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On sustainability and resilience of engineered systems

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3.1 Introduction

Scientists increasingly apply the term “anthroposphere” to highlight that the present geological era is significantly shaped by human activities. Exponential population growth, technological developments and industrialization have reached a state where the interactions between human enterprise, the Earth system at global scale and the environment at local scales harmfully affect the conditions for future societal developments. Scarcity of natural resources, arable and inhabitable land, drinking water and threats to livelihoods in general, are progressively affecting societal developments – with social unrest and migration as a consequence. Emissions from human activities to the environment are broadly recognized to adversely affect the geology and biosphere of the Earth system itself and thereby in several ways, including global climate change, affect the very same living conditions facilitating human civilization as we know it today. At the scales of regions and cities, pollution of air, drinking water and soil, substantially impairing welfare, health and livelihoods for present and future generations is not only a threat but already a reality for millions of people. Failure to achieve and maintain sustainable societal developments, a global catastrophic risk (Faber 2011), must be taken seriously at all levels of societal decision making.

At the same time as society is directing focus on sustainable societal developments there is an increasing demand for improved public welfare, calling for enhanced efficiency and reliability in all activities of the free market as well as in public and private governance. Globalization and technological developments associated with an ever increasing volume and complexity of critical infrastructure, financial, industrial and market systems, on one hand enable meeting such demands; on the other hand they comprise a new challenge, namely the management of risks due to systems failures and possible cascading failures across systems. Such failures are associated with substantial consequences in terms of service provision losses. Over the last 1–2 decades significant research and development efforts have addressed this challenge through the concept of resilience, aiming to minimize risks associated with service disturbances and disruptions by means of an integral consideration of governance and technological measures.

Whereas sustainability addresses decision making for the management of adverse effects of human activities on the Earth system with derived consequences to welfare, resilience may be seen to address decision making for the management of adverse effects originating from the
Earth system and human activities on the functionalities of social institutions which facilitate welfare. It is thus evident that there is a strong coupling between sustainability and resilience, and that the two terms ultimately express the same mechanisms from two different perspectives, see also Figure 3.1.

However, the more precise character of the coupling between sustainability and resilience is as yet not fully understood in either theoretical or practical terms. Consequently, improved knowledge facilitating decision support for sustainable and resilient societal developments is a highly ranked topic on both the political and the academic agendas.

The present chapter addresses resilience and sustainability of interlinked human and natural systems in the context of providing decision support for societal developments. Based on earlier works of the author (Faber et al. 2017, 2018; Faber & Qin 2016), concepts of resilience and sustainability, and especially their interrelations, are addressed and explored in the context of providing decision support for societal developments.

Section 3.2 starts out with an abridged overview of central insights and ideas from the vast literature on resilience, sustainability and decision analysis, achieved over the past 3–4 decades in the fields of mathematics, economy, ecology and engineering. The purpose of this overview is to provide a basis for the development of a framework facilitating decision making with respect to resilient and sustainable societal developments. Section 3.3 provides a proposition for such a framework. To this end the recent concept of Planetary Boundaries forwarded in Rockström et al. (2009) and Steffen et al. (2015), together with the framework for systems risk modeling from Faber et al. (2007) and JCSS (2008) and the novel formulations of resilience and sustainability failure introduced in Faber et al. (2017) play important roles. The constituents of this framework are addressed in Section 3.4 with focus on the probabilistic representation of system characteristics, modeling of disturbances (or hazards/exposures) and modeling of consequences in different metrics in the particular context of sustainability and resilience. To this end the systems risk modeling framework proposed in JCSS (2008) is utilized and extended to represent the joint functionalities of interlinked systems, the characteristics of their performances with respect to disturbances and the multidimensional attributes and criteria associated with their performances. To accommodate for the utilization of the proposed framework for ranking of decision alternatives, a generic probabilistic representation of
possible system states associated with benefits and losses is provided. This modeling basis also facilitates for the representation and analysis of cascading system failures. To account for the impacts to the environment and health and safety originating from human activities such as land use, applied technology and the built environment, life cycle analysis (LCA) is introduced. Societal preferences for investments into health and life safety are accounted for through the marginal life saving principle and the Life Quality Index (Nathwani et al. 1997). Absolute limits for impacts to the environment are included in terms of limited budget constraints, derived using the concept of Planetary Boundaries (Rockström et al. 2009).

Finally, in Section 3.5 a short discussion and outlook is provided on practical challenges associated with resilient and sustainable societal developments and suggestions for future research and educational activities are summarized.

3.2 Abridged appraisal of knowledge developments in resilience, sustainability and decision analysis

During the last 3–4 decades substantial research efforts have been devoted to improving the understanding of resilience and sustainability of human and natural systems and decision analysis in support of societal developments. The following sections provide an abridged overview and discussion of these topics with the objective of providing a conceptual basis for supporting decisions on resilient and sustainable developments and management of interlinked human and natural systems.2

3.2.1 Developments in the area of resilience

Fundamental work on resilience is presented in Pimm (1984) and Holling (1996) in which resilience of ecological systems is associated with the ability of systems to sustain disturbances and the time it takes until systems recover to their original states of functionality after disturbances. It is highlighted that not only the strength characteristics of the systems with respect to disturbances are important but the capacity building; facilitating recovery from disturbances are of key significance. As underlined in Derissen et al. (2011), however, the actual state of operation of a resilient system is not necessarily desired; the Earth system as an example has in several prehistoric eras taken resilient states which did not accommodate for the existence of humans. In fact one system may possess several states of equilibrium which on an individual basis could be considered resilient, however, which may exhibit functional characteristics differing significantly with respect to associated benefits — for humans and societal developments.

