Safety Science 146 (2022) 105567

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

The policy operations room: Analyzing path-dependent decision-making in wicked socio-ecological disruptions

Janne I. Hukkinen [a,*], Jussi T. Eronen [b], Nina Janasik [a], Sakari Kuikka [b], Annukka Lehikoinen [b], Peter D. Lund [c], Helmi Räisänen [a], Mikko J. Virtanen [d]

[a] Environmental Policy Research Group, Helsinki Institute of Sustainability Science, Faculty of Social Sciences, University of Helsinki, PO Box 54 (Unioninkatu 37), 00014 Helsinki, Finland
[b] Ecosystems and Environment Research Programme, Helsinki Institute of Sustainability Science, Faculty of Biological and Environmental Sciences, University of Helsinki, PO Box 65 (Viikinkaari 1), 00014 Helsinki, Finland
[c] Department of Applied Physics, School of Science, Aalto University, PO Box 15100 (Puumiehenkuja 2), 00076 Aalto Finland
[d] Faculty of Social Sciences, Tampere University, 33014 Tampere University, Finland

ARTICLE INFO

Keywords:
Path dependence
Decision-making
Simulation exercise
Gaming
Reliability
Critical infrastructure
Policymaking
Sustainability
Crisis management

ABSTRACT

The magnitude and speed of change in complex human-environmental systems pose a systemic dilemma for societies. Human-induced environmental changes have pushed Earth's socio-ecological systems into an era of chronic, complex, and rapid disruptions, which call for quick intuitive decisions and effective implementation. Yet the complexity, interconnectedness and long lead times of the problems would require thoughtful and time-consuming weighing of evidence by a broad range of experts. To address the dilemma, we develop a framework, the Policy Operations Room (POR), for simultaneous practice and analysis of decision-making that prevents decisions made under time pressure from leading to unwanted socio-ecological disruptions decades ahead. The POR framework is based on earlier research on control rooms of critical infrastructures and simulation exercises of emergency response, and preliminary data from our first experiments with PORs. It immerses the policymakers in a simulated "time machine" that combines the real-time reliability management of control rooms with the long-term planning for crisis avoidance and preparedness. The POR framework can contribute significantly to novel styles of decision-making by policymakers, engineers, and corporate strategists responsible for developing urgent, forward-looking, and evidence-based policies to cope with the coming challenges of human-environmental interaction.

1. Introduction

The magnitude and speed of change in intertwined webs of human-environmental systems create a persistent dilemma for decision-makers (IPBES, 2018; IPCC, 2018; Khanna, 2016; Lade et al., 2020). On one hand, human-induced environmental changes have pushed Earth's socio-ecological systems into an era of chronic, complex, and rapid disruptions – the COVID-19 pandemic being the latest example – which call for quick decisions and effective implementation. Decisions are often made in an intuitive crisis mode within a brief window of opportunity (Rochlin, 1997; Roe, 2013). On the other hand, the complexity, interconnectedness, and long lead times of the problems would require thoughtful and time-consuming weighing of evidence by experts from a broad range of professions and disciplines (Dryzek, 1997; Rask et al., 2012). To tackle the dilemma, we develop a framework for simultaneous practice and analysis of decision-making that enables decisions made under time pressure to address unwanted socio-ecological disruptions decades into the future.

Policy design in the Anthropocene era requires interdisciplinary collaboration among academics and practitioners to address a multitude of geographical levels, interconnected boundaries, and socio-ecological complexities (Little et al., 2016; Sterner et al., 2019). Although these guiding principles form a reasonable platform for policy development, many decisions taken in a hasty crisis mode are path-dependent, both in the sense of past decisions restricting current decision options and current decisions creating future constraints. Over time, technologies in socio-ecological systems gain a mass of technical and organizational components that continue to grow toward specific goals; economic

* Corresponding author.
E-mail address: janne.i.hukkinen@helsinki.fi (J.I. Hukkinen).

https://doi.org/10.1016/j.ssci.2021.105567
Received 31 March 2020; Received in revised form 20 October 2021; Accepted 24 October 2021
Available online 1 November 2021

calculations reinforce the systems with unamortized assets and investment plans; institutions support the systems with legislation and regulation; and educators and experts ensure their cognitive continuity (Arthur, 2009; Hughes, 1987; Hämäläinen & Lahtinen, 2016). Identifying the best ways of supporting long-term sustainability and comprehensive resilience despite the urgency of decisions will be a key challenge for the near future (Beddoe et al., 2009; Gal, 2012; Schill et al., 2019). The societal benefits are considerable, because major environmental shocks often organize and differentiate communities unjustly (Fussell & Elliott, 2009).

Science advising mechanisms (SAMs) have a long tradition worldwide in providing external evidence-based advice to complex policy processes and decisions. Science advising can range from using science advisors, science councils and advisory committees to national academies of science and learned societies. SAMs have gained importance as political decisions increasingly involve complex issues or systems that require competences beyond the traditional political realm (Kaaronen, 2016; OECD, 2015). Policies have become wicked, i.e., characterized by urgency, path-dependence, complexity, uncertainty, value conflicts, indeterminate solutions, and high demand for expertise, often of interdisciplinary nature (Hukkinen, 2016; Rittel & Webber, 1973). The European Commission has established a specific SAM, which draws information from a broad expertise base with the help of European Academies of Science (European Commission, 2015; SAPEA, 2017). It strives towards evidence-based policy making but also quick and proficient responses to sudden emergencies that may fall upon Europe. The emergence of SAMs points toward a distinct need to develop procedures for urgent decisions with long lead times.

We propose a test bed – the Policy Operations Room (POR) – to practice and analyze urgent decision-making with path-dependencies. POR is a situation room for interactive decision-making among policymakers, managers, and experts to deal with wicked issues. The POR framework is inspired by a long tradition of research on control rooms and simulation exercises: the former because of its focus on forward-looking crisis avoidance rather than post-crisis emergency management (Roe & Schulman, 2015), the latter because of its design instructions for simulated decision experiments based on future scenarios and other available information (Boin et al., 2004). Novel insights can be gained by running long-term scenarios that span decades or even longer during a simulation exercise lasting only a couple of hours, thus immersing the exercise participants in a simulated "time machine" that combines the real-time reliability management of control rooms with the long-term planning for crisis avoidance and preparedness. The additional benefit of long-term scenarios is that they force decision-makers to consider path-dependencies and other factors that usually fall outside their political mandate or expertise.

We suggest that the control room model of high reliability management, which successfully maintains reliable operations despite a wicked operating environment, is transferable to a strategic policymaking context involving urgent decisions with long-term lock-in effects. We show that simulation exercises based on analogous application of decision principles from a high reliability control room, or the POR framework, can help policymakers to consider the long-term path-dependence (be it desirable or not) of urgent decisions made during wicked socio-ecological disruptions under high uncertainty. We argue that in long-term strategic policymaking settings it is possible to benefit from the same operational procedures with which control room operators stabilize critical infrastructures and ensure reliability.

2. Materials and methods

To build the POR framework, we utilize two much-studied decision settings: simulation exercises of emergency response and control rooms of critical infrastructures. Both offer relevant but by themselves incomplete components for our purposes. Simulation exercises are platforms where emergency managers can test emergency response activities, such as those required during natural disasters (Boin et al., 2004). They yield important information on the procedures and skills required for decision-making under extreme time constraints. Control rooms of critical infrastructures are settings in which the operators make quick decisions to keep the critical services on line 24/7 without endangering the structural integrity of the critical infrastructure over the long term (Roe & Schulman, 2018). The reliability of public utilities and air transport, for example, relies on control room operations (Casal-Campos et al., 2018). We extract design principles from these two lines of research for a decision setting that permits consideration of long-term path-dependencies despite the urgency of decisions. For this, we also rely on preliminary data from our first experiments with the framework.

