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# Resilient flood-risk management at the municipal level through the lens of the Functional Resonance Analysis Model

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ABSTRACT

This exploratory study takes a closer look at the flood Risk Management (RM) system at a municipality level. The current practices of RM in municipalities follow to a large extent, a standard structure of RM processes. Their application comes short of addressing the wide range of local specificities and other complexity related socio-technical factors that can have widespread impacts, much beyond the municipal scope. This study uses concepts and ideas from the resilience engineering literature to enhance the practices of the RM system. We apply the Functional Resonance Analysis Method (FRAM) to investigate the extent to which key RM activities are in line with generating anticipating, monitoring, responding and learning capabilities in the flood RM system. We examine the performance of RM functions, how they are coupled, and whether they can be sustained in the wake of a flood event. A triangulation of various qualitative research approaches is adopted, namely using semi-structured interviews, document analysis and workshop. Our findings reveal how the application of FRAM provides a deeper understanding of the underlying factors that shape the resilience of the RM process.

## 1. Introduction

Approaches to flood Risk Management (RM) are well documented in recent literature. They have addressed a wide range of issues, namely building societal adaptive capacity [15], maintaining social stability and critical infrastructure [19,54], community resilience [18] and flood forecasting methods [69]. The focus has been mainly on the national and regional levels, including land use planning, development, controls, and floodplain-management measures. Flood RM at the municipal level has been less studied, even though it is equally essential, as municipalities serve a crucial role in managing flood-related crises. To highlight the importance of the role of local authorities in managing the risks from climate extremes at the local level, Cutter et al., [17] state: "Disasters occur first at the local level and affect local people. These localised impacts can then cascade to have national and international ramifications" (p. 296). Since crisis management is a part of the RM process, the quality and effectiveness of crisis management depend on how RM is structured and performed. Hence, one of the focuses of this paper is to explore flood RM at the municipal level.

On the other hand, various authors [5,8,11] suggest that improving the RM process requires holistic approaches. The "holistic" notion is here used as opposed to an asset-based approach that considerably overlooks the critical role of interdependencies and tight couplings between different elements of the system. Accordingly, Aven [6] states "more research is needed to develop practical models and methods that can analyse resilience in a risk framework". To this end, this paper also builds on the premise that resilience concepts provide the necessary grounds for such a holistic approach. Resilience is about anticipating future developments and threats, monitoring emerging threats, responding to regular and irregular disturbances effectively, and learning from experience [35].

We use the *guidance* provided by the Norwegian Directorate for Civil Protection [22] as a framework, and data from two different Norwegian municipalities (Stavanger and Egersund), to investigate how resilience may be embedded in flood RM. We explore the relationship between what has been described by Hollnagel [[38]: 26] as the four resilience capacities (anticipate, monitor, respond to and learn), and different operational aspects of the RM system at the municipal level. For this purpose, we apply the Functional Resonance Analysis Method (FRAM - [36]) as a tool to examine how flood RM system operates rather than explore it in terms of its architecture and components. Hence, beyond its conceptual context, this work also contributes to further extend the applied knowledge on Resilience Engineering (RE).

The remainder of this paper is structured as follows: Section 2 presents the theoretical basis for the main concepts used in this study, including flood risk as a concept, RM, a review of the main ideas in the

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resilience concept, and the Functional Resonance Analysis Method (FRAM). Section 3 provides an overview of the approach taken and of the data sources used to support it. Section 4 outlines the application of FRAM to model how a flood RM system functions in practice in terms of its functions and their relations. The insight provided by the FRAM modelling exercise to further study the resilience capabilities in the RM system, is discussed in Section 5. Finally, Section 6 concludes and provides recommendations for further research.

## 2. Theoretical background

### 2.1. The resilience concept

Resilience has become “an umbrella term” for a system property and as a “normative concept” [19]. The concept is referred to as a “mechanism” (process), as an “ability” and as a “capacity” of an organisation/system to bounce back after disturbances. For instance, in socio-technical systems, Goessling- Reisemann and Blöthe (2019) define resilience as a “system's ability to maintain its services under stress and in turbulent conditions” (p. 2). In the crisis-management field, it is described as “the capacity of the system to quickly resume critical functions that were affected by a shock to the system” [10]. In the scope of resilience engineering Woods [71], defines resilience as the system performance that emerges from generating and managing adaptive capacities. This definition is in line with the four potentials in resilient organisations, previously mentioned [38], which have also been referred to as the four cornerstones of resilience engineering [35], as follows:

- Knowing what to expect; that is, how *to anticipate* future developments, threats and opportunities, such as potential changes, disruptions, pressures and their consequences. This is the ability to address the potential. According to Spaaij [63], anticipation refers to efforts made to predict and prevent potential dangers before damage is done” (p.88). This is about identifying potential developments and opportunities beyond the range of current operations [35].
- Knowing what to look for; that is how *to monitor* that which is, or can become, a threat in the near term. This is the ability to address critical issues. Monitoring looks typically for specific conditions or relies on certain indicators, known as “leading indicators”, because they indicate what may happen before it happens [34].
- Knowing what to do; that is, how to respond to regular and irregular disruptions and disturbances. This is the ability to address the actual.
- Knowing what has happened; that is, how to learn from experience. This is the ability to address the factual.

