Risk, Uncertainty, and Ignorance in Engineering Systems Design

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Abstract

Uncertainty is the third major perspective in understanding and designing engineering systems, along with complexity and human behaviour. Risk, a corollary of uncertainty, is understood as the effect of uncertainty on objectives. When designing engineering systems, you cannot not manage risk – even ignoring risk equates to a decision to accept it. Engineering systems are characterised by long life cycles, changing operational environments, and evolving stakeholder values, leading to a wide range of uncertainties in their design and operation. Productively engaging with this uncertainty is critical for successfully operating and especially (re-)designing engineering systems.

This chapter provides an overview of managerial practices to address the three levels of increasing uncertainty in engineering systems design: from (1) managing risk, to (2) managing uncertainty, to (3) managing ignorance. We differentiate for each level of uncertainty between two levels of value diversity: (1) primarily commensurate values (i.e. agreement on core values by critical stakeholders) and (2) primarily incommensurate values (i.e. no agreement on core values). The managerial practices we discuss are "classic" risk management, public engagement, scenario planning, robust decision-making, resilience, and applying the precautionary principle. In addition, we briefly illuminate the actuality of management practices dealing with the different levels of uncertainty beyond explicit, formal processes, the understanding of managing uncertainty as both modelling and decision support practices and personal and organisational biases in the context of addressing uncertainty.

Keywords

Engineering systems · Engineering systems design · Resilience · Risk management · Robust decision-making

Introduction: Addressing Uncertainty in Engineering Systems Design – Conceptualising "Risk Management"

What Is "Risk Management" for Engineering Systems?

Traditionally, managerial approaches addressing various levels and types of uncertainty in decision-making are summarised under the label of "risk management." Broadly defined, risk management is an inclusive set of organisational practices to support decision-making during the design of engineering systems interventions under varying conditions of uncertainty. The simplest definition of risk is the effect of uncertainty on objectives (ISO 2018). Later in this chapter, we will differentiate between three levels of uncertainty (risk, uncertainty, and ignorance) and correspondingly introduce three categories of managerial practice, i.e. management of risk, management of uncertainty, and management of ignorance (see Fig. 2). It is worth pointing out that we understand ignorance simply as a technical term describing a lack of knowledge and information, without any implicit value judgement (such as “ignorance due to a lack of education” or “wilful ignorance”).

There are many of both *sources of uncertainty* and their *impact categories* in the context of engineering systems design. The sources of uncertainty in engineering systems design fall into three major categories (Willumsen 2020):

1) Uncertainties originating from requirements are driven by a complex stakeholder landscape, lack of historical data, and long life cycles, including changing contexts of operation.
2) Uncertainties regarding technical feasibility originate from numerous and diverse subsystems and their interfaces, including their differing technology maturity and life cycles (e.g. innovation and obsolescence cycles).
3) Uncertainties arise from the organisational domain, i.e. our ability to plan and execute the design and implementation of engineering systems interventions, including our processes, skill levels, and organisational integration.

The impact categories in the context of engineering systems are as manifold as the objectives of engineering systems. These objectives range from cost and technical performance to societal value creation to environmental and sustainability impacts. This makes a unified quantification of impacts challenging, as different impact categories cannot easily be converted into one another (say, safety vs. sustainability risks). In addition, as we will explore later in this chapter, stakeholder groups hold diverging views on values and priorities, which must be accommodated in prioritisation and treatment of uncertainties.

As engineering systems designers, we cannot not manage risk, uncertainty, or ignorance. Even if individuals or organisations make a conscious decision not to engage in risk management and ignore, say, uncertainty regarding future market demands, they will have made a risk management choice: to accept to absorb the full and unmitigated range of consequences of the risks in their design task. The managerial practices of risk management, and by extension the management of uncertainty and ignorance, extend beyond formalised processes, as discussed by Willumsen (2020) and shown in Fig. 1: risk management activities can either be formalised (e.g. a risk identification workshop) or informal (e.g. a lunchtime conversation with a critical supplier). Furthermore, we can explicitly engage in risk management (e.g. reviewing our top ten risks), or we can implicitly engage in risk management (e.g. reviewing incomplete requirements). Combined, these two dimensions yield four domain management in practices:

- Formal, explicit risk management processes (the focus of this chapter)
- Informal, explicit risk management processes (e.g. ad hoc reactions to plan deviations or inclusion of design margins due to a “gut feeling”)
- Formal, implicit risk management processes (all aspects of designing engineering systems interventions that address uncertainties and their impact, without formally calling them risk management, e.g. validation and testing)
- Informal, implicit risk management processes (such as building social capital and trust-based relationships among team members, suppliers and customers, etc.)

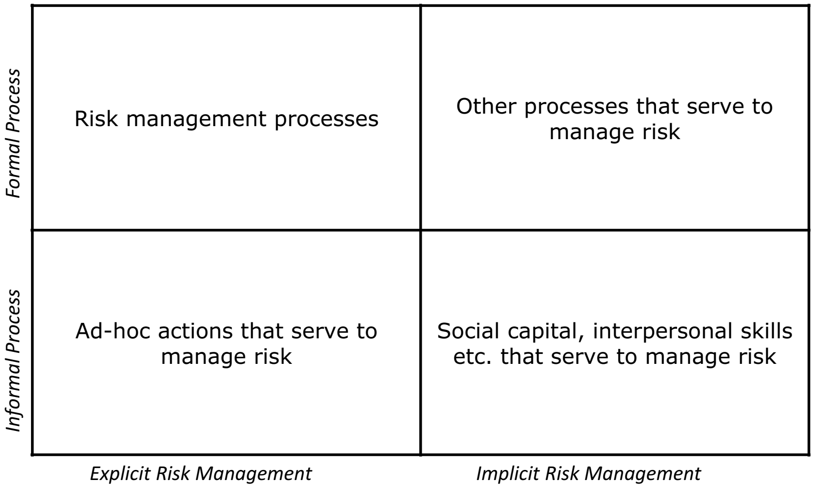

Fig. 1 Risk management is more than formal, explicit risk management processes (following Willumsen 2020)

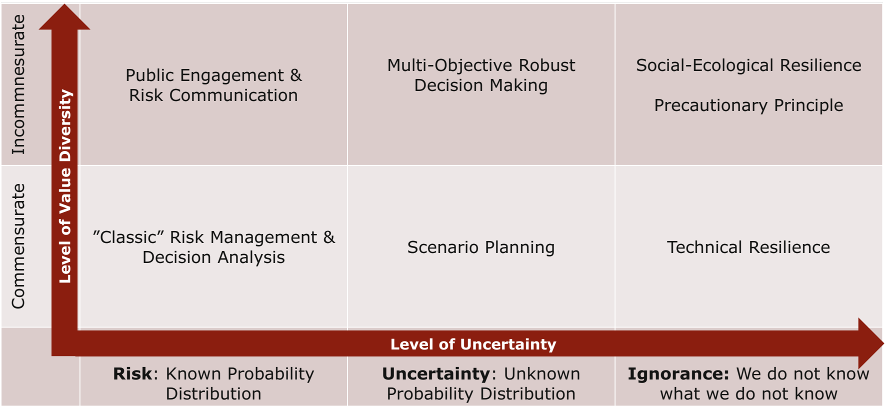

Fig. 2 Example practices for managing risk, uncertainty, and ignorance in engineering systems design

This chapter will primarily focus on formal, explicit management practices of uncertainties in the context of engineering systems. To be precise, we will discuss the management of risk, uncertainty, and ignorance into two social contexts: commensurate values, i.e. contexts where stakeholder values align, and incommensurate values, i.e. contexts where stakeholder values do not align. Additionally, we will briefly highlight decision-making and thinking biases in the context of uncertainty.