2.1. Research on simulation exercises and control rooms

Simulation exercises. Empirical research on urgent decision-making does not have the luxury of first waiting for the disruption to begin and then launching research in sync with the disruption. Prezelj and Doerfel (2017) point out that although organizations cannot plan in detail for unpredictable events, they can build multifunctional capacities through crisis exercises based on less probable scenarios. Simulation exercises are methodological tools that synthesize a complex system and allow observation of the participants' behaviour and decision-making (Vieira Pak & Castillo Brieva, 2010). Scenario-based simulation exercises have a dual use: they are used by emergency managers to test emergency procedures, contingency plans, and response skills, but they can also serve scientific knowledge production. Formats include discussion-based table-top exercises, such as seminars and workshops, or operation-based exercises requiring mobilization and use of resources, such as drills or full-scale exercises (Skryabina et al., 2017; UNDRR, 2020).

Simulation exercises are often run as serious games that tend to focus on the reactive management of an abrupt crisis, with flooding as the most popular theme. Some exercises also cover the mitigation phase where the players' decisions to invest in mitigation affects how well they survive the next crisis in the game (Solinska-Nowak et al., 2018). Serious games and exercises are popular with themes like decision-making and policymaking without necessarily including crisis or disruption: many address issues related to sustainable resource management and climate change adaptation (den Haan & van der Voort, 2018; Flood et al., 2018). These types of simulated conditions may promote learning through the application of competencies and knowledge acquired in earlier successfully handled situations (Orsato et al., 2019). The literature recognizes the need for simulation exercises to include more complex, transboundary, and surprising crises (Edzén, 2014; Gomes et al., 2014; Quarantelli et al., 2018; Tena-Chollet et al., 2017). To our knowledge, there are no exercises allowing the participants to experience the long-term path-dependencies of urgent decisions that span decades or more.

Control rooms. Roe and Schulman (2015) contrast two types of disruption management: control rooms aiming at reliable operation of critical infrastructures and emergency response operations aiming at recovery from failed infrastructures. Critical infrastructures are systems or services without which the security, socio-economic functioning, and public health and safety of modern societies would be incapacitated, including energy management, logistics, manufacturing, food supply, defense, finance, health and social services, and information and communication systems (National Emergency Supply Agency, 2018; U. S. Department of Homeland Security, 2013). Both types of management make use of the simulation exercises described above.

From the point of view of the risks and uncertainties of decision-making (Stirling & Gee, 2002), control rooms are very different from emergency response operations. In control rooms, managers strive to ensure operating conditions that yield themselves to probabilistic risk management while remaining vigilant for things slipping into the realm of ignorance – or unknown unknowns (Fig. 1). They operate in the vicinity of the diagonal in Fig. 1, making every effort to remain above the

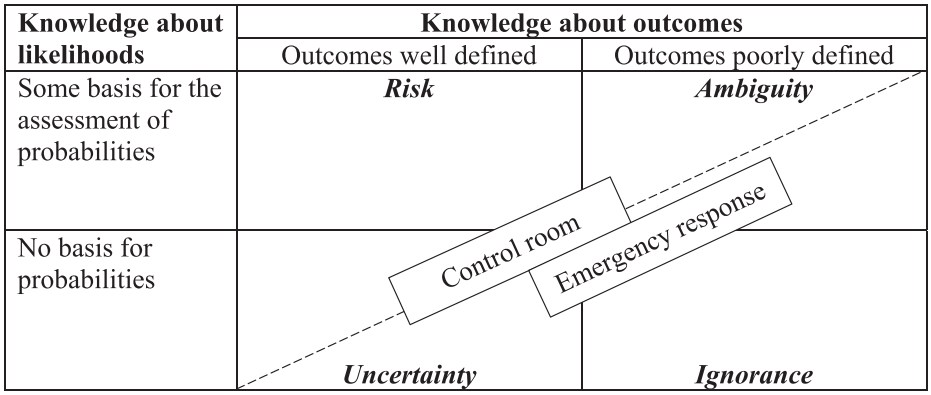

Fig. 1. Decision contexts in control room and emergency response operations in Stirling and Gee's (2002) typology of risks and uncertainties. Control room operators strive to make decisions on the basis of risks while staying alert for unknown unknowns. Emergency responders assume unknown operating conditions.

diagonal in the realm of known risks, but being constantly aware of the possibility of drifting below the diagonal into the realm of ignorance. In contrast, for emergency responders concerned with an already failed critical infrastructure, risk management is relevant only to minimize harm resulting from the response operations. They must assume unknown operating conditions in which almost anything can happen because of poor knowledge of both consequences and probabilities, i.e., conditions located below the diagonal in Fig. 1 (Roe & Schulman, 2018).

What is remarkable about critical infrastructures is how reliably they are managed. High reliability management refers to the ability of control room operators and their teams to maintain a situational awareness that largely prevents system-wide failures (Rochlin, 1997; Roe & Schulman, 2015). Earlier research on complex and tightly coupled technical systems, such as critical infrastructures, would lead one to expect them to be ridden with inevitable failures (Perrow, 1999). Yet control rooms succeed in managing critical systems very reliably in real time and over decades (Roe & Schulman, 2018). Important lessons can therefore be drawn from control room experiences for other sectors of society by teasing out the factors that ensure consideration of the long term despite the urgency of decision-making.

Highly reliable management in control rooms shares the following features: it is non-fungible, i.e., efforts to maximize techno-economic efficiency erode reliability; it results from hazard-driven adaptation, which necessitates a constant preparedness for multiple hazards and awareness of errors; and it relies on improvisation, experimentation, and highly variable operations to manage the real-time contingencies emerging in critical infrastructure operations. Obviously, none of the above would be possible without a high level of expertise among control room operators (Roe & Schulman, 2008).

Comparison of simulation exercises and control rooms. Table 1 summarizes the key lessons from the literature on simulation exercises and control rooms.

Table 1 highlights intriguing tensions that should be addressed when developing the POR as an experimental platform for exploring urgent decisions with long-term impacts, i.e., decisions made within a time scale ranging from minutes to hours and resulting in decadal impacts.

Table 1
Key features of simulation exercises and control rooms of critical infrastructure.

Simulation exercises	Control rooms
• are useful for observing crisis decisions • benefit both preparedness and response • are scripted around scenarios, models, and role play • are useful when focus is on low-probability surprises • can be based on discussions or actual operations	• treat reliability as non-fungible • are based on hazard-driven adaptation • embrace improvisation and experimentation • assume high variability in operations • demand high level of expertise

First, preparing for the foreseeable crises occurring in the long-term future is different from responding to immediate crises. Second, the mindset that governs the avoidance of hazardous errors is different from that governing adaptation to the consequences of errors. Third, exercises can either be built with an emphasis on model-based scenarios with clear roles or narrative scenarios with improvised roles. Finally, decision-making with knowledge of risks differs from that made without such knowledge, i.e., decisions under high uncertainty. These tensions serve as a background for developing procedures that permit decisions made in urgencies to address socio-ecological disruptions decades ahead.