In Holling (1996) it is argued that engineered or designed systems are fundamentally different from natural systems. Whereas natural systems, such as in the case of organisms relying on endothermy, tend to seek optima in the vicinity of instability points where the potential gain is the highest, engineered systems are generally optimized such that their normal mode of operation is far away from regions of instability. Natural systems as Holling (1996) explains, ensure safe operation through functional diversity, i.e. by means of a number of highly reliable and redundant mechanisms. Moreover, different strategists may be recognized in natural systems. Holling (1996) elaborates on the r- and K-strategists; r-strategists being simple, fast in replication, less efficient and short lived and K-strategists being more complex, slower in replication, more efficient and long lived. In the event of disturbances of ecological systems comprised by K-strategists it is not unusual to see the less specialized r-strategists multiplying and dominating the system after the disturbance. This domination lasts until a certain time has passed and the K-strategists, due to their higher efficiency, have had time to outcompete the
r-strategists. Considering engineered systems similar mechanisms may be recognized. When for instance infrastructure systems developed and optimized over time have been subject to major disturbances, it is normal to re-establish the most fundamental functionalities of the disturbed system by means of less expensive and short lived – interim – infrastructures. These then provide sufficient functionality at typically lower levels and less efficiently until efficient long term renewals may be put in place. Moreover, as described in Nishijima and Faber (2009) the choice between quantity and quantity (less expensive and less durable infrastructure versus more expensive and long lived; r- vs. K-strategist) engineered solutions for the development of infrastructure can be optimized in balance with the economic capacity of a society. In Nishijima and Faber (2009) the term quality covers the aggregate susceptibility to degradation and damage caused by, e.g. natural hazards, corrosion and fatigue.

Anderies et al. (2004) address resilience characteristics of interlinked ecological societal systems in general and in Anderies (2014) in particular the role of the built societal infrastructure is discussed from the perspective of optimal allocation of available resources for enhancing resilience. It is suggested that different strategies for enhancing resilience may be devised optimally in dependency of the magnitude and frequency of disturbances (e.g. earthquakes, floods and wind storms). It is interesting to note that such strategies indeed have been in place for many years in the area of civil engineering where design criteria have been developed and broadly applied for design of structures with respect to earthquake excitation not only as a function of frequency and intensity but also as a function of consequences. In Janssen and Anderies (2007) resilience characteristics of systems are related to their robustness characteristics and it is highlighted that these are strongly dependent, to an extent that the terms resilience and robustness might indeed be synonymous. This dependency is illustrated and discussed further in Section 3.3.

Cutter et al. (2010), address community resilience in the context of natural hazards, terrorism risk management and protection of infrastructure. It is underlined that resilience is understood as the capacity of a community to recover from disturbances by their own means in the sense of Milet (1999) and that community characteristics and governance are of key importance for resilience. This perspective is opposed to the engineering perspective of Bruneau et al. (2009) in which resilience is considered an inherent quality of the infrastructure and built environment; by means of inbuilt redundancy, robustness, resourcefulness and rapidity. Cutter et al. (2010) propose a framework for base-line assessments for the resilience of communities in terms of the Disaster Resilience Of Place (DROP) model, see also Cutter et al. (2003). Based on this model, data analysis is undertaken for different communities and the baseline resilience performances of local communities are assessed and mapped.

The developments in research on resilience of systems in the different areas of research have led to a range of definitions, see also Doorn et al. (2018), including:

**Ecological systems**

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.

**Social systems**

Cutter et al. (2010) – Resilience… capacity of a community to recover from disturbances by their own means.

**Engineered systems**

In the following, however, the definition formulated by The National Academy of Science (NAS) will be pursued as basis for design and management of engineered systems:

NAS (2012) – Resilience…a systems ability to plan for, recover from and adapt to adverse events over time.

3.2.2 Developments in the area of sustainability

In 1987 the Gro Harlin Bruntland report “Our Common Future” (Bruntland 1987) put sustainability on the global political agenda for the first time. Since then the emphasis on the need for sustainable societal developments fueled by global warming has been intensified and remains one – if not the main – topic on the global political agenda. Sustainability has attained a prominent focus point for very substantial collaborative research and development projects of supra-national organizations such as the United Nations, the World Economic Forum, OECD etc.

Sustainability is also not new on the academic agenda. In the fundamental contributions by Solow (1974) sustainability is introduced from the perspective of economics. The economics of equity in markets of exhaustible resources are addressed and analyzed through ideal cases of scalable markets with different assumptions with respect to technological developments, population growth and exchangeability. In Solow (1991) a wider account of the concept of sustainability is provided highlighting the controversial aspects associated with intra- and inter-generational equity and posing the idea that economic gains from exploitation of exhaustible natural resources are fully reinvested into human capital and thereby transferred to the future. The assumption of exchangeability between human capital and exhaustible natural resources is associated with the concept of weak sustainability. Hard sustainability, conversely, assumes that exhaustible natural resources and human capital are strictly complementary.