A Sociotechnical Perspective of Risk Management Activities

Levels of Uncertainty and Level of Value Diversity

When considering "risk management" activities in the context of sociotechnical systems, there are two essential aspects. First, we need to decompose the term "risk" (see section "Level of Uncertainty: Risk, Uncertainty, and Ignorance") to incorporate three distinct concepts regarding the "degree of uncertainty" that a decision-maker faces: risk, uncertainty, and ignorance. Second, we need to distinguish methods applicable in situations where there is general agreement across stakeholders regarding their values, versus management techniques applicable to deal with, or resolve, conflicting stakeholder values. We chose to focus on "stakeholder values" instead of "stakeholder objectives" in this chapter for two reasons: First, objectives are based on values, so we focus on the more foundational concept. Second, values represent true stakeholder preferences, whereas formally (and publicly) articulated objectives may be influenced by several other considerations and thus not truly representing preferences. A simple example of values impacting risk management is the question "How safe is safe enough?." This is discussed in section "Level of Value Diversity."

Management of Uncertainties as Modelling and Decision Support Practice

The discipline of risk management has long acknowledged that risk management is more than technical risk assessment practices. We can broadly discern two categories of management activities (see Table 1): first, activities aiming at understanding, describing, and modelling engineering systems and their constituent elements and relationships as they pertain to the management of risk, uncertainty, or ignorance. This includes an explicit description of the degree of knowledge, or uncertainty, captured, or not captured, by those models. Second, management activities that enable and support decision-making processes, including the communication and visualisation of risk, uncertainty, and ignorance-related models.

The two types of activities are closely linked: The results of what and how we model inform our decision support processes, while the specific requirements of our

Table 1 Examples of two types of management activities addressing risk, uncertainty, and ignorance

Management as models of engineering systems ("understanding risk, uncertainty, or ignorance")	Management as models of decision support processes ("managing risk, uncertainty, or ignorance")
• Physical or virtual prototypes and their user interaction • Specific functional models, e.g. system dynamics simulations • Specific risk models and simulations, such as Monte Carlo simulations • Specific risk assessment techniques, such as fault tree analysis or barrier models	• Risk governance frameworks • Risk management process frameworks • Visualisation and communication guidelines • Decision-making heuristics, such as the precautionary principle or risk acceptance criteria

decision support processes determine the requirements for our risk, uncertainty, and ignorance-related models. While there are approaches to modelling very different degrees of uncertainty, we argue that system model-based approaches become more prevalent as more data are available and consensus on stakeholder value increases (i.e. systems are better known or designs have progressed further). In contrast, process model-based management techniques for these levels of uncertainties tend to be more prevalent for situations with significant uncertainty and less consensus on stakeholder values.

Personal and Organisational Biases Regarding Risk, Uncertainty, and Ignorance

Basic economic theory assumes that humans, and by extension organisations, are efficient and rational decision-makers, dependably making choices in their own best interest, i.e. maximising expected utility according to their own articulated criteria. However, as experiments and empirical data on decision behaviour clearly show, the reality is much more complex. This is particularly present in decision-making under uncertainty.

This led to, among others, the development of prospect theory: To account for changes in decision-making behaviour under uncertainty, utility theory-based choice models are replaced with value functions based on gains and losses (not to assets), and the role of probabilities is replaced by decision weights. This leads to value functions that are now concave for gains and convex for losses, accounting for real-life decision-making behaviour under uncertainty (Kahneman and Tversky 1979). Kahneman (2011) popularised a model of decision-making that discerns between two types of thinking: "fast thinking," or type 1 thinking, describes intuitive, quick, and mostly subconscious decision-making processes. "Slow thinking", or type 2 thinking, describes deliberate, analytical decision-making processes based on data and transparent decision criteria. Early discussions of type 1 thinking include using heuristics that extend past experiences to novel phenomena and lead to unreflected and possibly misguided intuitive decisions, expressed as representation bias, availability bias, or anchoring bias (Tversky and Kahneman 1974). Choices become skewed from what basic economic theory would predict, e.g. overweighting both very high and very low probability events relative to moderate probability events. Risk attitudes, i.e. risk aversion and risk-seeking behaviour, are different if decision problems are framed or perceived as chances of loss or chances of gain (Kahneman and Tversky 2013).

Other authors emphasise the value (and necessity) of "fast thinking," especially the use of heuristics as an enabler of decision-making under conditions of complexity, time constraint, and bounded rationality of the decider (Gigerenzer and Goldstein 1996; Gigerenzer and Selten 2002). This is important to keep in mind in the context of "real-life" risk management in the context of engineering systems: Just because theoretically, there may be a data-intensive analytical process available to us does not mean that pursuing a "slow thinking" decision is the best choice under all circumstances. Having said that, this chapter does focus on formal decision-making frameworks. For example, in the context of project risk management, these have been discussed and reviewed by McCray et al. (2002) and Stingl and Geraldi (2017).

Equally relevant to biases and heuristics in decision-making under uncertainty is the matter of public (technology) risk perception or, maybe better, risk-benefit perception (Fischhoff et al. 1978). One of the particular biases affecting risk-benefit perception is the affect heuristic (Slovic et al. 2007), leading, for example, to a lower inferred risk if the benefit of an option is perceived to be high and reversely, leading to a low inferred benefit if an option is perceived to have high risk.

In their review article, Renn and Benighaus (2013) identify several underlying factors shaping risk-benefit perception, including attention and selection, the use of cognitive heuristics (see above), evolutionary coping strategies, cultural patterns, and semantic images. Factors shaping individual risk perception, for example, depend heavily on the perceived degree of control, whether the exposure to the risk is voluntary, and whether the risk is novel (Slovic 1987, 2010). Tightly coupled to the question of individual risk perception is the phenomenon of "social amplification of risk" (Kasperson et al. 1988).

Level of Uncertainty: Risk, Uncertainty, and Ignorance

The words "risk" and "uncertainty" have a very long history, with these terms being used already in, for example, roman times when discussing business endeavours or harvests. As discussed earlier, ISO 31000 links the two in its definition of "risk as the effect of uncertainty on objectives" (ISO 2018). Its modern history begins with Knight (1921), who introduced a sharp distinction between risk and uncertainty. For Knight, risk is calculable, while uncertainty is not. That is, if one faces a choice where the consequences and their probability of occurrence are known, Knight calls it risk. If either the consequences or the probability of occurrence is not known, Knight calls it uncertainty.

In the mid-1950s, the sharp distinction drawn by Knight started being questioned. Knight focuses on whether probabilities are known, but what if, instead, probabilities merely reflect degrees of belief? Suddenly, a much broader range of phenomena can be treated following a risk-based approach. This idea of seeing probabilities as beliefs is also known as a Bayesian interpretation of probability, and it has substantially increased the use of risk-based approaches (Bolstad and Curran 2016).

