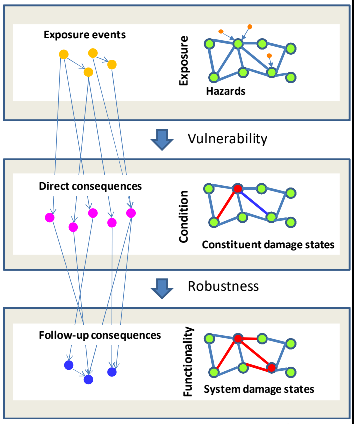
Hazards and disturbances

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: "Broken information"
- as for Type 1-3

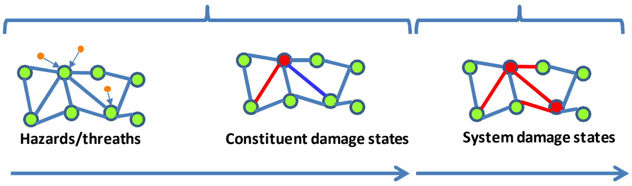


Probabilistic System Representation

Direct and indirect consequences

Phase 1
Disturbance effects

Phase 2
Redistribution effects



Damages and failure caused directly by disturbances

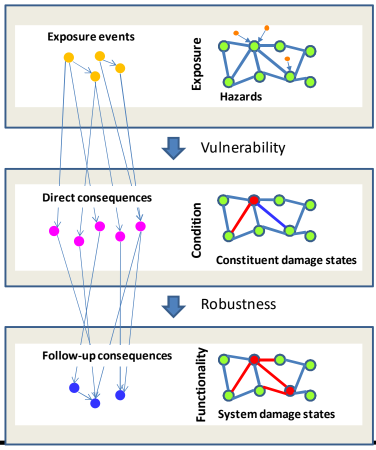
Damages and failures during internal redistribution

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

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

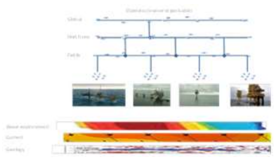
$$i = 1, 2, .., n_s$$

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

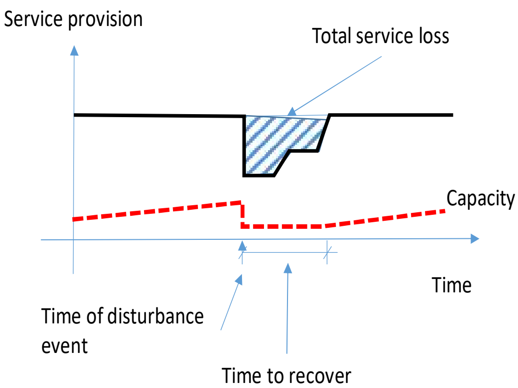
$$I_R(i) = \frac{c_{D,I}(i)}{c_{D,I}(i) + c_{D,P}(i)}$$