Kates et al. (2001) introduce sustainability as a science and highlight a number of central and pressing challenges for the research community including: (i) the need for better representations of the dynamic interactions (including time lags and inertia effects) in integral systems models of society and nature; (ii) improved understanding of how trends in society and environment affect sustainability; (iii) identification of what determines vulnerability and resilience of interlinked human and natural system for particular ecosystems and livelihoods; (iv) assessment of possible criteria for early warning of developments or conditions which seriously change interlinked human and natural systems; (v) identification of incentive structures, markets and regulatory frameworks which lead society on more sustainable tracks; (vi) utilization and improvement of present operational tools for monitoring and reporting for enhanced sustainable developments; (vii) better coordination, integration and dissemination of research and developments on decision support systems, systems modeling, etc. to enhance sustainable developments.

Preferences for investments into health and life safety at societal level is considered in Nathwani et al. (1997) who propose the Life Quality Index (LQI) as a demographical indicator expressing the societal preference for trade-offs between leisure time and time spent in productive activities. Based on the LQI, a criterion is derived that allows the assessment and prioritization of investments into health and life safety improvements at societal level in the same manner as applying the marginal lifesaving cost principle from health economics, see also Blomquist (1979). The concept of the LQI is further utilized in support of socio-economic sustainable decisions on design and maintenance of the built environment in Rackwitz et al. (2005), using renewal theoretical principles first proposed by Rosenblueth and Mendoza (1971). Optimal socio-economic sustainable decisions are derived on the design and maintenance of
the built environment which accounts for discounting in consistency with societal preferences and economic growth.

With the objective to better understand the impact of human activities on the environment, Hauschild (2015) suggests to couple quantitative sustainability assessment (from product oriented Life Cycle Analysis) with the concept of Planetary Boundaries (Steffen et al. 2015; Rockström et al. 2009). This in turn facilitates assessing the aggregate impacts of human activities at global level with respect to the main parameters controlling safe operating conditions for the planetary system. Moreover, such an approach may be utilized to account for environmental emissions in decision analysis for sustainable and resilient societal developments – as a consequence associated with decision alternatives which not only might have impacts at local spatial and short term temporal scales, but also at global spatial and long term temporal scales.

Based on the definition of resilience by the National Academy of Science (NAS 2012) and the concept of Planetary Boundaries proposed by Rockström et al. (2009) and Steffen et al. (2015), a novel decision analytical framework is proposed in Faber et al. (2017, 2018) for the representation and quantification of resilience and sustainability of interlinked systems. The novelty in the formulation is twofold, namely (i) the events of resilience and sustainability failure of systems are formulated in absolute and quantifiable terms and (ii) accounting for lack of knowledge and inherent natural uncertainty, they are assessed probabilistically so as to facilitate assessment of the annual probability of resilience and sustainability failure, respectively. Furthermore, through this modeling framework decisions relating to the design and operation of engineered systems as well as to the social capacity to react, deal with and learn from disturbance events can be optimized and ranked in accordance with their associated expected value of (service life) benefits. Possible acceptance criteria with respect to the probability of system resilience failure, welfare and risks to individuals and safeguarding qualities of the environment may moreover be accounted for. In this manner Faber et al. (2017) demonstrate how systems efficiency, robustness and resilience may be related and assessed. In Faber and Qin (2016) the framework and the results presented in Faber et al. (2017) are extended to consider one dimension of sustainability through the representation of resource consumption and thereby also indirectly CO₂ emissions associated with construction, operation and failure of infrastructure systems. First insights are achieved on how resilience, efficiency and sustainability relate to each other, which in turn facilitates the assessment of how resilient is resilient enough.

### 3.2.3 Developments in the area of decision analysis

Since the formulation of the Bayesian decision analysis by Raiffa (1961), Raiffa and Schlaifer (1961) and axioms of expected utility theory first postulated by Bernoulli (Cramer 1728) and later formally proven by von Neumann and Morgenstern (1943), the theoretical and methodical basis for decision support in the face of uncertainty may be stated to be available. A full account of the utilization of decision analyses in different fields of science and application is beyond the scope of the present text as focus is directed on developments with a particular relevance for the present problem setting.

In a normative decision analysis context, Fischoff (2015) provides a discussion of some of the main challenges in the utilization of decision analysis and concludes that decision analysis provides a very strong basis for supporting societal processes on communication and development of informed preferences. Miettinen and Hamäläinen (1997) highlight the merits of utilization of decision analysis in the context of life cycle analysis. Lawrence (2015), besides providing a very full account of the development of decision analysis, proposes decision analysis as a strong means of informed decision support in pursuit of sustainable societal developments.
and set focus on the potential of decision analysis in providing transparency regarding value settings and their impacts on the decision process.

In the context of descriptive decision analysis, a main scientific interest has been directed on the understanding of which factors and circumstances affect the preferences of decision makers and their decisions, and how this might be reflected in the formulation of utility functions. Empirical evidence from a substantial experimental basis has formed background for a general questioning of whether decision makers in reality can be assumed to be rational in the sense of following the axioms of expected utility theory (von Neumann and Morgenstern (VNM) rationality); see e.g. Kahnemann and Tversky (1979) and Slovic and Tversky (1974). Whereas it has been found that the concept of relative utility as proposed in the prospect theory (Kahnemann & Tversky 1979) may resolve this problem, the identified psychological effects affecting our ability to model and predict the behavior of decision makers also have bearings on normative decision making. Not least, the framing of the decision problems as highlighted in Tversky and Kahnemann (1981) is recognized to play a significant role and constitutes an important ethical dilemma. This of course also relates to the development of decision support for resilient and sustainable societal developments. How should such decision problems be formulated, which are the objectives and values to be pursued?