In light of recent developments such as climate change and the financial crises, there is now a resurgent interest in uncertainty proper, or Knightian uncertainty. That is, not everything can be reduced to risk using beliefs. What if different people have different beliefs? What about the evidential basis for beliefs? And how to make sense of the frequency with which surprises happen?

In this chapter, we follow the Knightian distinction between risk and uncertainty but add a third category, namely, ignorance. Decision-making under ignorance and without foresight is a concept first explored in ecology, where populations of organisms can be highly successful over time without being able to predict the future. As pointed out earlier, we understand ignorance as a simple technical term describing a lack of knowledge and information, without any implicit value judgement (such as "ignorance due to a lack of education" or "wilful ignorance").

The threefold distinction we are using (see Table 2) is broadly coherent with similar levels of uncertainty as can be found in, for example, Walker et al. (2003, 2013) and Kwakkel et al. (2010). The main difference is that we use a threefold distinction, while many conceptualisations of the level of uncertainty make additional, more fine-grained distinctions.

Table 2 Levels of knowledge and resulting theoretical and practical challenges. (Adapted from Oehmen et al. (2020))

Definitions	Theoretical challenges	Practice challenges
1. Management of risk • Risk: Possible outcomes with known probabilities (Knight 1921) • Conditional probability (Bayesian statistics): Incorporating prior believes into risk assessment (Bolstad and Curran 2016) • Risk management: Coordinated activities to direct and control an organisation regarding its risks (ISO 2018)	• Conflicting definitions of "risk" and "risk management" (Aven 2012, 2016; Aven and Renn 2019) • Articulation of organisational value of risk management (Willumsen et al. 2019)	• One-size-fits-all expectation of risk management standards vs. need for customisation (Oehmen et al. 2014) • Idealised formal risk management neglects actual risk management (including its informal aspects) (Ahlemann et al. 2013; Kutsch and Hall 2010) • Choice of appropriate risk management methods for given decision context and data quality (Tegeltija 2018)
2. Management of uncertainty • Uncertainty: Possible outcomes with unknown probabilities (Knight 1921) • Robust decision-making: Assessing performance across a broad range of possible futures to minimise regret (Walker et al. 2013)	• Delineation of uncertainty and risk (Aven 2012; Flage et al. 2014) • Development of some mathematically very advanced reasoning into actionable methods, while maintaining rigour (Tegeltija 2018)	• Incorporation and communication of uncertainty in decision-making (Funtowicz and Ravetz 1990) • Implementing and operationalising novel uncertainty management methods (Tegeltija 2018)
3. Management of ignorance • Ignorance: Unknown outcomes with unknown probabilities (Smithson 1989) • Resilience: The ability to resist or recover from unexpected events without foresight (Holling 1973)	• Theoretically sound operationalisation of resilience concepts into organisational practice (Wied et al. 2020a) • Reconciliation of expectation of productivity with need for resilience (Martin 2019)	• Articulation of specific and explicit resilience strategies for organisations (Wied et al. 2020a) • Orchestrate cultural shift from "predict and plan" to "monitor and react" (Kutsch et al. 2015; Rolstadås et al. 2011)

Level of Value Diversity

Risk management addresses the impact of uncertainty on objectives, i.e. the consequences of uncertainty (ISO 2018). What consequences matter and how to assign a value to them is a second dimension along which we can distinguish different approaches for managing risk. Classic decision theory assumes that all consequences can be aggregated into a single number of goodness, be it utility or monetary (Savage 1951). However, in many real-world situations, this assumption is problematic. Even if the different parties to a decision agree about what matters, they may still disagree about what is acceptable.

A classic example is the question "what is safe enough?." For example, in the context of flood risk management, we might all agree that we want to avoid floods. However, what is safe enough? How high should the embankments be, and at what costs? More severely, actors might care about quite different outcomes, and it might not be apparent at all how these different outcomes are to be aggregated into a single measure of goodness. Such aggregation is theoretically problematic (Arrow 1950; Franssen 2005; Kasprzyk et al. 2016), while often also a significant source of contestation (Rittel and Webber 1973) or ethically problematic (Taebi et al. 2020) (e.g. what is the value of a human life?). Continuing on the flood risk example, in Dutch water management practice over the last century, we can see a shift from focusing solely on flood risk in response to the 1916 floods, towards the consideration of environmental and socio-economic concerns next to flood safety in the evolving response to the 1953 flood, with environmental concerns taking centre stage in the mid-1990s (Correljé and Broekhans 2015). For ease of exposition, the remainder will distinguish between situations with commensurate values and incommensurate values. If values are commensurate, it is in principle possible to develop an uncontested and acceptable way of aggregating diverse outcomes into a single measure of goodness. If values are incommensurate, such an uncontested and acceptable procedure is ruled out.

An Engineering Systems Perspective on Managing Risk, Uncertainty, and Ignorance: Addressing Levels of Uncertainty and Levels of Value Diversity

In the following sections, we present an integrated view of engaging with different levels of uncertainty in engineering systems design that also accommodates different levels of value diversity among the stakeholders. This yields six quadrants, as illustrated in Fig. 2. Each quadrant is discussed in turn in the subsequent sections. We aim to present an overview of relevant risk, uncertainty, and ignorance management approaches (both system models and decision support processes) and illustrate their diversity; we do not aim to replicate the current bias in both application and academic publishing towards specific quadrants, especially the very intense use of methods describing risk under commensurate values. Some approaches, such as risk communication and public engagement, are relevant for multiple quadrants.

A general observation worth noting is that management approaches tend to offer higher fidelity system models as we move towards commensurate values and known probability distributions (the lower left-hand corner of Fig. 2). In contrast, the focus on general stakeholder engagement and decision support processes increases as we move towards ignorance and incommensurate values (the top right-hand corner).

Understanding and Managing Risk in Engineering Systems

Risk Under Conditions of Commensurate Values

The foundational concept of risk management is that risk can be expressed in the language of probability theory or more precisely, through frequency probabilities (see Bertsekas and Tsitsiklis (2008) and Blitzstein and Hwang (2019) for two introductory texts). They analyse the sample space of a random experiment and describe the occurrence of specific events in that sample space. The relative frequency of an event is defined as the probability of that specific event occurring in the sample space. The events being investigated are associated with a loss, leading to either a discrete description of risk, i.e. probability-loss pairs such as "the risk of exceeding the budget by 20% in the next 2 years is 5%," or continuous probability distributions expressed as probability density functions of a continuous outcome variable. These practices find broad application in engineering systems design, ranging from safety management to cost management to the estimation of future maintenance needs and user demand.

Frequency probabilities are well suited to capture aleatory uncertainty, i.e. uncertainty due to the inherent randomness of the natural world. However, to better capture epistemic uncertainty, i.e. uncertainty due to a lack of knowledge, Bayesian probability theory extends the concept of frequency probabilities to allow capturing and updating "beliefs" regarding future events (see Jaynes et al. (2005) for an introduction on Bayesian probability theory and statistics).