2.2. Preliminary experiments with policy operations rooms

In broad terms, the tensions for the design of a framework to explore urgent decision-making with long-term impacts, as identified in Section 2.1, have to do with 1) variable knowledge and 2) differences in emphasis on crisis preparedness (capacity to anticipate, respond, and recover from crisis) versus response (actions taken at the time of crisis to manage its immediate impacts) (United Nations, 2016). To stretch only slightly the concepts of crisis management, these are also the tensions that policymakers face when trying to reconcile long-term sustainability and resilience with the urgency of decisions. As the former president of the European Commission Jean-Claude Juncker once quipped, "we all know what to do, we just don't know how to get re-elected after we've done it" (The Economist, 2007). In other words, policymakers struggle with the tension between good knowledge over what decisions long-term sustainability demands of them and political pressure to focus on short-sighted crisis response to secure their own career.

To address the tensions in decisions over wicked problems, we constructed an analytical framework made of three variations of POR that cover decision situations with variable knowledge and variable emphasis on crisis preparedness versus response (Fig. 2). *Bayes-POR* focuses on decisions made with probabilistic knowledge of risks, such as those taken to increase preparedness. *Crisis-POR* focuses on decisions made with poor knowledge of the situation, such as those taken during crisis response. *Path-POR* is located between Bayes-POR and Crisis-POR and focuses on strategic decisions made as an urgent response to a policy crisis with a combination of risk knowledge on some aspects of the situation and ignorance on others.

We conducted preliminary experiments with each type of POR during 2019–2021 (Table 2). In 2019, we organized a half-day Path-POR exercise with the political leadership and high-level administrators and experts of the City of Helsinki, the capital of Finland. The objective of the exercise was to improve the city's capacity to promptly modify long-term energy and transportation policies in response to urgent socio-ecological disruptions induced by climate change. During January – March 2021, we organized a Bayes-POR comprising 3 half-day virtual

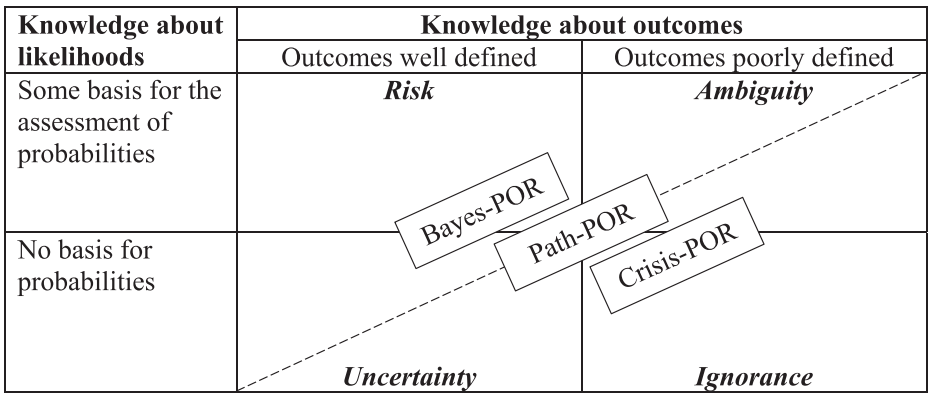

Fig. 2. Taking into account the variability of knowledge in the design of Policy Operations Rooms (PORs).

Table 2
Empirical observation of three types of Policy Operations Room (POR).

	Bayes-POR: City of Kotka 2021	**Path-POR: City of Helsinki 2019**	**Crisis-POR: Regional State Admin. Agency for So. Finland 2021**
Objective	To strengthen long-term crisis preparedness with probabilistic identification of uncertainties related to complex crises	To develop decision-making for urgent socio-ecological disruptions while addressing the long-term consequences of decisions	To prepare for actions required during an exceptional storm-induced emergency
Participants	City's experts and administrators (6)	City's top politicians (7)	Experts and administrators from So. Finland's municipalities, police and rescue force, critical infrastructure utilities, hospitals and NGOs (~500)
	Observers/facilitators (4)	City's experts and administrators (10)	
		Observers/facilitators (9)	Organizing game group (~30)
			Observers (55)
Venue and duration	Teams virtual platform, Miro whiteboard	City Board room	Valhalla virtual platform
	3 × ½ d	½ d	2 d
Scenario and script	A truck and a train carrying dangerous chemicals collide at the entrance of Kotka City center (an island) during popular summer festival	Helsinki forced to make urgent strategic decisions on energy and transportation policy to meet climate regulation	Strong and long-lasting thunderstorm causes disruptions in So. Finland's electricity and water/wastewater infrastructure
	Participants develop causal explanations of threats from crisis to city's long-term strategic goals	Participants choose one of three strategic options after situational snapshot of past decade's developments	Participants implement emergency procedures
Focus of observation	Decision-makers' strategic preparedness	Learning by decision-makers	Long-term implications of emergency procedures

(online) sessions with the administrators and experts of the City of Kotka in Southern Finland. The objective was to strengthen the city officials' long-term crisis preparedness by advising them in producing probabilistic assessments of the threats of a chemical accident on the city's strategic goals. Finally, in 2021 we participated as observers in a virtual Crisis-POR emergency preparedness exercise organized by the Regional State Administrative Agency for Southern Finland. While the objective of the exercise was to help the participating organizations to improve their emergency management procedures, our observations focused on teasing out the long-term implications of such procedures.

Analyses of the empirical data on PORs (Table 2) are ongoing. We have published only the first results of the 2019 Helsinki Path-POR (Järvensivu et al., 2021). For the present purposes we treat the empirical work as preliminary evidence that only gives indications for further development of the primarily literature-based POR framework presented in Section 3.

3. Results: The policy operations room (POR) framework

3.1. Three varieties of POR

Depending on the degree of decision-makers' knowledge and emphasis on preparedness versus response, the three PORs respond to the design challenges of an experimental platform to explore urgent

Table 3
Addressing the tensions of urgent decisions with long-term path-dependencies with Policy Operations Rooms.

Tension	**Design challenge**		
	Bayes-POR	***Path-POR***	***Crisis-POR***
Long-term pre-disaster preparedness versus immediate response	***Preparedness*** to respond in light of updated situational awareness	Long-term implications of decisions made under extreme time constraints	***Immediate*** response
Error avoidance versus adaptation to consequences of error	***Error avoidance*** and mitigation of consequences in case of an error	Control room for urgent decisions in critical policy infrastructure with precluded errors	***Adaptation*** to consequences of error
Model-based scenarios with clear roles versus improvisation	***Model-based*** and narrative scenarios	Narrative scenarios with surprises and improvisation	***Improvisation***
Risk knowledge versus ignorance	Probabilistic inference in light of updated ***risk knowledge***	Making sense of unknown unknowns if poor risk knowledge	Making sense of ***unknown unknowns***

decisions with long-term impacts (Table 3). First, simulation exercises have been successful for both preparedness and immediate response phases of crises, which indicates it is possible to combine in a single simulation exercise consideration of the long-term implications of decisions made under extreme time constraints. Second, since a key challenge is to avoid future errors, PORs strive to emulate decision-making in the control room of a critical infrastructure. The "critical policy infrastructure" is understood as a policy subsystem in which decision errors, or unacceptable deviance from pre-defined performance criteria, can be defined clearly. Third, there is a tension between improvising in the face of surprises and running the exercise with model-supported scenarios and clearly defined roles. This indicates that the design of the simulation exercise needs to utilize scenarios ranging from model-based to narrative ones that permit surprises and improvisation. Finally, just as control rooms, the PORs aim to simulate a decision environment where the scenarios push the participants from risk knowledge to a state of ignorance, of which they try to make sense individually and collectively during the exercise.

To address the challenges in Table 3, we propose a POR framework focusing on the *scenarios and decision space* that the exercise provides for the participants, the *participants, venue and duration* of the POR exercise, and *observation* of the exercise (see also Tena-Chollet et al., 2017). The scenarios and decision space in the framework are unique for each POR, while all three PORs share approximately the same participant groups, venue and duration, and observational aspects.