With respect to the practical application of decision analysis the vast number of publications on risk informed decision making across the engineering disciplines underline a general tendency to focus on the adverse consequences associated with a decision alternative, i.e. risks, see e.g. Aven and Zio (2011) and Fischoff (2015). Risk assessments have undergone significant regulation and unification over the last 2–3 decades (e.g. ISO31000:2009), however the emphasis of regulations on risk management also for the different specific application areas is mostly directed on procedural aspects and only rarely addresses systems modeling aspects (see e.g. ISO2394:2015; JCSS 2008). As a result the best practices on risk management have, over the different application areas, evolved somewhat uncoordinated and subject to rather different industrial needs and regulatory requirements which is why, in the context of decision analysis, they may at best be termed informal. Generally it is the case that both the bases, methods and the results of risk informed decision analysis conducted in different application areas are not consistent and compatible; see e.g. Faber and Stewart (2003).

It is interesting to note that Linkov et al. (2014) identify risk assessment as an inadequate means for assessing and ensuring resilience in the context of societal decision making. The perspective is taken that systems are too complex, that risk based strategies for ensuring appropriate system performances focus on hardening of the system against the effect of disturbances and do not capture the essentials of resilience. It is proposed in Linkov et al. (2014) that more research must be undertaken to understand resilience of systems and to facilitate implementation of strategies ensuring resilience already at early stages in their design.

In conclusion, following the framework proposed by the Joint Committee on Structural Safety (JCSS 2008), normative Bayesian decision analysis, provides an adequate methodical framework for the development of informed societal decisions on resilient and sustainable developments. Insights and results from descriptive decision analysis may and should however be accounted for in the representation of consequences.

### 3.3 Framework for decision making for resilience and sustainable developments

To facilitate the development of decision support for resilient and sustainable societal developments it is necessary to establish a representation of the considered system which
facilitates a ranking of decision alternatives that is consistent with available knowledge, coherent with preferences and objectives and conforming with possibly given requirements. Such a systems representation framework is presented in the following, closely following Faber et al. (2018).

### 3.3.1 Hierarchical decision analytical system representation

When providing decision support for the management of systems it is essential to establish representations of the systems which consistently map possible different decision alternatives into achievement of preferences of decision makers and involved stakeholders. This implies that the context of the systems are identified in terms of decision makers, stakeholders and their preferences, temporal and spatial boundaries, the physical characteristics of the systems, the performances of the system and possible and relevant decision alternatives together with their effect on the systems performances, see also Faber et al. (2007) and JCSS (2008).

A modeling issue which is often overlooked in decision analysis for systems concerns the organizational aspects of management; the governance structure. The governance of societal systems is typically organized hierarchically into subsystems each under their own management and decision makers, and with defined interfaces to both over- and underlying management levels and decision makers. Such hierarchies can and should be established prior to their detailed modelling and management optimization supported by decision analysis.

An example of a hierarchical representation considering management of infrastructure systems is illustrated in Figure 3.1. The lowest hierarchical level in the representation provided in Figure 3.1 is infrastructure management at municipality or community level. The idea being that the services provided by infrastructure at community level provide benefits to the same level but also that a part of this benefit is transferred to higher organizational levels e.g. in the form of a tax. This tax may then be used in order to establish and manage infrastructure systems which facilitate sharing and utilization of resources as well as service provision capacities across communities. To the extent that higher level management apply taxes from underlying levels also as a means for building financial reserves, these may also be utilized for the purpose of risk financing. Figure 3.1 also illustrates that service provision at community level takes basis in local conditions with respect to environment and natural resources, and of course are subject to the local conditions regarding disturbances, in the form of geo- and anthropological hazards.

At each individual level in the governance hierarchy, decision makers and stakeholders in principle are concerned mainly about ensuring the efficient management of their infrastructure on the basis of their available resources. Their objectives being to ensure adequate resilience and sustainability performance from their perspective. In pursuing these objectives any boundary conditions imposed on them – e.g. through environment, natural resources and hazards, but also in terms of regulations, codes and standards defined at higher levels in the governance hierarchy – must be accounted for and adhered to.

The general idea underlying the hierarchical governance structure illustrated in Figure 3.2 can be applied to other contexts of governance, e.g. for private organizations or industrial activities.

From a theoretical perspective it is fundamental that decision alternatives which are considered for the purpose of optimizing the design and/or management of engineered systems subject to uncertainty and incomplete knowledge in a normative decision context shall be ranked in accordance with their expected value of utility (or benefit) in accordance with Bayesian decision analysis and the axioms of expected utility theory, see e.g. Raiffa and Schlaifer (1961) and von Neumann and Morgenstern (1943).
To benefit fully from this theoretical and methodical basis for decision optimization it is necessary to formulate probabilistic models for the performances of the systems as well as to identify and represent the preferences of the decision maker with respect to the possible outcomes of the decisions. Crucial issues concern the probabilistic modelling of the considered systems and also the identification of strategies and options for their design, operation and management.