The ISO 31000:2018 "Risk Management – Guidelines" (ISO 2018) standard was developed to provide general risk management principles, an implementation and adaptation framework, as well as a reference process for risk management in organisations. It is deliberately not domain-specific to facilitate cross-functional integration of risk management processes. It provides a helpful reference framework to compare and reconcile various specific risk management activities. The main elements of the ISO 31000:2018 risk management reference process are:

- **Risk identification:** Identification and description of key risks within the scope of the risk management activities. Structured along sources of uncertainty as well as affected objectives.
- **Risk analysis:** Qualitative and/or quantitative modelling and description of risks in context. The specific methods and descriptions being used (e.g. point estimates vs. continuous probability distributions) depend on fundamental

scoping decisions (see below). This includes analysis of time-dependent (i.e. dynamic) factors, as well as sensitivities and confidence analysis.
- **Risk evaluation:** Categorisation of risks regarding the type of future action that will be taken to respond to them and associated decision support. It includes articulating actionable criteria or limits that inform decisions regarding risk responses. Other than directly influencing the probability of occurrence and/or impact of a risk, outcomes of risk evaluations are also a "do nothing" option, as well as additional risk analysis or adjustment of objectives.
- **Risk treatment:** The process of articulating and implementing risk responses, including setting up metrics to assess their effectiveness and risk re-evaluation (i.e. if a risk that has been responded to is now below the threshold for further action).
- **Monitoring and review of risk, mitigation, and risk management**: Monitoring maintains transparency during the risk management process, facilitates a continuous improvement process, and integrates the risk management process into quality management and other process management processes.

As well as contextualising management processes:

- **Communication and consultation during risk management:** Engagement of stakeholders to facilitate a common understanding of the risk landscape and risk management process but also to integrate expertise and experience into the risk management process.
- **Establishing scope, context, and criteria for risk management:** Customisation of risk management process towards the needs of key stakeholders, including scoping risk identification activities or articulating risk evaluation and treatment guidelines.
- **Recording and reporting risk management activities and outcomes:** Documentation and dissemination of key activities and outcomes of the risk management process, such as risk registers or mitigation actions.

There exist a range of engineering-specific risk management processes (see Table 3), including risk management processes proposed by NASA (Dezfuli et al. 2010; NASA 2014, 2017; Stamatelatos et al. 2002), risk management processes as part of systems engineering (Walden et al. 2015), project risk management processes (e.g. PMI 2017; TSO 2017), or a wide range of domain-specific safety management standards (e.g. the ISO 45000 family of standards).

The project management literature offers several risk management frameworks, for example, as part of the PMI *Project Management Body of Knowledge* (PMI 2017) or the PRINCE2 project management framework (TSO 2017). The focus is on project management-related risks (such as cost and schedule) and also addresses other organisational risks, external risks, and technical risks. Risk management aims to protect against adverse impacts on scope, schedule, cost, and quality.

There are also several risk management standards and guidelines that were developed by the NASA, focusing on developing and operationalising highly

Table 3 Overview of select risk management reference processes (see text for references)

ISO 31000	PMI	NASA	INCOSE
Risk identification	Identify risks	Identify risks	Analyse risks
Risk analysis	Qualitative risk analysis Quantitative risk analysis	Analyse risk	
Risk evaluation	Plan risk response		
Risk treatment	Implement risk response	Planning	Treat risks
Monitoring and review	Monitor and control risks	Communicate, control, and track risks	Monitor risk Manage the risk profile
Communication and consultation	*Implicit*		
Establishing the context	Plan RM	Develop strategy	Plan risk management
Recording and reporting	*Implicit*	*Implicit*	*Implicit*

integrated technical systems. This includes the NASA's *Risk-Informed Decision Making Handbook* (Dezfuli et al. 2010), guides for probabilistic risk assessment in the context of complex technical programmes (Stamatelatos et al. 2002), or formal risk management process standards (NASA 2014, 2017). Risk here is defined as the potential for performance shortfalls of the system under development. It considers safety, technical (i.e. technical performance), cost, and schedule risks.

The INCOSE risk management recommendations also focus on the development of complex systems. It considers technical performance, cost, schedule, and programmatic risks (the last one describing a source of uncertainty instead of an impact category). It embraces simple point estimates for risks and addresses human factors such as risk perception and the fact that different risks may hold different importance among stakeholders.

A central shared assumption of these risk management approaches is that stakeholder value, while it may differ to some degree from stakeholder to stakeholder, can ultimately be expressed as a quantifiable measure of *utility* (Pratt 1964).

The foundation of modern-day risk analysis is the idea of subjective expected utility as axiomatised by Savage (1954). According to this theory, an individual decision-maker who adheres to the axioms of rationality has both a personal utility function and a personal probability distribution (typically Bayesian, hence subjective). The optimal decision is then the one that maximises the expected utility. Experiments with people have shown that people deviate systematically from the correct decision according to subjective expected utility theory (Kahneman 2011). This has given rise to various bodies of work that try to explain these systematic deviations of real-world behaviour from what is considered correct according to subjective expected utility, for example, through heuristics and biases. More recently, Savage has been criticised from a more mathematical point of view: there is a fundamental difference between the expected value over time and the expected value across events (Peters 2019). For example, if we have 100 fair dice, the expected value will be the same as the expected value of rolling one of these dice 100 times. If, however, we have 100 unfair dice, the expected value over the ensemble of dice is not the same as the expected value of rolling one die 100 times.

For engineering systems design, the concept of systemic risks is also relevant. Systemic risks describe a situation where failures of single or multiple components cause a cascading effect that will degrade (or completely negate) system-level performance (Acharya et al. 2017). As a concept, it originated and is well established in in the financial sector, describing risks where the collapse of single (or very few) financial institutions can cause the breakdown of an entire country's or region's financial system (de Bandt and Hartmann 2001). While extensively studied in the context of financial systems (Fouque and Langsam 2013), the application of the concept of systemic risk beyond financial system is still scarce (Gros et al. 2016).

Risk Under Conditions of Incommensurate Values

Under conditions of incommensurate values, our fundamental philosophical world view becomes highly relevant: Do we adopt a positivist attitude (Wicks and Freeman 1998), where a fact-like "true" answer exists, or do we take a social constructivism perspective (Kukla 2000), where the correct answer becomes everything depends on how each individual perceives reality and makes sense of it? This is highly relevant in engineering systems design, for example, regarding the legitimacy and cost justification of large engineering systems interventions, or the comparative safety merits of alternative technical and organisational choices.

Risk management rooted in the technical and natural sciences has a natural bias towards a positivist, fact-based, or "technocratic" worldview: With enough analysis and conversation, everyone will agree to the numbers on my Excel sheet, including the overall optimal priorities and weights. Effectively, the belief is that incommensurate values are just poorly analysed commensurate values and can be transformed into those. The risk management process frameworks discussed in the previous section cover this approach under "communication and consultation."

Under conditions of incommensurate values, we have to embrace a post-positivist stance (Geraldi and Söderlund 2018) in order to resolve the paradox of both respecting and accommodating individual perceptions of risk (and reality) while at the same time implementing a structured and objectively controllable risk management process. This section will briefly illuminate three relevant bodies of work in this context: risk-related public engagement, risk communication, and social movement theory.