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

Probabilistic System Representation

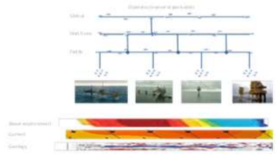


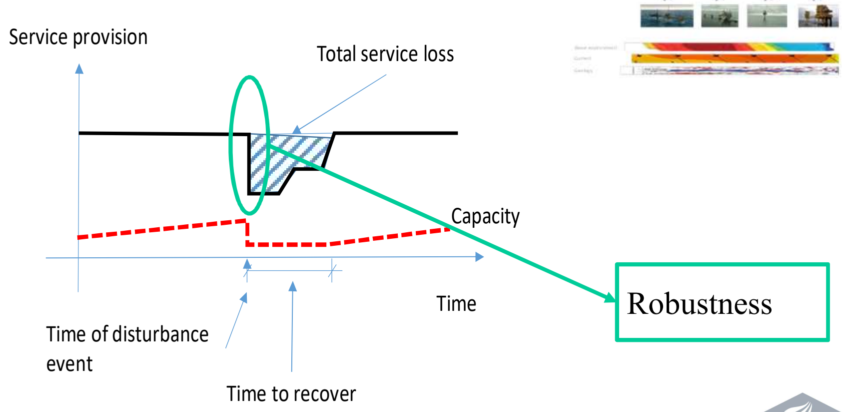
Probabilistic resilience modeling



Probabilistic System Representation

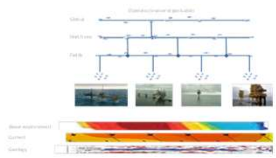
Probabilistic resilience modeling

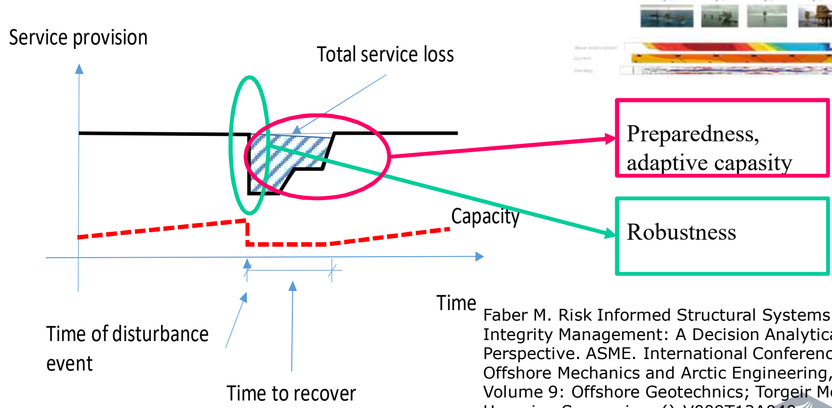




Probabilistic System Representation

Probabilistic resilience modeling

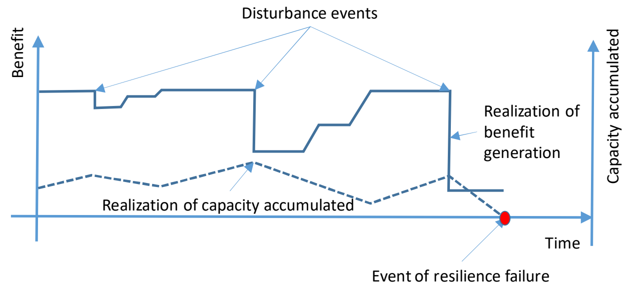




Faber M. Risk Informed Structural Systems Integrity Management: A Decision Analytical Perspective. ASME. International Conference on Offshore Mechanics and Arctic Engineering, Volume 9: Offshore Geotechnics; Torgeir Moan Honoring Symposium ():V009T12A040. doi:10.1115/OMAE2017-62715.

Probabilistic System Representation

Resilience modeling



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

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)

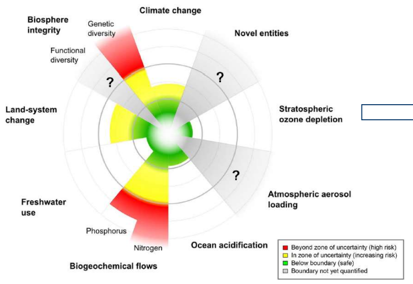
Impacts to the environment are addressed through:
- Quantitative Life Cycle Analysis (substances/energy) (Hauschild, 2015)

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

Probabilistic System Representation

Sustainability modeling

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

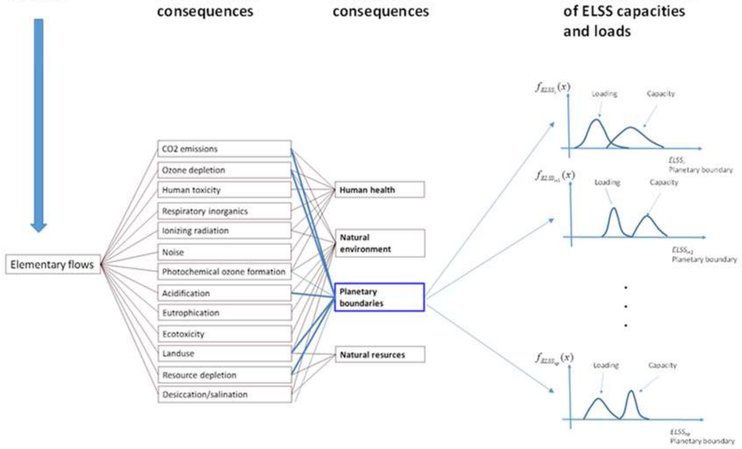


Local /national and sector wise allocation of capacities

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

Probabilistic System Representation

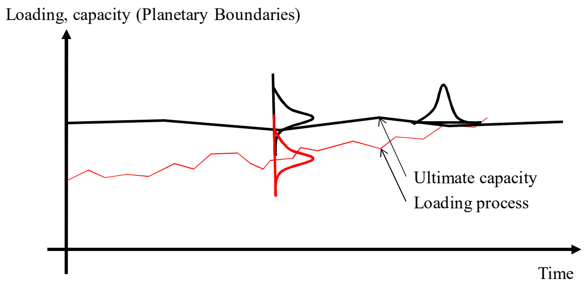
Decision | Differentiated consequences | Categorized consequences | Probabilistic model of ELSS capacities and loads