An illustration considering design and management of infrastructure systems is provided in Figure 3.3. The considered system is comprised of the infrastructure system, the social system (governance), the geo-hazards and anthropological hazard systems (disturbances), the ecological/life support system (environment) and the regulatory system. The temporal performance of the interlinked system must be accounted for, e.g. through time-slicing, whereby the condition of the system is modeled, e.g. on an annual basis, and the condition of the system at one particular time (e.g. one year) depends on the system performance history in the past.

The performances of the interlinked system at any given point in time (in the time slice model from Figure 3.3) may be assessed from the principal framework illustrated in Figure 3.3. As opposed to most common approaches for risk informed decision support the framework illustrated in Figure 3.4 includes not only risks in the sense of expected value of losses of different relevant metrics (e.g. loss of lives, damages to the qualities of the environment and financial losses) but also the benefits associated with decision alternatives – the main objective of engineered systems. This extension facilitates as will be addressed in Section 3.4 that resilience and sustainability may be modeled and quantified and thereby adequately addresses the shortcomings of traditional risk modeling as a basis for resilience assessments highlighted by Linkov et al. (2014).

Based on the systems modeling framework illustrated in Figure 3.4 it is possible to assess and rank different decision alternatives for the design and management of engineered systems in accordance with expected value of utility or any particular metric of preference.

As indicated in the figure the space of acceptable decision alternatives might be limited by e.g. maximum acceptable risks to life, loss of qualities of the environment and financial losses. The concept of the Life Quality Index proposed by Nathwani et al. (1997) readily provides a framework for assessing the acceptability of life risks to individuals.
The scenario based modeling also facilitates assessments of e.g. intensity and duration of loss of critical services, which are typically of particular interest in the context of resilience optimization, and additional requirements in this respect may straightforwardly be added. At smaller geographical and temporal scales, which are normally assumed when considering resilience performance of engineered systems, requirements with respect to impacts on the qualities of the environment are most often specified in regulations, standards and codes. Requirements relating to the performance of interlinked governance and technical systems on the other hand are as of yet not available but can, as shown in Section 3.4.4, be formulated in probabilistic terms.

At global geographical scale and considering long time horizons, acceptance criteria with respect to environmental impacts are not yet available. One possible approach to the identification and formulation of such requirements is however available through the concept of Planetary Boundaries introduced by Rockström et al. (2009) and Steffen et al. (2015). The general idea behind the concept of Planetary Boundaries is that the Earth system has limited capacities to sustain the stresses imposed by human activities. These capacities may be expressed in terms of Planetary Boundaries, quantified in accordance with best available knowledge. At the present time 11 such Planetary Boundaries have been identified. Much research is still necessary on the quantification of associated capacities but already now so-called domains of safe operation of the Earth system are suggested in terms of value ranges for several of these, see Steffen et al. (2015). As described in Section 3.4.5 the concept of the Planetary Boundaries facilitates a quantitative probabilistic assessment of impacts together with associated acceptance criteria.

### 3.4 System representation and characteristics

To proceed in the presentation of the proposed framework the following sections closely following Faber et al. (2018), provide additional details on the representation of systems as well as on the individual systems characteristic indicated in Figure 3.4.

#### 3.4.1 Exposures and disturbance events

As illustrated in Figure 3.4 a system is assumed subjected to exposure events (disturbances) representing, in principle, all possible events with the potential to generate consequences. In the context of resilience and sustainability modeling and assessments, exposures may be...
understood in the sense of disturbances. However, it should be underlined that disturbance events as addressed in the vast majority of research on resilience are associated with relatively rare, sudden and high intensity damaging events. Here the perspective is taken that not only such events should be accounted for but rather any type of exposure event. These may be categorized as (see also Faber 2011):

- **Type 1 hazards:** Large scale averaging rare and high consequence events: Rare in place and time, potentially associated with catastrophic consequences. Over sufficient large scales in time and space the associated risks are predictable, which greatly facilitates their management. Typical examples of this type of hazards include geo-hazards, e.g. earthquakes, floods, strong wind storms, etc.

- **Type 2 hazards:** Frequent in time and space with relatively small consequences, which is why they are commonly overseen or collectively ignored. Cognition biases such as tunneling and framing (see Kahnemann & Tverski 1984) play important roles in this. Over sufficient scales in time and space they might be associated with devastating cumulative consequences. Moreover, their cumulative effects may trigger more disastrous consequences of the same characteristics as those of Type 3 hazards. Typical examples are emissions to the environment, exploitation of resources, extinction of species, inefficient or inadequate regulations, inadequate budgeting, human errors etc.

- **Type 3 hazards:** Extremely rare and potentially disastrous events which are unpredictable even over large extents in time and space and for which basically no knowledge is available. May be triggered by the cumulative effects of Type 2 hazards. Examples include super volcano eruptions, impacts by asteroids, high intensity solar storms, global climate change as well as major malevolent actions. The management of risks due to this type of hazard cannot be planned for in the same manner as Type 1 hazards since little is understood with respect to probability of occurrence and evolution of consequences. Conditional risk assessments might

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**Figure 3.4** Illustration of systems modeling framework accounting for both the generation of capacities as well as losses.