3.2. Scenarios and decision space

The script of each POR is constructed around case-specific scenarios and decision space. Scenarios are causal descriptions of plausible – but not necessarily probable – pathways of future trends and events, forcing reactions from the decision-makers, and articulated to facilitate informed decisions about the future (Hukkinen, 2008; Little et al., 2016). Decision space refers to the range of options at the decision-maker's disposal (Alexander, 1982). The script of a POR follows a temporal sequence of trends and events, where events follow from past trends and require urgent decisions that lead to future trends (Fig. 3). To simulate decision situations with different degrees of knowledge, the decision space is different in the three PORs. In Bayes-POR, the entire set of disruption events, decision options and causal paths through time from one event to another are transparent and constantly updated by the participants. In Path-POR, participants know only the historical sequence of events that led to the current event requiring decisions. In Crisis-POR, participants are immersed into a hypothetical disruption event with little knowledge of either its past or potential futures. Let us have a closer look at each.

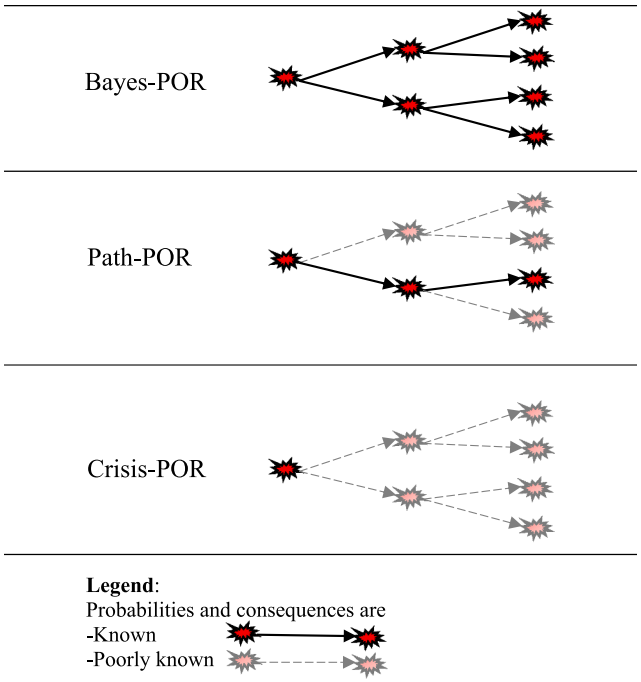

Fig. 3. PORs as decision trees.

Bayes-POR. The aim of Bayes-POR is to study decision-making over path-dependent socio-ecological disruptions with risk knowledge facilitated by Bayesian probabilistic reasoning, and to identify key management routes and actions. All risk and resilience management decisions rely on human capability to construct a realistic picture of the ongoing situation. This situational awareness under uncertainty can be conceptualized as a Bayesian probabilistic phenomenon, composed of two main elements: 1) prior experiences and expectations based on such experiences, and 2) currently available information concerning the situation and how reliable the participants think this information is in a probabilistic sense. Bayesian logic (Bayes & Price, 1736) has been compared to the functioning of the human brain (Clark, 2016; McGrayne, 2011). Every observation we make is used to update our former (prior) belief, which results in new, improved (posterior) understanding. The updating can be used iteratively, i.e., every new observation further updates our former posterior, which is then used as a new prior. This knowledge can be used to decide whether additional knowledge is needed before final decision is made. The Bayesian logic is also called "inverse logic" because it can be used not only to predict events given the causal factors but also for diagnostically inferring the likely causes based on the observed events (Fienberg, 2006). Similarly, situational awareness may sometimes be based on a particular observation and our interpretation of what caused the phenomenon.

To enable a Bayesian approach to decision-making, the scenarios and decision space are more narrowly scoped and clearly defined than in the two other PORs. Here, the Bayes-POR consists of two main components. First, causal mental mapping (Jones et al., 2011; Parviainen et al., 2019) is used to structure and explain within the multi-disciplinary group of participants the reasoning and causal views of individuals, as well as the procedures and principles of their background organizations in different decision points of the scenario (Fig. 3). Second, the mental map is translated to a Bayesian network (Helle et al., 2015; Jensen & Nielsen, 2007) that is used interactively to modify the scenario and test how the relationship between the time and quality of information at the time of decision develops dynamically and what information matters the most when determining the best next decision. For this, Bayesian decision analysis offers a numeric estimate called the value-of-information, i.e., how much one should allocate for improved knowledge before deciding (Quirk, 1976).

Path-POR. The aim of Path-POR is to investigate urgent decision-making with long-term path-dependencies in a situation where the participants struggle to maintain risk knowledge without slipping into the unknown. The concept of a Path-POR draws inspiration from the reliable management observed in the control rooms of critical infrastructures with conflicting service objectives and time frames, such as electricity grids and water management (Perrow, 1999; Rochlin, 1997; Roe & Schulman, 2008). Control rooms achieve reliable management by bringing physically together a wide range of technical, scientific, and managerial expertise, and having the experts make management decisions with specific boundary conditions and time limits (van Eeten & Roe, 2002). Ideally, Path-POR would integrate the capacity of a control room to generate quick and often intuitive management decisions over complex issues with the capacity to consider the long-term policy implications of such decisions.

The scenarios and decision space used to "screen-write" the Path-POR have two specific features. First, to strike a balance between the need to highlight the decadal path-dependencies of decisions and the need to facilitate improvised decisions in the face of surprises, the

scenarios are structured as tree-shaped paths branching at decision points that offer the participants a fixed number of decision options (Fig. 3). Surprise can be introduced by writing for each possible decision sequence a unique scenario, and by inserting "injects" that require quick decisions from the participants (UNDRR, 2020). Path-dependence is maintained by making sure that whichever scenario path the participants choose, all paths are composed of temporally interlinked decision points with pre-determined technological, economic, social, or cognitive lock-ins. Second, to prevent the participants from deferring urgent decisions to emergency professionals as a way of dealing with errors, the Path-POR should be sensitive to precluded policy consequences on one hand and emergency management defaults on the other. Precluded policy consequences define the boundaries of the decision space by specifying the intolerable consequences, or "policy errors." Precluded emergency management defaults define the boundaries of the decision space by specifying the unacceptable management actions – the "easy-ways-out," such as calling the emergency rescue services – that fail to address the wicked long-term path-dependencies.

Crisis-POR. Crisis-POR aims to investigate decision-making over sudden socio-ecological crises characterized by poor knowledge and the need to rapidly construct situational awareness. The achievement of reliable management under conflicting objectives and tight time constraints is of continued research interest (see, e.g., *Safety Science*, *Journal of Contingencies and Crisis Management,* and *International Review of the Red Cross*). The novelty of the Crisis-POR that we propose is to magnify the degree of wickedness in the disruption scenarios to be managed in a crisis exercise. As a result, multiple expertise is needed in the emergency response exercise. Earlier research indicates that a particularly critical interface emerges across control room operators and emergency responders during the recovery phase after disruption (Roe & Schulman, 2015).

The scenarios and decision space of Crisis-POR follow those of a typical emergency response exercise. In addition, the design considerations here strive to make the participants encounter surprises that push them to a state of ignorance and challenge their situational awareness. The scenario is prepared by a group of substance experts with the necessary knowledge to develop a logical and appropriate storyline (Moats et al., 2008). The scenario is divided into smaller incidents, which are communicated to the participants by injects, such as phone calls, emails, or reports, to allow participants' reactions to take place (UNDRR, 2020). A key challenge is achieving a balance between inconceivability and credibility, so that the simulation has unexpected elements but not to the extent that it would be discredited by the participants (Boin et al., 2004). Computer-based simulations can be used as part of the exercise or scenario development (Moats et al., 2008; Chou et al., 2018).