Public engagement or public participation is a highly relevant field once we accept that risk management is a discursive process in situations of incommensurate value. Public engagement can yield similar benefits to a co-creation process, in leveraging both collective knowledge and creativity and creating buy-in and ownership with the engaged stakeholders (Sanders and Stappers 2008). However, they may also yield the opposite result and create anger and mistrust if they do not meet quality standards and stakeholder expectations (Innes and Booher 2004; Rowe and Frewer 2000). Public engagement can be differentiated into communication, consultation, and engagement and their associated methods (Rowe and Frewer 2005). Engagement of the public will always be shaped by the existing knowledge and reflection of the groups that are being engaged and requires careful consideration when developing engagement formats (Whitmarsh et al. 2011).

Closely linked to public engagement are risk communication and its corollary, risk perception. It forms part of every engagement process. A practical and fair risk communication process respects our natural risk perception biases (see section "Personal and Organisational Biases Regarding Risk, Uncertainty, and Ignorance" in this chapter) while preparing a "slow thinking" engagement with the subject matter. The opposite is, however, much easier: exploiting our natural perception biases to amplify risk perception. Therefore, responsible risk communication has a dual role of addressing the subject matter at hand and being part of improving the quality of societal discourse by demonstrating and training appropriate communication methods. Some of the most relevant factors include the following (Kasperson 2014; Renn and Benighaus 2013; Wachinger et al. 2013):

- Personal experiences of specific risks are the strongest communication and powerfully shape the risk perception of individuals.
- Trust in the communication relationship is also highly relevant. It is a foundational factor in enabling fact-based risk communication. It is arguably much more significant than "facts." This becomes particularly challenging if there is a perceived conflict of interest by one of the parties, e.g. a company arguing for the safety and benefit of their own products.
- One element influencing trust is the open communication of the quality of a risk assessment, for example, through the NUSAP model (Funtowicz and Ravetz 1990). It makes risk assessments more credible by providing context information on the origin and quality of data, the underlying model, and the experience of the assessors.
- A paradoxical observation is that a high personal perception of risk does not necessarily translate into action. This is particularly relevant if the objective of the communication is to incentivise action, such as personal or organisational preparedness. The reasons for inaction also highlight options for accompanying action and include (1) acceptance of risk, as perceived benefit significantly outweighs perceived risk; (2) denial of agency for taking mitigation action, i.e. "not my problem to solve"; and (3) perceived lack of sufficient resources to take action.
- Media exposure to risk and risk narratives plays a lesser but still significant role as an amplifier in the causal chain between experience, trust, perception, and action.
- Communication must relate to risk perception. Four aspects of risk perception can be discerned that significantly impact risk communication (Renn and Benighaus 2013). This makes it evident that there will not be a "one size fits all" communication strategy. These aspects include (1) cultural background, including the

questions mentioned above of identity and meaning; (2) social-political factors, such as trust and personal values; (3) cognitive-affective factors, such as reference knowledge or prior beliefs; and finally, (4) heuristics of information processes, such as the affect heuristic or dread risks.

- This highlights that both scope and persistence are required for a successful communication campaign, especially if it involves complex subject matter. Highlighting the risk of tobacco smoking was a success after 30 years, while we still have not found a successful approach to discuss the disposal of nuclear waste (Kasperson 2014). The scope is relevant, as a complex subject matter will affect a large group of stakeholders, most likely in different ways. Persistence is relevant, as a "slow thinking" engagement requires time, especially to reach a larger population group.
- Concerning the affect heuristic discussed above, a communication strategy that credibly establishes the benefits of a specific action will automatically reduce the perceived risk, and in reverse, a communication strategy that aims to maximise perceived risk will automatically discredit any possible benefits.
- The affect heuristic also has implications for more established technologies: As benefits are being taken for granted (e.g. mobile phones) and thus become less immediately apparent, the concern for potential risks (i.e. "5G radiation") increases.
- Risk communication involving low probability but high consequence events is difficult, as other risk perception factors play a significant role. This includes dread risk (based on novelty and degree of perceived control over the risk) and the resulting social amplification of risk. The resulting implications for risk communication are: if novelty and lack of control are emphasised, the risk will be communicated as much more substantial (and vice versa).
- It remains a fact that decision-makers are not particularly interested in detailed risk- and uncertainty-based assessments. There is a natural conflict of interest that encourages decision-makers to find "hard evidence" supporting their actions to minimise their liability in case of negative outcomes. Risk communication is not just a challenge for the general public.

Social movement theory plays an essential role in linking public engagement and risk communication to action, especially public action. When contemplating large engineering systems interventions, public support (or opposition) is crucial. Arguably, the objective of engagement and communication is to incentivise constructive actions and disincentivise destructive action. Social movement theory offers an explanatory framework for when and why people move from being complacent to taking collective action. Work on social movement theory in the context of large engineering projects has shown that three major factors are influencing public action (Scott et al. 2011):

- A perceived opportunity or threat. This may concern a wide range of values, such as power, civil liberties, money, or health. The relationship to risk communication is twofold: Either the public sees an opportunity to overcome a long-established

perceived risk, or there is a perception of an emerging threat that must be countered.
- Mobilising structures: Mobilising structures include means of communications as well as creating opportunities for action. Risk communication, especially if it aims to amplify risk perception, profits from social amplification of risk, i.e. the tendency of an appealing story to turn “viral” in both traditional media and social media. To be effective, this must be accompanied by a concrete option for action – from a “like” to protest and boycotts.
- Framing of the narrative: The framing provides the “fuel” for action by fulfilling the affective requirement for emotions. The most effective drivers are fear and anger, creating an imbalance favouring the amplification of risk perception by exploiting perception biases. It also creates the collective identity of “us vs. them” necessary to incite action, further playing into the hands of those seeking to reduce the problem to a simple black-and-white storyline.

Understanding and Managing Uncertainty in Engineering Systems

Uncertainty Under Conditions of Commensurate Values

As engineering systems design tasks often include a high degree of technical novelty and design systems for very long life cycles with currently not precisely known operating environments or user needs, conditions of uncertainty are common where knowledge of probabilities is unavailable to designers.

The first commonly used method for dealing with uncertainty is through a Delphi (Linstone and Turoff 1975). The Delphi method derives its name from the ancient Greek oracle of Delphi, which rulers throughout ancient Greece consulted before any significant undertaking. The Delphi method is a well-established method for exploring uncertain futures developed in the mid-1950s at the RAND Corporation (Linstone and Turoff 1975). In essence, the Delphi method is a structured, iterative, and qualitative form of expert elicitation. A panel of experts is identified. Each of them is asked to fill out a survey. Next, the experts’ answers are collected and synthesised, and a new survey is sent out. This new survey contains anonymised responses from the first round as selected by the people running the Delphi. Each expert can now update her answer as well as respond to any thoughts of the other experts. This second round of surveys is again analysed to see where experts are converging and where disagreements remain. By iterating in this way, over time, the method aims at arriving at a consensus among the panel of experts. Essential in performing a Delphi is to carefully structure the flow of information, have repeated feedback and updating of beliefs of experts in light of this, as well as ensure anonymity of the experts.