*Source: Modified from Faber et al. 2018.*
be utilized to quantify speculation on the robustness and resilience of society at different scales – by basing risk assessments on certain extents of damages of the systems providing societal functionality – conditional, or “what if” assessments.

- Type 4 hazards: Events triggered by incorrect information and knowledge. Examples include consciously and unconsciously omitted or manipulated information, “fake news” as well as censored and erroneous observations. Consequences associated with this type of hazard may resemble the consequences associated with Type 1–Type 3 hazards. The management of this type of hazard may be supported by means of sensitivity analysis (see e.g. Faber et al. 1997) and by means of inclusion of options for validation of information and knowledge playing a significant role for the ranking of decision alternatives.

3.4.2 Modeling of cascading failures

The system modeling approach suggested by the JCSS (2008) subdivides the scenarios of events leading to consequences into three parts, namely the hazard (or disturbance) events, direct consequences and indirect consequences, see also Figure 3.5. The direct consequences comprise either (i) all losses caused directly by the disturbance event or (ii) all losses caused by failure states of the constituents of the system except functionality related losses. The indirect consequences are assumed to be caused by (a) all losses caused in the process of internal redistribution after the disturbance event or b) the functionality losses alone. Besides the differentiated consequence modeling, two phases are introduced in the modeling of the progression of failure of the system: the initiation phase and the propagation phase, see also Faber et al. (2017). In the initiation phase $m_H$ constituent failures are assumed generated by the hazard event $H_i$. In the propagation phase further $l_H$ constituent failures are generated by the joint effect of internal redistribution of system demands and hazard events, see also Figure 3.5.

It is assumed that all possible $i=1,2,...,n_S$ different scenarios of hazard events with their occurrence probabilities $p(i)$, direct consequences associated with constituent failure events during the initiation phase $C_{D,I}(i)$ and propagation phase, respectively $C_{D,P}(i)$ and the indirect consequences $C_{ID}(i)$ have been identified and assessed. The probabilistic system representation $S$ can then be written as:

$$S = (i, p(i), C_{D,I}(i), C_{D,P}(i), C_{ID}(i)), \quad i = 1,2,...,n_S.$$  

(3.1)

3.4.3 Quantification of robustness

The robustness of systems may be understood as the degree to which a system is able to contain or limit the immediate consequences of disturbance events. Risk based formulations for the quantification of systems robustness are first provided in Baker et al. (2008) and JCSS (2008) and later enhanced in Faber (2015) where the robustness index of a system with respect to a given scenario $i$, i.e. $I_R(i)$ is:

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

(3.2)

The direct and total consequences $c_D(i)$ and $c_T(i)$ entering Equation (3.2) may be interpreted in dependence on the focus of the system assessment (or rather the definition of the system...
boundaries). If the focus of the system assessment is directed on the representation and analysis of cascading failures Equation (3.2) may be rewritten as:

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

(3.3)

where $c_{D,I}(i)$, $c_{D,P}(i)$, represent the direct consequences associated with the initiation phase and the propagation phase of the $i^{th}$ failure scenario of the system, respectively.

If the emphasis is directed on the ability of the system to contain the development of consequences Equation (3.2) may be rewritten as:

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

(3.4)

As the scenarios $i$ are random in nature, as reflected by their occurrence probabilities $p(i)$, it is realized that the robustness index $I_R(i)$ itself is a random variable which may be analyzed further by categorization and ordering of the different scenarios in accordance with the hazard, damage, failure and consequence events they are composed of. In this manner robustness indexes for a given system can be assessed probabilistically conditional on e.g. the type and/or intensity of the hazard event as well as the magnitude of direct, indirect or total consequences. Moreover, the scenario based approach allows for keeping account of which constituent damages and failures contribute the most to, e.g. poor robustness performance as well as to the total consequences.

### 3.4.4 Quantification of resilience

A relatively large variety of propositions for the modeling and quantification of systems resilience are available in the literature, see e.g. Tamvakis and Xenedis (2013), Cimellaro et al. (2009), Linkov et al. (2014) and Sharma et al. (2017). Most often the suggested models are directed on the short term representation of the ability of the system to sustain and recover from disturbances, without substantial loss of functionality and without the support from the outside. Typically the attention in resilience modeling is directed on the representation of the

![Figure 3.5](source: Modified from Faber et al. 2018.)

"Illustration of the representation of cascading failure events."
effect of specified disturbances on service provision and the characteristics of the recovery in terms of degree of recovered service versus time and total loss of service, see Figure 3.6.

Until recently, only implicit consideration has been devoted to the modeling of the capacity of systems to recover from disturbances. However, following the life-cycle benefit considerations in the resilience model presented in Faber et al. (2016), systems resilience should account for not only the loss of functionality, but also for the generation of the capacity which is critically important for the successful – and fast – reorganization, adaptation and rehabilitation, following disturbances and hazard events, see Figure 3.6.

Therefore a life-cycle model of systems resilience is proposed here in which scenarios of both benefit generation and losses are modeled and analyzed and where insufficient resilience or systems resilience failure is defined as exhaustion of system capacity (social, economic and/or environmental). Resilience, in the same manner as robustness is thereby a system characteristic of a random nature and requirements to resilience may only be specified meaningfully in probabilistic terms, e.g. through an acceptable annual probability of resilience failure.