Probabilistic System Representation

Sustainability modeling

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



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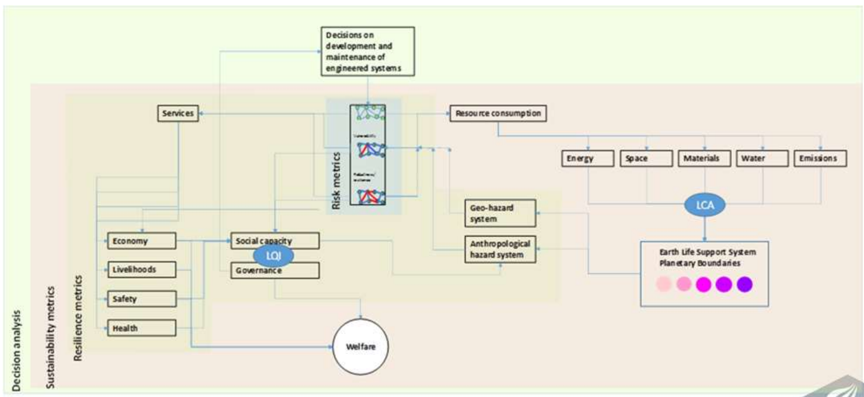
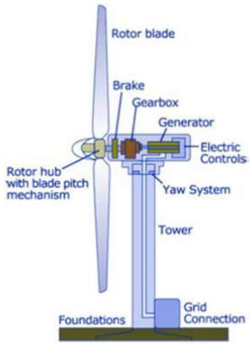
Probabilistic System Representation

Overall framework



Resilience of Wind Turbine Park

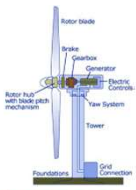
Example – wind turbine park with 10 identical WT’s

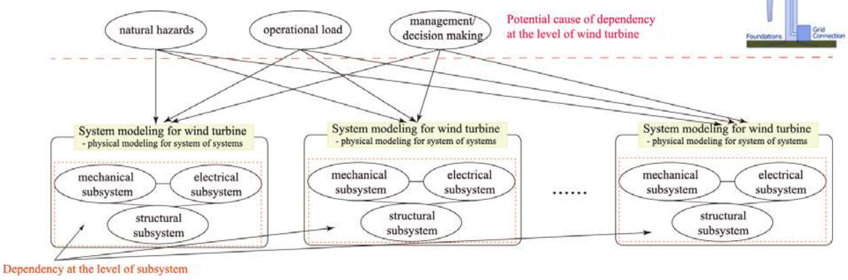


Qin, J. and Faber, Resilience Modeling and Management of Wind Turbine Parks, IFIP W.G. 7.5, Reliability and Optimization of Structural Systems , Zurich, June 26-29, ETH Zurich, 2018.

Resilience of Wind Turbine Park

Probabilistic systems modeling





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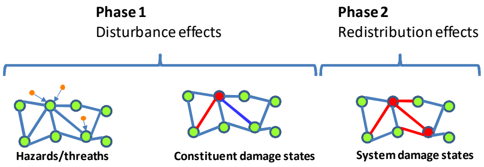
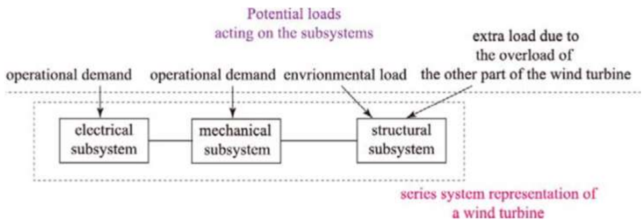
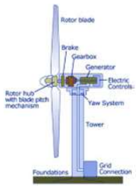
Resilience of Wind Turbine Park