A second widespread way of dealing with uncertain futures is by scenario planning. The term “scenario” is derived from the movie and theatre world. It used to indicate the “course of events” or the “story in its context.” Working at the RAND

Corporation, Herman Kahn started using the term scenario for his work on exploring the possible ways in which nuclear exchange with the Soviet Union might unfold (Bradfield et al. 2005). At the end of the 1960s and the beginning of the 1970s, the term scenario was also used in other areas. Known examples can be found in the reports to the Club of Rome, where exhaustion of the world's natural resources stock is sketched (Meadows et al. 1972, 2004), and in the energy scenarios that played a central role in the "Social Discussion Energy Policy" in the Netherlands at the beginning of the 1980s. In that discussion, scenarios were sketched in which, based on policy choices, an essential part of Dutch electricity would be generated through nuclear energy, coal, or reusable resources (sun, wind, and water). Scenarios are also used in the business sector. The most striking example of this is Shell. Thanks to the scenario Shell developed in the late 1960s and early 1970s, the company was better prepared than the competition for the unexpected changes in the oil market during the oil crisis that was precipitated by the OPEC in the 1970s (Chermack 2017).

During the last decennium, working with scenarios has become very popular in the private and public sectors. At the same time, the use of the term has widened considerably. The term "scenario" is so general that it can indicate every form of exploration of the future, including explorations based on extrapolations, regression models, or causal simulation models. For example, in international climate research, they speak of diverging climate scenarios resulting from "high" or "low" emission scenarios. The term is also used in other disciplines, such as safety science. There it involves the possible combinations of disrupting circumstances that cause failures. The consequence is that we cannot speak of "the" scenario approach. Approaches vary widely, where the terms "scenario" and "scenario approach" are used differently.

This variety of ways in which the term scenario is being used can be structured by considering three different dimensions (Enserink et al. 2010). These dimensions are:

- **Time**: a scenario describes either an uncertain future at a certain point in time or the dynamics over time from the present situation to a future one.
- **Values**: some scenarios are explicitly normative, describing, for example, an ideal future utopia or a dystopia. Other scenarios instead remain silent on the desirability of the described events and offer an exploration of what might or could (but not should) happen. Explorative scenarios are often used to stress test candidate strategies on their robustness, while normative scenarios are often used as a starting point for discussing how we might arrive at that desired future.
- **Scope**: scenarios can differ in what aspects of a problem or system are considered. A context scenario describes a possible external context of a policy problem. A policy scenario described what the implementation of a given policy might look like. A strategic scenario describes both context and policy.

Many methods exist for creating scenarios. These methods can be grouped into different families, depending on their origin. Arguably the best-known family of methods is known as scenario logic. Scenario logic methods are typically used for creating context scenarios. It typically starts with identifying critical exogenous forces affecting the system under investigation. Next, these forces or factors are grouped based on relatedness. These groups are sometimes also known as megatrends. The various megatrends are evaluated regarding how uncertain their future evolution is and how significant their impact on the system is. The aim is to identify the two or three critical megatrends that are highly uncertain and strongly affect the system. These two or three megatrends form a scenario logic. Given two megatrends, you have four scenarios by taking the extreme ends of both megatrends. Given three megatrends, you have eight possible scenarios. Typically, not all eight would be fully developed. Instead, analysts are encouraged to pick the non-trivial, more surprising combinations and develop these into fully fledged scenario narratives. This is motivated by the fact that scenario analysis aims to engage in a strategic conversation. Best case, worst case, and business as usual scenarios are at the forefront of everyone's mind, so these do not tend to foster a strategic conversation.

Uncertainty Under Conditions of Incommensurate Values

The conditions of uncertainty in engineering systems design extent to conditions where in addition to the absence of probability data, there is also a lack of agreement, or at least significant ambiguity, regarding the alignment of critical stakeholder values. As engineering systems design challenges involve large stakeholder groups, this situation is not unusual and has been explicitly addressed in situations requiring long-term policy decisions governing engineering systems design.

In recent years, primarily in the context of climate adaptation and climate mitigation, there has been a growing interest in developing and testing new approaches for supporting multi-stakeholder decision-making under uncertainty. Typically, in these contexts, the various parties to a decision do not agree on which outcomes matter and their relative importance. Moreover, they do not know what the future will look like and might have profoundly different ideas about this. This combination of value incommensurability and Knightian uncertainty is also called "deep uncertainty." Under the label of decision-making under deep uncertainty, various approaches have been put forward.

What unites the various approaches for supporting robust decision-making under deep uncertainty is three key ideas:

1. **Exploratory scenario thinking**: In the face of deep uncertainty, one should explore the consequences of the various presently irreducible uncertainties for decision-making. Typically, in the case of complex systems, this involves the use of computational scenario approaches. The use of models is justified by the observation that mental simulations of complex systems are challenging to the point of infeasibility (Sterman 1989; Brehmer 1992).
2. **Adaptive planning**: Adaptive planning means that plans are designed from the outset to be adapted over time in response to how the future may unfold. The way a plan is designed to adapt in the face of potential changes in conditions is

announced simultaneously with the plan itself rather than in an ad hoc manner post facto.

3. **Decision aiding**: Decision-making on complex and uncertain systems generally involves multiple actors agreeing. In such a situation, decision-making requires an iterative approach that facilitates learning across alternative framings of the problem and learning about stakeholder preferences and trade-offs in a collaborative process of discovering what is possible (Herman et al. 2015). In this iterative approach, the various decision-making approaches under deep uncertainty often put candidate policy decisions into the analysis by stress testing them over a wide range of uncertainties. Their effect on the decision then characterises the uncertainties. The challenges inherent in such processes are reviewed in depth by Tsoukiàs (2008).

The various approaches for decision-making under deep uncertainty all follow essentially the same stepwise approach. One starts with the identification of promising decision alternatives. This can be based on expert opinion, but often it involves the use of (many-objective) optimisation. The aim is to find solutions that collectively represent the trade-offs across the various incommensurable objectives. Next, these solutions are evaluated across many different scenarios. These scenarios represent alternative ways in which the various uncertain factors might play out in the future. The results of this evaluation are analysed in the next step using various machine learning algorithms. The aim is to partition the space spanned by the various uncertain factors into regions where policies can satisfy pre-specified minimum performance requirements and regions where policies fail to do so. Ideally, these regions are characterised by human interpretable rules. Next, the analyst faces a choice. If the regions of failure are judged to be significant, a second iteration starts. New or modified policies that are expected to be less vulnerable are put forward, stress-tested, and analysed. This iterative process continues until a set of solutions emerges that is judged to perform satisfactorily across the entire uncertainty space. Once such a set is found, the final step is to analyse the trade-offs on the various objectives under uncertainty.

Central in decision-making under uncertainty is the idea that decisions and the resulting engineering systems interventions and governing policies should be robust. A wide and varied literature exists on how to measure robustness. A significant distinction is between robustness as being able to perform satisfactorily in many scenarios and robustness as not regretting the choice. A well-known and often used satisficing robustness metric is the domain criterion. The domain criterion measures the fraction of scenarios in which a given policy option can meet pre-specified performance constraints. In the outlined approach to supporting decision-making under deep uncertainty, this domain criterion is implicitly used to partition the uncertainty space into regions of success and failure. Satisficing metrics focus on each policy option.