In Figure 3.7 this idea is illustrated for the simple case of a system for which the only explicitly considered capacity is a financial reserve established as a fixed percentage of the annual benefit generated by the system over time. The general shape of the benefit loss curves in the aftermath of disturbances reflects that a period of time will pass before the service can be re-established. In the first instance only up to a certain level, reflecting that interim solutions are foreseen, implemented and operated, while waiting for the preparation and implementation of complete and possibly even improved system rehabilitation.

Resilience failure occurs if at some point in time one or more of the available capacities are exhausted. It should be underlined that resilience failure in principle can also occur as a consequence of disturbances of a “slow burner” character, such as the effect of inefficient governance and cognitive errors (Type 2 Hazard from Section 3.4.1).

In Figure 3.7 two time histories of benefit generation and accumulated economic reserves are illustrated. It is seen how disturbance events both reduce the capacity generation as well as the accumulated capacity reserves. In the time history illustrated with a green line it is seen that a disturbance event exhausts the accumulated reserves and causes a resilience failure.
The probability of resilience failure $P_{RF}(t, a)$ may in this manner be represented and assessed probabilistically as:

$$P_{RF}(t, a) = 1 - P\left[ t(X(\tau), a) - s(X(\tau), a) > 0, \forall \tau \in [0, t] \right],$$

where $t(X(\tau), a)$ is a function representing a given capacity of the system at time $\tau$ and $s(X(\tau), a)$ is a function representing the demand or stress on the system caused by a disturbance event at time $\tau$. $X(\tau)$ is a vector of random variables which may depend on time and $a$ is a vector containing all decision alternative which may affect the resilience performance of the system.

It may be realized that Equation (3.5) indeed represents a first excursion problem.

As for the case of robustness, conditional resilience failure may be modeled and assessed utilizing the scenario based life-cycle oriented approach. Conditioning on disturbance events of given characteristics, the conditional event of a system being resilient can be defined as the event of successful recovery within a given time horizon without exceeding available resources.

Examination of Figure 3.7 reveals that the first immediate drop in the benefit rate (service provision or functionality) after a disturbance event relates directly to the systems robustness as described by Equation (3.3). However, the index of robustness defined by Equation (3.4) can be seen to also represent the resilience characteristics of a system. If this index for a given scenario is equal to 1 it implies that the system suffers no functionality related losses. This in turn is only possible if the services provided by the system are successfully reestablished immediately after the disturbance event – implying perfect resilience performance. Even with moderate assumptions concerning the contribution of indirect consequences to total consequences it is apparent that cascading failures and loss of functionality play a significant role for the resilience of the system.

### 3.4.5 Quantification of sustainability

Addressing sustainability necessitates a joint consideration of impacts to the environment, health and welfare of people, economy and exhaustion of natural resources from the perspective of intergenerational and intra-generational equity. In addition to the impacts already considered in the modeling of resilience, the focus is directed on how to account for impacts to the environment.
The general idea followed is to apply the concept of Planetary Boundaries as a means to represent the capacities of the Earth system which are central for the continued development of society as we know it today. In the following these characteristics of the Earth system are referred to as the Earth Life Support System (ELSS). It is further assumed that to any decision alternative relating to the design and management of an engineered system it is possible to assign system states and corresponding consequences relating to impacts on the qualities of the environment imposing stresses on the ELSS. Following Hauschild (2015) this relationship might be established through Life Cycle Analysis as applied in support of Quantitative Sustainability Assessments (QSA) in the context of product development. The principle is illustrated in Figure 3.8.

According to Steffen et al. (2015), the ELSS may become unstable if its capacities to cope with emissions and other disturbances caused or influenced by human activities are exhausted. Research is still ongoing to understand and assess the capacities of the ELSS with respect to CO₂ emissions, acidification of the oceans, extinction of species, fresh water use etc. However, it may be assumed that for each of the presently identified 11 critical boundary variables it is (or will soon be) possible to formulate criteria of the form:

\[ r_i(x, \tau, a) - s_i(x, \tau, a) \leq 0, \quad i = 1, 2, \ldots, n_B, \]  

(3.6)

where \( r_i(x, \tau, a) \) and \( s_i(x, \tau, a) \) are complex functions describing the capacities and the stresses or demands acting on the ELSS with respect to its \( n_B \) Planetary Boundary variables at a given point in time \( \tau \). \( x \) is a vector of variables entering the functions and \( a \) is a vector of decision alternatives which may influence both the capacities and the stresses.

Assuming that the variables \( x \) are associated with uncertainty we may assess system sustainability probabilistically along the same lines as system resilience failure, i.e.:

\[ P_{SF,ELSS}(t, a) = 1 - P \left\{ \{ r(X(\tau), a) - s_i(X(\tau), a) > 0 \} \forall \tau \in [0, t] \right\}. \]  

(3.7)

The probability of sustainability failure \( P_{SF,ELSS}(t, a) \), may, as for the case of resilience failure, be assessed as a first excursion problem. In the general case where all \( n_B \) planetary boundary variables are considered this becomes a vector valued first excursion problem.