3.3. Participants, venue and duration

To create a setting for both practicing and observing decision-making with a wide range of expertise, POR participants include decision-makers, experts knowledgeable in the specific socio-ecological themes of the exercise, and researchers observing the exercise. As cities have emerged as a dominant organizing ground for humanity in the face of sustainability challenges (McDermott et al., 2019), our research group has engaged city and regional governments as the first collaborators in PORs. Since PORs aim to facilitate consideration of the long-term implications of decisions made under time pressure, the exercises ideally target two types of decision-maker: those responsible for long-term strategy, such as high-level policymakers in national, regional, and city governments, and those responsible for urgent crisis decisions, such as professional emergency responders. Consideration of the long term is likely to persuade policymakers to think beyond securing their re-election and emergency responders to consider the lock-in effects of immediate crisis response.

Since PORs aim to simulate urgent decision-making realistically, the venue should be where such decisions would be taken in an actual situation, such as the meeting rooms of cabinet ministers, board rooms of cities, or situation rooms of emergency responders. To achieve a sense of urgency, the duration of the exercise should be in the range of 2–4 h. Access to computers and audio-visual equipment is important to immerse the participants in audio-visual scenario dashboards and interaction with decision tools such as Bayesian algorithms, sustainability toolboxes, and web-based simulation tools (Buytaert et al. 2012; Lu et al. 2019).

3.4. Observations

Researchers observing a POR exercise need to cover several aspects. Adjusting earlier protocols for the observation of simulation exercises ('t Hart, 1997), pertinent questions include at least the following:

What are the socio-cognitive processes with which the participants frame the decision problem? By framing we refer to how the participants "tame" the problems (Edzén, 2014) by moving from the realm of the unknown unknowns to making sense of the situation (Fig. 2). Even in the face of complete surprise and absence of knowledge, the human mind applies a variety of heuristic devices such as analogies and past experiences with which to impose ordered patterns on the situation (Hukkinen and Huutoniemi, 2014; Honkela et al., 2014). To understand the emergence of situational awareness and its relationship to decision-making, researchers in the POR need to document both the operational reasoning and practices, and the development of situational awareness among the participants. When knowledge of the situation is poor (Crisis-POR, Path-POR), the focus of observation is on the heuristics used to make sense of the unknowns, particularly on operational errors to be avoided in all circumstances. When situational knowledge is good (Bayes-POR), the focus is on the participants' understanding of causalities and level of uncertainty, and willingness to use their collective mental model to justify their decisions. For a systematic view of the socio-cognitive processes of framing, it is necessary to consider the observed heuristics and probability assessments as part of a social learning process: the POR participants are members of a community of practice engaged in cycles of social learning that spans individual and group levels (Orsato et al., 2019).

What are the organizational and power dynamics during decision-making? In bringing decision-makers and experts together on equal terms, PORs create a decision environment unlike the everyday work environment of the participants. This is likely to raise tensions between formal power and expert power (Hukkinen, 2008). PORs accentuate this tension by simulating situations that demand quick expert assessment and decisions. It is therefore necessary to observe how the tension between formal versus expert power plays out, how conflicts are resolved, what are the situations where one overrides the other, and what are the consequences for decision-making.

What are the information and communication flows during the exercise? Two aspects of communication are particularly important to observe. First, to what extent do the POR participants share knowledge to arrive at collective situational awareness? Organizational and power dynamics that are taken for granted in everyday work situations may impede such knowledge sharing. Second, do the participants have the skills to evaluate the potential value of additional information prior to decision-making under varying conditions, given the cost of not acting? Additional information may be obtained externally from communication channels available during the POR or internally from the participating experts.

Is the overall flow of the exercise conducive to further development of the POR? Ideally, POR stays not just an exercise but infiltrates the normal procedures and practices of policymakers and experts. To fine-tune the POR framework and extract benefits for actual strategic decision-making, the scripting of the exercise, the roles of the organizing researchers and the POR participants, the functioning of the venue and its supporting equipment, and the overall flow of the exercise should be

observed and assessed.

To respond to these questions, data collection should be based on written note taking at a minimum, possibly also audio- and videotaping. Since interaction with the other actors in cross-organizational groups has been shown to promote deep learning and real-life cooperation (Khorram-Manesh et al., 2016; Norström et al., 2020), supervised discussions and interviews should follow the POR exercise to ask the participants for feedback and opinions on further development ('t Hart, 1997).

3.5. Practical application of the framework

The practical applicability of the POR framework is summarized in a step-by-step flow chart in Fig. 4. Since empirical experimentation with the POR framework is still ongoing (Section 2.2), the design steps described in Fig. 4 are indicative only and need fine-tuning after more results.

The first step in the design of a POR is to determine what is known of the crisis and what are the crisis management objectives (Fig. 4). As summarized in Table 3, three types of situations can be identified: causal risk knowledge that lends support to avoiding errors; expertise in making sense of uncertainties that lends support to precluding or coping with errors; and persistent uncertainty that lends support to adaptation to the consequences of errors.

The second design step outlines the general principles of POR design for crisis decisions (Fig. 4). If risk knowledge is available and crisis management focuses on avoiding errors and improving resilience, the advisable decision setting is Bayes-POR in which the disruptions, decision options and causal paths are transparent and updated by the decision-makers. If expertise is available to deal with uncertainty and preclude or cope with errors, then the advisable option is Path-POR where the decision-makers know only the path of events that led to the current situation in need of decisions. Finally, if major uncertainties leave no choice but to adapt to the consequences of possible errors, the recommended option is Crisis-POR in which decision-makers are immersed in disruptions and assumed to cope with them.

The third design step provides a preliminary outline for a POR intended specifically for *strategic crisis decisions*, i.e., urgent decisions made in a crisis but with a view on long-term consequences (Fig. 4). Here we draw on the preliminary findings from the three empirical experiments with PORs (Section 2.2). The findings are presented in chronological order of the PORs to highlight the cumulative learning that we as organizers and observers gained when proceeding from one POR to the next.

A key finding of the 2019 Helsinki Path-POR was that the qualitative narrative scenarios with decadal audio-visual snapshots and decision options failed to challenge the decision-makers to reflect seriously on the long-term consequences of their decisions. Instead, the politicians were broadly satisfied in having arrived at decisions efficiently and professionally, while the experts and administrators, who in debriefings were concerned about the long-term, remained largely quiet during the exercise (Järvensivu et al., 2021). Based on these observations, the long-term consequences of current decisions need to be made more prominent in the politicians' awareness and agenda by giving a stronger voice to the city-level experts and administrators (Fig. 4). Therefore, only experts and administrators and no politicians were invited to the 2021 Kotka Bayes-POR. Furthermore, the scenario paths describing the long-term consequences of the crisis were tuned to more concrete and quantitative. We described the participants' thinking as graphical causal paths by which the crisis could threaten the city's long-term strategic goals. Based on the descriptive information of the causalities and the level of uncertainty related to them, we then represented the systemic mechanisms probabilistically with a Bayesian network model.