In contrast, regret metrics are comparative. A well-known regret metric is minimax regret. This metric first assesses for each scenario what the best performance is. Next, for each policy option, one calculates the difference between the best possible performance and the performance obtained by the option under consideration. The most robust (or least regret) option has the lowest maximum regret across all scenarios. Since satisficing and regret metrics measure different dimensions of what it means for a policy option to be robust, it is good practice to use both.

Understanding and Managing Ignorance in Engineering Systems

Ignorance in engineering systems design implies that we are unaware of, for example, critical requirements, technical limitations, or future operating scenarios. Given the long life cycles of engineering systems and the diverse stakeholder base during their design and operation, addressing "ignorance" during engineering systems design and later construction and operation is critical. This implies embracing the fact that engineering systems design is never finished but requires ongoing attention during construction and operation as new knowledge emerges – or at the very least, evidence of the absence of critical knowledge.

There is a continuum of management practices to address conditions of ignorance during the design, construction, and operation of engineering systems. The particular challenge is here, again, to address both technical and social factors – be it as "sources" of ignorance or as impact areas of ignorance. In the following sections, we will discuss the associated capabilities under the umbrella term of resilience.

We define resilience as an engineering system's capability to provide critical functions under conditions of unforeseen change, i.e. responding to the effects of ignorance. For a discussion of the history of resilience thinking and a review of a range of definitions, please see Alexander (2013), Rose (2017), and Wied et al. (2020).

Following Holling's original thinking on ecological resilience, there are two related key aspects in resilience management (Holling 1973, p. 21): First, resilience management addresses recognised ignorance. It is based on the assumption that future events are not foreseen and practically not foreseeable in their diversity. In practical terms, resilience management starts where a carefully crafted risk register ends – resilience management expects the unexpected. The second aspect is that, consequently, resilience management emphasises general preparedness to respond to a surprising future instead of specialised capabilities to respond to particular events.

To operationalise resilience in a specific context, we need to answer three questions (Wied et al. 2020b).

1) Resilience of what? What are the key performance attributes of the engineering systems that are the focus of attention? Performance attributes may be critical functions, such as a certain level of communication capability or food supply. They may also be indirectly expressed through protecting the integrity of specific system elements (e.g. protecting an institution or community) or system relationships (e.g. maintaining control).
2) Resilience to what? Ideally, resilience provided general preparedness for any unforeseen changes: sudden or gradual, temporary or permanent, internal or

external, technical or social, affecting any element and possible combination of the engineering systems. In practical terms, there must be scoping decisions, leading to a not-quite-general preparedness.

3) Resilience how? The bulk of this section deals with resilience management practices for engineering systems. They address both structural factors (i.e. the configuration of the engineering systems with its elements and relationships) and dynamic factors of system behaviour and governance.

Commensurate with the range of definitions of resilience (see above), there are various conceptualisations of resilience response timelines. Figure 3 summarises several resilience-related properties of engineering systems:

- Preparedness describes the degree to which an engineering systems can be considered "generally prepared" to face unexpected, adverse changes.
- Robustness describes the capability of an engineering systems to continue providing critical function at a practically nominal rate while being impacted by unexpected changes.
- Resistance expresses capabilities to affect a graceful degradation of functionality that is both slow and able to maintain critical levels.
- Recoverability summarises the engineering systems capability to recover from short-term disruptions and/or adapt to permanent changes.
- Antifragility expresses the concept that engineering systems can improve by exposure to unforeseen changes and achieving a performance exceeding pre-disturbance levels.

The following two sub-sections introduce resilience models and practices that are relevant in the context of engineering systems. We consider approaches relating to both socio-organisational resilience (project resilience, organisational and organisational network resilience, team and individual resilience) and technical

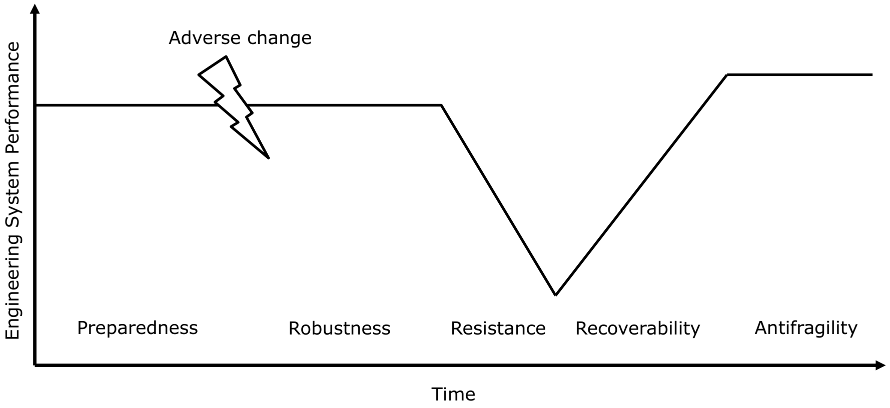

Fig. 3 Resilience-related properties of engineering systems

and engineering resilience approaches as dealing with ignorance under conditions of commensurate values: Performance attributes are typically clearly articulated and agreed upon. In the second section, we consider resilience approaches that cover conditions of incommensurate or unknown values, such as socioecological approaches to resilience and the application of the precautionary principle.

Ignorance Under Conditions of Commensurate Values

Technical and engineering resilience: From an engineering perspective, resilience is an emergent system property that mitigates between uncertain conditions and system performance (Jackson and Ferris 2013; Uday and Marais 2015; Wied et al. 2020b). Typical related properties are summarised in Table 4. It has been studied in the context of systems engineering, alongside other related emergent properties such as survivability (Ellison et al. 1999), changeability (Ross et al. 2008), flexibility (Broniatowski 2017; Ryan et al. 2013), or robustness (Potts et al. 2020; Ross et al. 2008). The focus is on maintaining defined functions, avoiding discontinuities, and rapidly recovering functionality to a pre-disruption state. In the safety community, the concept of "resilience engineering" (Hollnagel et al. 2006; Leveson 2020; Aven 2022) has emerged.

Socio-organisational resilience: While any structuring will somewhat remain arbitrary, we will discuss socio-organisational resilience into three categories: (1) Individual and team resilience; (2) project and organisational resilience; and (3) supply chain and industry resilience (see Table 5).