The dimension of sustainability relating to health and welfare may be represented through the indirect relation between economy and life expectancy as provided by the Life Quality Index (LQI) see e.g. Kübler (2005):

\[ LQI = g^w (1 - w)^{l - w}. \]  

(3.8)

The parameter in Equation (3.8) represent three demographic social indicators, namely the gross domestic product per capita \( g \), the life expectancy \( l \) and the fraction of life spent to earn a living \( w \). By introducing an elasticity labor factor \( \beta \), a factor indicating, the trade-off between wealth and longevity can be expressed as \( q = w / (\beta l (1 - w)) \).

The GDP may be modeled through the monetary benefits generated from the services provided by the engineered systems, less the expenditures associated with construction, maintenance, reconstruction and renewals. The relationship between the development of the economy and life expectancy at birth at nation state level is studied in Kuebler (2005) and Faber and Virguez-Rodriguez (2011):

\[ \frac{dg}{g} = \frac{1 - w}{w} \frac{dl}{l}. \]  

(3.9)
Figure 3.8 Illustration of the mapping of system changes imposed by a given decision alternative to elementary flows, LCA quantifications and consequences in metrics of relevance for resilience and sustainability assessments.
As a function of different decision alternatives $a$ it is thus possible to model trajectories over time of the development of the LQI and thereby to assess the development of societal welfare for given policies affecting the decision alternatives contained in $a$, see Equation (3.10):

$$LQI(x, \tau, a) = g(x, \tau, a)^w/\lambda(x, \tau, a)^{-w}(1-w)^{-w}.$$  

(3.10)

Moreover by relating the social capacity to deal with disturbances in terms of reorganization, restructuring and adaptive learning in and after the event of a disturbance, to the LQI as a function of time, the dynamic effect between general societal welfare and resilience can be represented. Using this model a societal sustainability failure criterion may be formulated through the event that the LQI decreases below a critical level $LQI_{LMS}$ and the probability of societal sustainability failure $P_{SF, Soc}(t, a)$ can be assessed along the same lines as resilience failure and sustainability failure, i.e.:

$$P_{SF, Soc}(t, a) = 1 - P\left\{\{LQI(X(\tau), a) - LQI_{LMS} > 0, \forall \tau \in [0, T]\}\right\}.$$  

(3.11)

Figure 3.9 provides an overview of the various metrics, system characteristics and assessments entering the decision analysis of systems in the context of supporting decisions for resilient and sustainable societal developments.

3.5 Conclusions

Research in resilience and sustainability has attracted tremendous resources and efforts over the past 3–4 decades. The fundamental principles and concepts mostly originate from the fields of economy, ecology and social sciences but applications of these for the design and management of engineered systems may be found in a relatively wide range of engineering disciplines. For engineered systems, however, research in resilience and sustainability has developed largely in parallel, the two fields to a large extent considered and approached as individual topics. It is nevertheless evident that at a fundamental level the two concepts are strongly related or even equivalent depending on the boundaries assumed when defining the considered system. Traditionally resilience of engineered systems is addressed at scales in time and geography which are much smaller than those assumed when addressing sustainability, with a strong focus on safeguarding the services provided by the systems – in part from the environment. Sustainability on the other hand puts emphasis on the safeguarding of the qualities of the environment from adverse effects originating from these services in the long run and at the scale of Earth. In the formulations of resilience and sustainability provided in the foregoing sections it is shown that resilience and sustainability of engineered systems may be approached in the exact same manner by introducing resilience and sustainability failure as the event that one or more capacities of considered systems are exhausted. If resilience of the global Earth systems is considered it is thus clear that resilience failure is equivalent to sustainability failure if resilience is addressed in a long term perspective. Moreover, resilience of engineered systems at smaller scales necessitate resilience (or sustainability) at global scale.

Another important point from the foregoing sections is that resilience and sustainability of engineered systems in the same manner as the system characteristic robustness, due to lack of knowledge and inherent natural variability, only meaningfully can be approaches and modeled probabilistically. Requirements to resilience and sustainability as a consequence must defined, e.g. in terms of acceptable annual probabilities of resilience failure and sustainability failure, respectively. From this perspective it immediately becomes clear that tradeoffs exist and
Decisions on development and maintenance of engineered systems

Resource consumption

Geo-hazard system

Anthropological hazard system

Energy
Space
Materials
Water
Emissions

Planetary Boundaries

Earth Life Support System

LCA

Risk metrics

Services

Social capacity

LQI

Governance

Decision analysis

Sustainability metrics

Resilience metrics

Economy
Livelihoods
Safety
Health

Welfare

Figure 3.9 Illustration of interrelations between risk, resilience and sustainability as well as associated metrics and techniques for their assessments.
must be accounted for when deciding how resilient engineered systems and sustainable societal developments should be. The more short term welfare in society will depend on what is considered to be acceptable risks associated with resilience failures at local geographical scales (e.g. at community level) as well as society’s risk appetite for the risk of sustainability failures at global scale. More research on these tradeoffs must be achieved in the nearer future to facilitate timely and informed societal decision making.

Notes

1 Various alternative terms are used in the literature: in ecology the term is typically “disturbance,” in disaster risk and environmental risk management the terms “hazards” is frequently applied and in engineering and insurance a typical term is “exposures.”
2 In the following the term “engineered systems” refers to in principle all societal systems originating from human decisions, including systems sometimes referred to as “self-organized systems.” This inclusion is made since self-organized systems only exist in the context of decision making if they are known and if they are allowed to be self-organized.

References