The 2021 Kotka-POR confirmed the lessons learned from the Helsinki-POR. Making the long-term consequences of the crisis visible empowered the participants with explicit, concrete, and quantitative knowledge of the potential threats from inadequate preparedness to the city's strategic goals (Fig. 4). But the Kotka exercise also highlighted the need to better understand the actual constraints that the rush of crisis decisions imposes on long-term considerations. After all, the

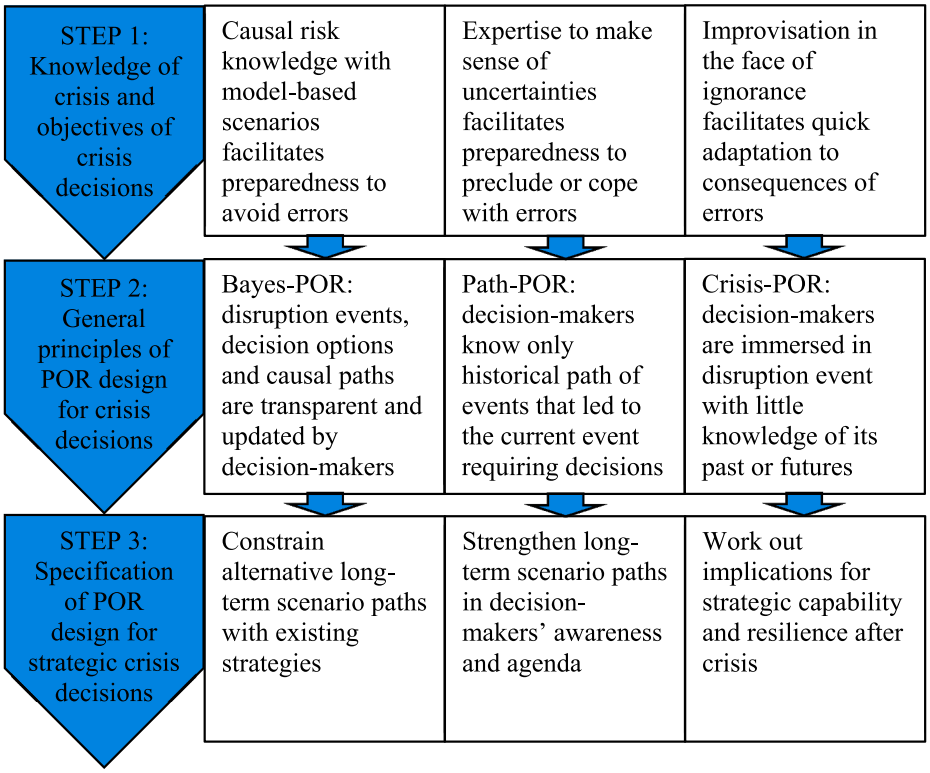

Fig. 4. Design steps of Policy Operations Room (POR) for variable crisis knowledge and management objectives.

participants had the luxury of spending three half-days on deliberations (Table 2). This takes us to the 2021 Regional Crisis-POR.

The key finding of the 2021 Regional Crisis-POR was that currently used information technologies in crisis management make it very challenging to maintain a shared situational awareness of the crisis. An even greater challenge would be to achieve a shared situational awareness for the purposes of considering the long-term consequences of a crisis. Under the conditions we observed, long-term strategic capability and resilience can only be worked out afterwards (Fig. 4).

4. Discussion

The POR framework we have laid out provides tailored guidance for the design of strategic crisis management under variable crisis knowledge and management objectives. The framework is, however, theoretically grounded, and at this stage we have only preliminary empirical data on its practical application. Challenges and opportunities for future research and development therefore remain.

The analogy between the control room of a critical infrastructure and POR is not straightforward. The critical infrastructure clearly specifies the mandate of a control room. In contrast, drawing the boundaries of the policy to be decided on in a POR is anything but straightforward, as seen for example in the complex interactions of climate policy. Even if such boundary work were successful, the challenge of determining policy errors remains. Awareness of errors to be avoided under all circumstances is the defining feature of control room operations. A failed policy is subject to much more interpretation than a failed critical infrastructure. The framework outlined here therefore needs empirical testing and fine-tuning to determine the viability of the "high reliability policy" that the POR implies.

The three variations of POR we have investigated offer valuable ingredients for designing tailor-made decision platforms for specific circumstances. We are currently testing a hybrid POR that builds on the lessons learned from the experiments we have conducted to date (Section 3.5). We will run POR exercises during 2022–2023 in three Finnish cities (Helsinki, Tampere, Kotka), focusing on adaptation of each city's long-term strategies to chronic climate-induced crises. Two exercises will be organized per city. In the first one, experts and administrators alone will participate. Their deliberations are facilitated with computer simulations of extreme heat wave, fire, and flooding events and a dashboard displaying the chronic multi-hazard consequences. The second one will be with experts, administrators, and politicians together, who are asked to modify the city's strategies for coping with chronic crises. The hybrid format is calibrated to address the three issues raised by our earlier POR experiments (Fig. 4). First, a POR devoted to experts and administrators alone strives to boost their science-based argumentation in the subsequent joint deliberations with politicians. Second, the scenarios are kept realistic for the participants by tying chronic multi-hazard events to each city's existing strategies. Third, condensing the long-term consequences of crises into an audio-visual dashboard strives to overcome the problem of being able to consider the long-term only after the exercise.

Although our discussion has focused on PORs as exercise platforms, we think POR variations can be tuned to platforms for actual decision-making whenever the challenge is to tackle the long-term consequences of decisions made under chronic crises. Incorporating POR procedures in policymaking can help to safeguard political democracy during crises. Socio-ecological disruptions, should they become chronic, threaten to normalize authoritarian powers initially intended for exceptional situations alone. Sustainability and democracy face three challenges (Barry, 2008; Heidenreich, 2018): 1) securing a requisite level of expertise in sustainability decisions without defaulting into meritocracy; 2) securing citizens' participation and deliberation without losing the effectiveness of organized decision making; and 3) reconciling the need for urgent strategic decisions with the slow pace and short time span of decisions in today's democracies. The POR framework responds to these challenges by providing a research-based experimental platform to systematically develop decision-making procedures that are both democratic and effective.

5. Conclusion

The seeds of the crises we are experiencing presently were sown decades ago. This applies to future crises as well. To make the impending socio-ecological disruptions ahead more manageable, we proposed here a novel test bed called Policy Operations Room for urgent decision-making with long-term path-dependencies. In the POR framework, decision-makers, experts, and researchers practice urgent policymaking as if they were operating a critical policy infrastructure with a keen sense for policy errors. The POR framework can contribute significantly to the development of novel styles of decision-making for urgent, forward-looking, and evidence-based policies to cope with the coming challenges of human-environmental interaction.

CRediT authorship contribution statement

Janne I. Hukkinen: Supervision, Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Jussi T. Eronen**: Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Nina Janasik**: Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. **Sakari Kuikka**: Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Annukka Lehikoinen**: Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing. **Peter D. Lund**: Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Helmi Räisänen**: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Mikko J. Virtanen**: Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank two anonymous reviewers for their valuable comments. We gratefully acknowledge funding from the Academy of Finland's Strategic Research Council Grant no. 312623, 312624, 312625, and 312626 and Academy of Finland Grant no. 338553 and 338558.