Individual and team resilience directly impact overall engineering systems resilience, as human action and decision-making (or non-action and non-decision-

Table 4 Resilience as an emergent property (following Wied et al. 2020b)

Category of resilience properties	Emergent resilience properties
Recovery	Recover, return, self-righting, reconstruction, bounce back, restore, resume, rebuild, re-establish, repair, remedy
Absorption	Absorb, tolerate, resist, sustain, withstand, endure, counteract
Adaptation	Adapt, reorganise, transform, adjust, re-engineer, change, flexibility, self-renewal, innovation
Reaction	Respond, react, alertness, recognition, awareness
Improvement	Improve, grow
Prevention	Prevent, avoid, circumvent
Minimal/graceful deterioration	Minimal, restricted, acceptable, contained, graceful deterioration/ degradation
Anticipation	Anticipate, predict, plan, prepare
Coping	Coping, cope
Survival	Survival, persistence
Mitigation	Mitigation, manage consequences
Others	Learning, management, action, resourcefulness

Table 5 Overview of socio-organisational concepts of resilience

Area of socio-organisational resilience	Key aspects
Individual and team resilience	Critical review of the concept of individual psychological resilience (Fletcher and Sarkar 2013) Factors shaping individual resilience to high-stress environments (Rees et al. 2015) Review of "team resilience" concepts in workplace context (Chapman et al. 2020) and empirical study of influencing factors (Alliger et al. 2015) Relationship of individual psychological resilience and organisational incentives (Shin et al. 2012) Describing and enhancing resilience of small groups (Zemba et al. 2019)
Resilience of temporary (i.e. projects) and permanent organisations	Theory and practice of resilience in project management (Kutsch et al. 2015; Wied et al. 2020b) Organisational capabilities enabling recovery and disaster response (Chang-Richards et al. 2017; Choi et al. 2019; Steinfort 2017), including business continuity (Herbane et al. 2004; Hiles 2010) Review of "organisational resilience" concepts, theoretical framing, and quantification approaches (Barin Cruz et al. 2016; Burnard and Bhamra 2011; Duchek 2020; Linnenluecke 2017; Vogus and Sutcliffe 2007; Wood et al. 2019)
Supply chain and enterprise resilience	Concepts and application of supply chain resilience (Bhamra et al. 2011; Brusset and Teller 2017; Kamalahmadi and Parast 2016; Sheffi 2017) Resilience of extended enterprises and industries (Erol et al. 2010; Sheffi 2005)

making) are vital to any sociotechnical system. Resilience, as a psychological concept on the individual and group level, most commonly describes the ability of individuals and groups to maintain performance under extraordinary circumstances and learn from those experiences.

The organisational level focuses on capabilities, practices, and organisational structures that relate larger groups of individuals with one another and their technical infrastructure within permanent and temporary organisations. Research in this domain addresses both generic resilience capabilities, practices, and theories and contains a significant body of work explicitly dedicated to response and recovery activities. Both project and organisational perspectives on resilience are highly relevant in the engineering systems context, as they form integral parts of the operation of and intervention in engineering systems.

Supply chain and enterprise resilience: The most comprehensive level of socio-organisational resilience in engineering systems is the resilience of extended supply chains and enterprises. They can be seen as the overall possible "organisational solution space" to operate and change engineering systems. Resilience concepts here focus both on currently implemented supply chains and enterprise architectures and their possible alternative configuration, including the reconfiguration of existing partners and adding/removing stakeholders.

Ignorance Under Conditions of Incommensurate Values

The concept of “incommensurate values” becomes problematic in the context of ignorance and resilience, as resilience by definition does not rely on foresight. However, in practical terms, resilience does require us to explicitly articulate the resilience “of what” and “to what.” While not necessarily representing incommensurate values, we will in the following discuss concepts of “general resilience” that do not necessarily expect an articulation of specific common resilience targets.

The resilience discussion is typically placed in the context of “social-ecological systems,” as the primary source of adverse events that is studied are “unprecedented disturbances” from natural disasters and their knock-on effects, resulting in “unfamiliar, unexpected and extreme shocks” (Carpenter et al. 2012). They discuss system-level properties that partially overlap with those discussed for technical or engineering resilience, such as diversity, modularity, openness, reserves, feedbacks, nestedness, monitoring, leadership, and trust.

In social-ecological systems theory, resilience is an integral part of the dynamics and development of those systems, alongside adaptability and transformability (Folke et al. 2010). In this context, adaptability describes the system’s capability to continually “adapt” to changing external stimuli to stay within critical performance thresholds, while transformability refers to the capability of the system to transcend those thresholds into new development paths. A vital attribute here is nestedness, i.e. the capability of learning on the subsystem level from more minor disturbances to create system-level resilience capabilities. A central argument thus becomes that we must focus on smaller-scale resilience to enable larger-scale resilience that may be too complex to influence directly.

A significant area of research is the relationship between system-level resilience and sustainability. This is a two-way relationship, as humans both shape the biosphere and are in turn shaped by it (Folke et al. 2016). In this context, sustainability is an enabler of long-term resilience and the lack of sustainability becoming a driving need for additional resilience. The governance of sociotechnical transitions in the context of social-ecological resilience is one key area (Smith and Stirling 2010; Wilkinson 2012).

Attempts to further characterise “general resilience” through taxonomies yield similar characterisations as those of specific resilience discussed previously (Maruyama et al. 2014), i.e. type of shocks, target systems, time-phase of concern, and type of recovery, while still attempting to identify higher-order resilience principles such as redundancy, diversity, and adaptability.

Other aspects of general resilience include social-ecological memory and how diversity in those memories is relevant to foster general resilience (Nykvist and Von Heland 2014).

A specific focus in the context of resilience provides the school of thought surrounding the precautionary principle. While the precautionary principle is discussed in a context that does not necessarily use the term “resilience,” the objective is similar: protecting sociotechnical, or social-environmental, systems from harm in the face of ignorance as well as uncertainty (Sandin et al. 2002).

However, the precautionary principle does imply that action is mandatory in order to protect health and the environment (Sandin 1999) and has an explicit legal (Sunstein 2003) and ethical (Manson 2002) dimension. The precautionary principle has become a central element of national and international policy making (Foster et al. 2000; Kriebel et al. 2001), while the expected “standard of proof” necessary to justify action remains debated.

The “standard of proof” debate highlights an interesting tension: The tension between the “need for certainty to take action” and the “need to take action under uncertainty.” It pervades all types of management and decision-making under conditions of risk, uncertainty, and ignorance.

Conclusion

We believe that effectively engaging – and leveraging – uncertainty in all its facets is a critical success factor in engineering systems design. In this chapter, we introduced a more nuanced interpretation of the term “risk management” that, we believe, does justice to the complexity of engineering systems design tasks. By decomposing “risk” along levels of increasing uncertainty into risk, uncertainty, and ignorance, we enable a more goal-oriented development, discussion, and use of “risk management practices” that fit their specific purpose. As complex stakeholder landscapes also characterise engineering systems design tasks, we further differentiate our practices for commensurate and incommensurate stakeholder values.

“Classic” techniques of risk management must further evolve to fully address emergent risk phenomena in cyber-physical-social systems, including, for example, risks associated with the performance, validation, and trust in AI-based systems. The applications of uncertainty management must further grow into the mainstream of early engineering systems design activities, supporting a broader exploration of solution alternatives and enabling a more meaningful early-stake stakeholder dialogue to build trust and legitimacy. With the large engineering systems level interventions necessary to make the sustainable transformation of our critical infrastructure a reality, our design approaches also need to be able to handle the uncertainty inherent in future climate developments. And finally, we must embrace resilience as a core design objective, both in terms of achieving technical resilience and supporting societal resilience, and thus cohesion, through engineering systems design.

Cross-References

- ▶ Designing for Emergent Safety in Engineering Systems
- ▶ Engineering Systems Design: A Look to the Future
- ▶ Engineering Systems Integration, Testing, and Validation
- ▶ Engineering Systems Interventions in Practice: Cases from Healthcare and Transport

- ▶ Flexibility and Real Options in Engineering Systems Design
- ▶ Properties of Engineering Systems
- ▶ Technical and Social Complexity
- ▶ The Evolution of Complex Engineering Systems

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