Probabilistic systems modeling

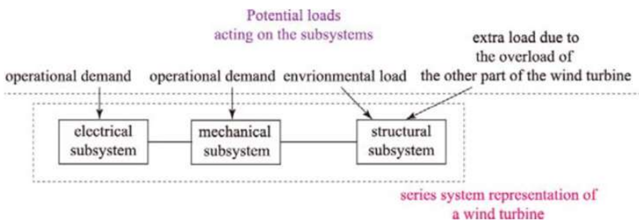


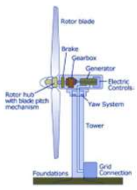




Resilience of Wind Turbine Park

Probabilistic systems modeling





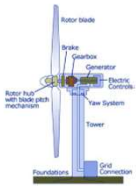
Structural subsystem

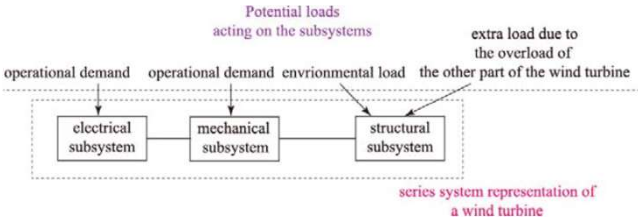
$$g_H = z_1 R_H - L_H$$

R_H : Log-Normal with expected value equal to 1, CoV equal to 0.3

Resilience of Wind Turbine Park

Probabilistic systems modeling





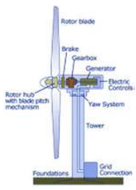
Structural subsystem

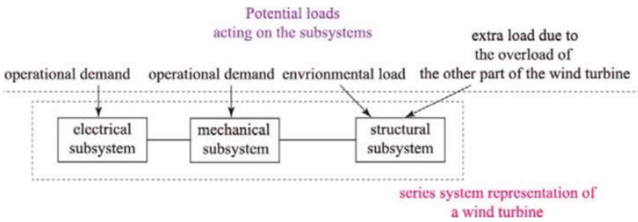
$$g_H = z_1 R_H - L_H$$

L_H : Wind loads on individual structures from storm events
Annual occurence rate of storms $\lambda_S = 3$
Intensity is Gumbel distributed, $\mu_{L_H} = 1$, $CoV_{L_H} = 0.4$
Correlation of wind loads on different structures ρLH = 0.8

Resilience of Wind Turbine Park

Probabilistic systems modeling





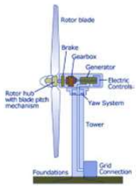
Structural subsystem

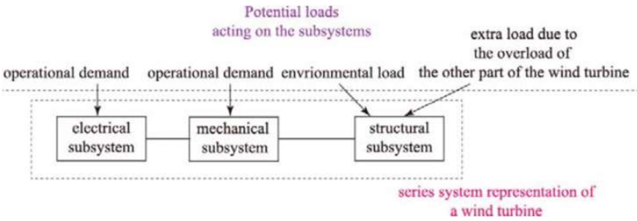
$$g_H = z_1 R_H - L_H$$

z_1 : Design parameter to calibrate structural reliability for individual structures to a given target value

Resilience of Wind Turbine Park

Probabilistic systems modeling



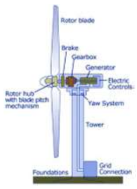


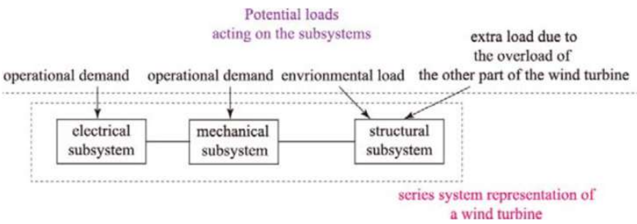
Structural subsystem

Target level of design	Reliability calibration to environmental load: Probability of failure due to environmental load $\Pr(g_H < 0)$	Reliability calibration to environmental load: z_1	Conditional failure probability of the structural subsystem given the failure of the electrical subsystem or the mechanical subsystem of the same wind turbine
High target level	1.1×10^{-3}	3.5	0.1
Low target level	1.2×10^{-2}	2.5	0.3

Resilience of Wind Turbine Park

Probabilistic systems modeling





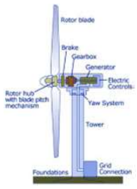
Electrical/mechanical subsystems

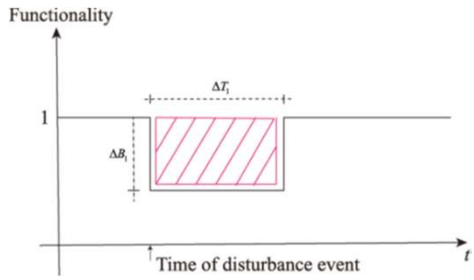
Mean time to failures (hours)