References

Alexander, E.R., 1982. Design in the decision-making process. Pol. Sci. 14 (3), 279–292.
Arthur, W.B., 2009. The Nature of Technology: What It Is and How It Evolves. Penguin, London.
Barry, J., 2008. Towards a green republicanism: constitutionalism, political economy, and the Green State. Good Soc. 17, 1–11.
Bayes, T., & Price, R. (1736). LII. An essay towards solving a problem in the doctrine of chances. By the late Rev. Mr. Bayes, F. R. S. communicated by Mr. Price, in a letter to John Canton, A. M. F. R. S. *Philosophical Transactions of the Royal Society, 53,* 370-418.
Beddoe, R., Costanza, R., Farley, J., Garza, E., Kent, J., Kubiszewski, I., Martinez, L., McCowen, T., Murphy, K., Myers, N., Ogden, Z., Stapleton, K., Woodward, J., 2009. Overcoming systemic roadblocks to sustainability: the evolutionary redesign of worldviews, institutions, and technologies. PNAS 106 (8), 2483–2489.
Boin, A., Kofman-Bos, C., Overdijk, W., 2004. Crisis simulations: exploring tomorrow's vulnerabilities and threats. Simulat. Gam. 35 (3), 378–393.
Buytaert, W., Baez, S., Bustamante, M., Dewulf, A., 2012. Web-based environmental simulation: Bridging the gap between scientific modeling and decision-making. Environ. Sci. Technol. 46 (4), 1971–1976.
Casal-Campos, A., Sadr, S.M.K., Fu, G., Butler, D., 2018. Reliable, resilient and sustainable urban drainage systems: An analysis of robustness under deep uncertainty. Environ. Sci. Technol. 52 (16), 9008–9021.

Chou, C.-C., Jeng, A.-P., Chu, C.-P., Chang, C.-H., Wang, R.-G., 2018. Generation and visualization of earthquake drill scripts for first responders using ontology and serious game platforms. Adv. Eng. Inf. 38, 538–554.
Clark, A., 2016. Surfing Uncertainty: Prediction, Action, and the Embodied Mind. Oxford University Press, Oxford.
den Haan, R.-J., van der Voort, M., 2018. On evaluating social learning outcomes of serious games to collaboratively address sustainability problems: a literature review. Sustainability (Switzerland) 10 (12), 4529. https://doi.org/10.3390/su10124529.
Dryzek, J.S., 1997. The Politics of the Earth: Environmental Discourses. Oxford University Press, Oxford.
Edzén, S., 2014. Table-Top Exercises for Emergency Management: Tame Solutions for Wicked Problems, In: 2014 47th Hawaii International Conference on System Sciences, Waikoloa, HI, pp. 1978-1985.
European Commission, 2015. Commission decision of 16.10.2015 on the setting up of the High Level Group of Scientific Advisors, Commission decision C(2015) 6946 final. Brussels: European Commission.
Fienberg, S.E., 2006. When did bayesian inference become "Bayesian"? Bayesian Analysis 1, 1–40.
Flood, S., Cradock-Henry, N.A., Blackett, P., Edwards, P., 2018. Adaptive and interactive climate futures: systematic review of 'serious games' for engagement and decision-making. Environ. Res. Lett. 13 (6), 063005. https://doi.org/10.1088/1748-9326/aac1c6.
Fussell, E., Elliott, J.R., 2009. Introduction: Social organization of demographic responses to disaster: studying population–environment interactions in the case of Hurricane Katrina. Organization & Environment 22 (4), 379–394.
Gal, O., 2012. Understanding global ruptures: a complexity perspective on the emerging 'middle crisis'. In: Dolphin, T., Nash, D. (Eds.), Complex New World: Translating new economic thinking into public policy. IPPR, London, pp. 147–160.
Gomes, J.O., Borges, M.R.S., Huber, G.J., Carvalho, P.V.R., 2014. Analysis of the resilience of team performance during a nuclear emergency response exercise. Appl. Ergon. 45 (3), 780–788.
Hämäläinen, R.P., Lahtinen, T.J., 2016. Path dependence in operational research—how the modeling process can influence the results. Oper. Res. Perspect. 3, 14–20.
Heidenreich, F., 2018. How will sustainability transform democracy? Reflections on an important dimension of transformation sciences. GAIA, 27, 357-362. Anonymous 1. Anonymous 2.
Helle, I., Ahtiainen, H., Luoma, E., Hänninen, M., Kuikka, S., et al., 2015. A probabilistic approach for a cost-benefit analysis of oil spill management under uncertainty: a Bayesian network model for the Gulf of Finland. J. Environ. Manage. 158, 122–132. https://doi.org/10.1016/j.jenvman.2015.04.042.
Honkela, N., Toikka, A., Hukkinen, J., Honkela, T., et al., 2014. Coming to grips with scientific ignorance in the governance of endocrine disrupting chemicals and nanoparticles. Environ. Sci. Policy 38, 154–163. https://doi.org/10.1016/j.envsci.2013.11.006.
Hughes, T.P., 1987. The evolution of large technological systems. In: Bijker, W.E., Hughes, T.P., Pinch, T. (eds.), The Social Construction of Technological Systems. The MIT Press, Cambridge, MA, 51-82. Anonymous 3. Anonymous 4. Anonymous 5.
Hukkinen, J., 2008. *Sustainability Networks: Cognitive Tools for Expert Collaboration in Social-Ecological Systems*. Routledge, London.
Hukkinen, J.I., 2016. A model of the temporal dynamics of knowledge brokerage in sustainable development. Evid. Policy 12, 321–340. https://doi.org/10.1332/174426416X14712607933264.
Hukkinen, J.I., Huutoniemi, K.I., 2014. Heuristics as cognitive tools for pursuing sustainability. In: Huutoniemi, K., Tapio, P. (Eds.), *Transdisciplinary Sustainability Studies: A Heuristic Approach*. Routledge, London, pp. 177–193.
IPBES Intergovernmantal Science-Policy Platform on Biodiversity and Ecosystem Services (2018). The Regional Assessment Report on Biodiversity and Ecosystem Services for Europe and Central Asia – Summary for Policymakers. IPBES Secretariat, Bonn.
IPCC Intergovernmental Panel on Climate Change, 2018. Global Warming of 1.5 ℃ – Summary for Policymakers. IPCC Switzerland: Intergovernmental Panel on Climate Change.
Järvensivu, P., Räisänen, H., Hukkinen, J.I., et al., 2021. A simulation exercise for incorporating long-term path dependencies in urgent decision-making. Futures 132, 102812. https://doi.org/10.1016/j.futures.2021.102812.
Jensen, F.V., Nielsen, T.D., 2007. Building Models. In Jensen, F.V., Nielsen, T.D. (Eds.), Bayesian Networks and Decision Graphs. Information Science and Statistics. Springer, New York, NY, 51-108.
Jones, N.A., Ross, H., Lynam, T., Perez, P., Leitch, A., 2011. Mental Models: An Interdisciplinary Synthesis of Theory and Methods. Ecology and Society, 16, 46. Anonymous X.
Kaaronen, R., 2016. Scientific Support for Sustainable Development Policies A Typology of Science–Policy Interfaces with Case Studies. Sitra studies 118. Helsinki: Sitra.
Khanna, P., 2016. Connectography: Mapping the Future of Global Civilization. Random House, New York, NY.
Khorram-Manesh, A., Lupesco, O., Friedl, T., Arnim, G., Kaptan, K., Djalali, A.R., Foletti, M., Ingrasia, P.L., Ashkenazi, M., Arculeo, C., Fischer, P., Hreckovski, B., Komadina, R., Voigt, S., Carlström, E., James, J., 2016. Education in disaster management: what do we offer and what do we need? Proposing a new global program. Disaster Medicine and Public Health Preparedness 10 (6), 854–873.
Lade, S.J., Steffen, W., de Vries, W., Carpenter, S.R., Donges, J.F., Gerten, D., Hoff, H., Newbold, T., Richardson, K., Rockström, J., 2020. Human impacts on planetary boundaries amplified by Earth system interactions. Nat. Sustain. 3 (2), 119–128.
Little, J.C., Hester, E.T., Carey, C.C., 2016. Assessing and enhancing environmental sustainability: a conceptual review. Environ. Sci. Technol. 50 (13), 6830–6845.
Lu, Z., Broesicke, O.A., Chang, M.E., Yan, J., Xu, M., Derrible, S., Mihelcic, J.R., Schwegler, B., Crittenden, J.C., 2019. Environ. Sci. Technol. 53, 9341–9351.
McDermott, K., Kurucz, E.C., Colbert, B.A., 2019. Collaborative civil society organizations and sustainable cities: the role of "mobilizing leadership" in building the integral commons. Org. Environ. 32 (3), 234–254.
McGrayne, S.B., 2011. The Theory That Would Not Die. Yale University Press, New Haven.
Moats, J.B., Chermack, T.J., Dooley, L.M., 2008. Using scenarios to develop crisis managers: applications of scenario planning and scenario-based training. Adv. Dev. Human Resources 10 (3), 397–424.
National Emergency Supply Agency, 2018. Security of Supply Scenarios 2030. National Emergency Supply Agency, Helsinki.
Norström, A.V., Cvitanovic, C., Löf, M.F., West, S., Wyborn, C., Balvanera, P., Bednarek, A.T., Bennett, E.M., Biggs, R., de Bremond, A., Campbell, B.M., Canadell, J.G., Carpenter, S.R., Folke, C., Fulton, E.A., Gaffney, O., Gelcich, S., Jouffray, J.-B., Leach, M., Le Tissier, M., Martín-López, B., Louder, E., Loutre, M.-F., Meadow, A.M., Nagendra, H., Payne, D., Peterson, G.D., Reyers, B., Scholes, R., Speranza, C.I., Spierenburg, M., Stafford-Smith, M., Tengö, M., van der Hel, S., van Putten, I., Österblom, H., 2020. Principles for knowledge co-production in sustainability research. Nat. Sustain. 3 (3), 182–190. https://doi.org/10.1038/s41893-019-0448-2.
OECD, 2015. Scientific Advice for Policy Making: The Role and Responsibility of Expert Bodies and Individual Scientists. OECD Science, Technology and Industry Policy Papers, No. 21. Paris: OECD Publishing. https://doi.org/10.1787/5js33l1jcpwb-en.
Orsato, R.J., de Campos, J.G.F., Barakat, S.R., 2019. Social learning for anticipatory adaptation to climate change: Evidence from a community of practice. Organization & Environment, 32, 416-440. Anonymous 6.
Parviainen, T., Lehikoinen, A., Kuikka, S., Haapasaari, P., et al., 2019. Risk frames and multiple ways of knowing: coping with ambiguity in oil spill risk governance in the Norwegian Barents Sea. Environ. Sci. Policy 98, 95–111. https://doi.org/10.1016/j.envsci.2019.04.009.
Perrow, C., 1999. Normal accidents. Princeton University Press, Princeton NJ.
Prezelj, I., Doerfel, M.L., 2017. Resilience in a complex and unpredictable world. J. Contingencies Crisis Manage. 25, 118–122.
Quarantelli, E. L., Boin, A., & Lagadec, P., 2018. Studying Future Disasters and Crises: A Heuristic Approach. In: Rodríguez, H. et al. (Eds.), Handbook of Disaster Research, Handbooks of Sociology and Social Research, 61-83.
Quirk, J.P., 1976. Intermediate Microeconomics. Science Research Associates, Chicago.
Rask, M., Worthington, R., Lammi, M., 2012. Citizen Participation in Global Environmental Governance. Earthscan, London.
Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci. 4 (2), 155–169.
Rochlin, G., 1997. Trapped in the Net: The Unanticipated Consequences of Computerization. Princeton University Press, Princeton NJ.
Roe, E., 2013. Making the Most of Mess: Reliability and Policy in Today's Management Challenges. Duke University Press.
Roe, E., Schulman, P.R., 2008. High Reliability Management: Operating on the Edge. Stanford University Press, Stanford CA.
Roe, E., Schulman, P.R., 2015. Comparing emergency response infrastructure to other critical infrastructures in the California Bay-Delta of the United States: a research note on inter-infrastructural differences in reliability management. J. Contingenc. Crisis Manage. 23 (4), 193–200.
Roe, E., Schulman, P.R., 2018. A reliability & risk framework for the assessment and management of system risks in critical infrastructures with central control rooms. Saf. Sci. 110(Part C), 80-88.
SAPEA, Science Advice for Policy by European Academies, 2017. Guidelines on Advising Policymakers and Society & Procedures for Quality Assurance of Scientific Advice. SAPEA, Berlin.
Schill, Caroline, Anderies, John M., Lindahl, Therese, Folke, Carl, Polasky, Stephen, Cárdenas, Juan Camilo, Crépin, Anne-Sophie, Janssen, Marco A., Norberg, Jon, Schlüter, Maja, 2019. A more dynamic understanding of human behaviour for the Anthropocene. Nat. Sustain. 2 (12), 1075–1082.
Skryabina, Elena, Reedy, Gabriel, Amlôt, Richard, Jaye, Peter, Riley, Paul, 2017. What is the value of health emergency preparedness exercises? A scoping review study. Int. J. Disaster Risk Reduct. 21, 274–283.
Solinska-Nowak, Aleksandra, Magnuszewski, Piotr, Curl, Margot, French, Adam, Keating, Adriana, Mochizuki, Junko, Liu, Wei, Mechler, Reinhard, Kulakowska, Michalina, Jarzabek, Lukasz, 2018. An overview of serious games for disaster risk management – prospects and limitations for informing actions to arrest increasing risk. Int. J. Disaster Risk Reduct. 31, 1013–1029.
Sterner, Thomas, Barbier, Edward B., Bateman, Ian, van den Bijgaart, Inge, Crépin, Anne-Sophie, Edenhofer, Ottmar, Fischer, Carolyn, Habla, Wolfgang, Hassler, John, Johansson-Stenman, Olof, Lange, Andreas, Polasky, Stephen, Rockström, Johan, Smith, Henrik G., Steffen, Will, Wagner, Gernot, Wilen, James E., Alpízar, Francisco, Azar, Christian, Carless, Donna, Chávez, Carlos, Coria, Jessica, Engström, Gustav, Jagers, Sverker C., Köhlin, Gunnar, Löfgren, Åsa, Pleijel, Håkan, Robinson, Amanda, 2019. Policy design for the anthropocene. Nat. Sustainability 2 (1), 14–21.
Stirling, Andy, Gee, David, 2002. Science, precaution, and practice. Public Health Rep. 117 (6), 521–533.
Tena-Chollet, F., Tixier, J., Dandrieux, A., Slangen, P., 2017. Training decision-makers: Existing strategies for natural and technological crisis management and specifications of an improved simulation-based tool. Saf. Sci. 97, 144–153.
't Hart, Paul, 1997. Preparing policy makers for crisis management: the role of simulations. Journal of Contingencies and Crisis Management 5 (4), 207–215.

The Economist (2007). The quest for prosperity, Special Report. March 17. https://www.economist.com/special-report/2007/03/17/the-quest-for-prosperity (accessed: 6 February 2020).

UNDRR UN Office for Disaster Risk Reduction (2020). *Words into Action: Design and Conduct of Simulation Exercises – SIMEX*. Geneva: UNDRR.

United Nations (2016). Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction, UN General Assembly A/71/644. New York NY: United Nations.

U.S. Department of Homeland Security, 2013. NIPP 2013: Partnering for Critical Infrastructure Security and Resilience. Homeland Security, Washington DC.

van Eeten, M.J.G., Roe, E., 2002. Ecology, Engineering, and Management: Reconciling Ecosystem Rehabilitation and Service Reliability. Oxford University Press, Oxford.

Vieira Pak, M., Castillo Brieva, D., 2010. Designing and implementing a role-playing game: a tool to explain factors, decision making and landscape transformation. Environ. Modell. Software 25, 1322–1333.