Target level of design	Electrical subsystem	Mechanical subsystem
High target level	450643	1236712
Low target level	25708	90472

Resilience of Wind Turbine Park

Consequence modeling

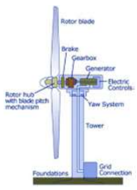


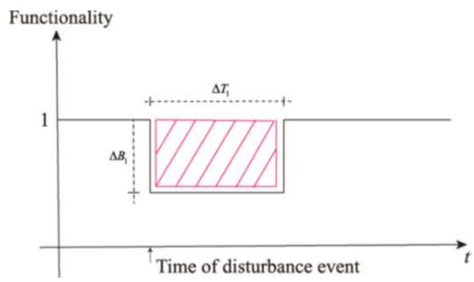


Variable	Distribution	Low preparedness				High preparedness			
		Expected value			COV	Expected value			COV
		Structural subsystem	Electrical subsystem	Mechanical Subsystem		Structural subsystem	Electrical subsystem	Mechanical subsystem	
ΔT_1	log-normal	ΔB_1	$\Delta B_1 / 3$	$\Delta B_1 / 3$	0.2	$\Delta B_1 / 2$	$\Delta B_1 / 6$	$\Delta B_1 / 6$	0.1

Resilience of Wind Turbine Park

Consequence modeling

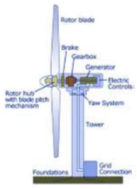


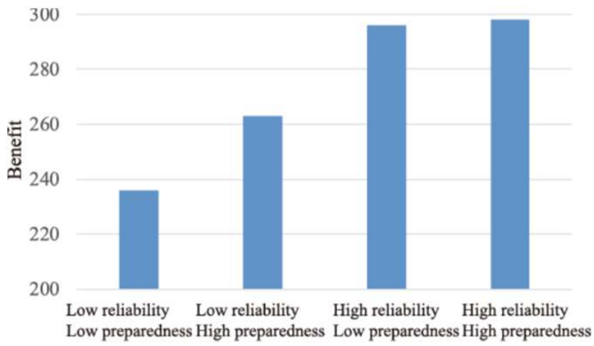


Type of subsystems	Replacement cost
Electrical subsystem	0.6
Mechanical subsystem	0.4
Structural subsystem	2

Resilience of Wind Turbine Park

Results – service life benefits

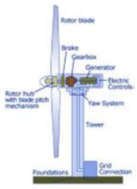


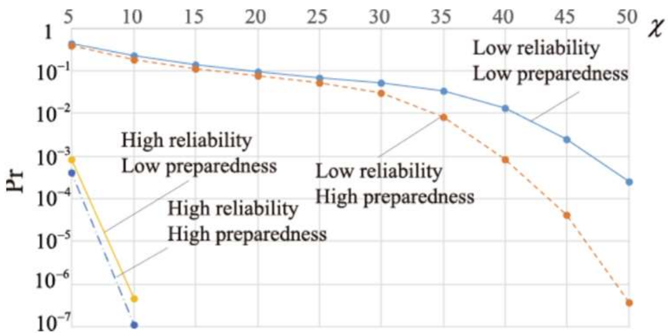


Expected value of accumulated benefits over 30 years service life

Resilience of Wind Turbine Park

Results – resilience performance





Service life probability of resilience failure as function of capacity saving strategy (χ %)

Conclusions and Outlook

The proposed approach facilitates that in principle any system may be assessed with respect to optimality, risks, robustness, resilience and sustainability characteristics

The novelty and potential of the approach is that resilience and sustainability can be modelled and quantified probabilistically

The main idea is to model resilience/sustainability failure as the event that a capacity of the system is exhausted

There is still a lot of challenges to address – not least on systems modeling - we are now applying the approach to systems of different scales and contexts – and would be very happy for collaborations

Building scientific research perspectives: infrastructures of tomorrow for energy transition

IFSTTAR - December 4th 2018 Amphithéâtre Coriolis
Cité Descartes - Champs sur Marne

Thanks for your attention ☺

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Risk
Reliabiliy
Resilience
Sustainability
Built
Environment