Resilience must be appropriately framed in a specific system purpose (e.g., ecology, city, community, system, etc.) and scope (e.g., individual, organisational, regional, and global). We focus on resilience in the RM system at an organisational level (municipality). For the purpose and scope of this paper, we define resilience as “a system's capabilities to sustain, restore and even improve its functionality under turbulent circumstances.”

The turbulent condition relates to “dynamic changes in system structure and environment, irregular conditions, limited predictability, and surprises acting on the system” ([31]: 122). Fig. 1 illustrates the main components of resilience capability.

In our view, resilience is not only about recovering from disturbances, but also about moving forward. In particular, it is about adapting to disruptions of a system and rapidly improving to normal functionality, or above, through learning that leads to changes (e.g., reorganisation and rebuilding). According to Parsons et al., [48], the capacities that enable adaptation are related to “the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem-solving and balance power among interest groups.” Learning, however, is a challenging task. Boin et al., (2016: 130-132) point to two barriers that hinder learning from experience: the fear of being exposed to adverse reactions, and publicity and strategic amnesia, such as the manipulation of organisational memory. Lack of “institutional memory” to maintain and share organisational experiences [68] and the potential lack of fit between lessons from the past and the demands of future events [26] are other obstacles to learning, hence resilience capability.

### 2.2. Functional Resonance Analysis Method (FRAM)

The principles of FRAM are firmly grounded on the Resilience Engineering thinking and are formally described by Hollnagel [36]. Although it is not intended to be a “resilience analysis” tool, it provides a unique insight into system functioning and the functional relations within systems. It is on this same basis that FRAM was considered as a suitable tool to address the purpose of this paper. In 2004, the first version of FRAM was presented, named as Functional Resonance Accident Model (FRAM), as an approach to study a system in terms of its functions, their connections and their potential variability and its effect on system's performance [33]. Since then, FRAM is utilised with many different purposes, namely research studies and applied for work, relating to accident investigation and analysis, the pursuit of alternative approaches to risk assessment, as well as many others in the scope of system analysis. FRAM is also applied in a wide diversity of domains, including; aviation ([20,30,32]; Patriarca et al., 2017; [28]), railway [9,27], healthcare [16,52], construction [59], maritime [49,56], flooding [2] and security [67].

The underlying thought behind FRAM is the systemic view. A significant characteristic of the systemic perspective is that it considers an organisation as “a multi-minded, socio-cultural system, a voluntary association of purposeful members who have come together to serve themselves by serving a need in the environment” [29]. This means that the functionality of a system rests on a non-linear, dynamic combination of different functions through the whole system. The description of “functions” is at the core of FRAM. This description is mainly produced through the identification of the following six aspects (Fig. 2): Input (I: that which the function processes or transforms or what it starts with), Output (O: the result of the function), Preconditions (P: that must exist before a function can be executed), Resources (R: that which the function needs to produce the output), Time (T: related to starting time, finishing time or duration, etc.) and Control (C: how the function is monitored or controlled). The model is generally represented by hexagons connected through their aspects. It is essential to mention that these connections only represent potential couplings between functions. These couplings, however, may or may not become active or operational, as different functional scenarios might be simulated through the model. These simulations are referred to as instantiations of the FRAM model.

In the FRAM terminology, a function is “the means necessary to achieve a goal” e.g., as an activity or a task [37]. It is also referred to “what an organisation does” (Ibid). For instance, in the risk-management process, different functions are different operational, technical and organisational activities involved in identifying risk, conducting vulnerability analysis, risk evaluation, risk treatment and control. Functional resonance is a crucial concept in FRAM approach. It is an analogy that depicts the growing dynamics inherent in the complex systems. The effect of resonance relates to the inevitable performance variability that emerges from the need to adjust work (both individual and collectively as an organisation) to continuously changing conditions.

In contrast to cause-effect relations, functional resonance highlights the non-linear nature of ties between coupled (i.e. interdependent) elements in complex systems (which in the scope of FRAM, are described as functional elements). While many different approaches can

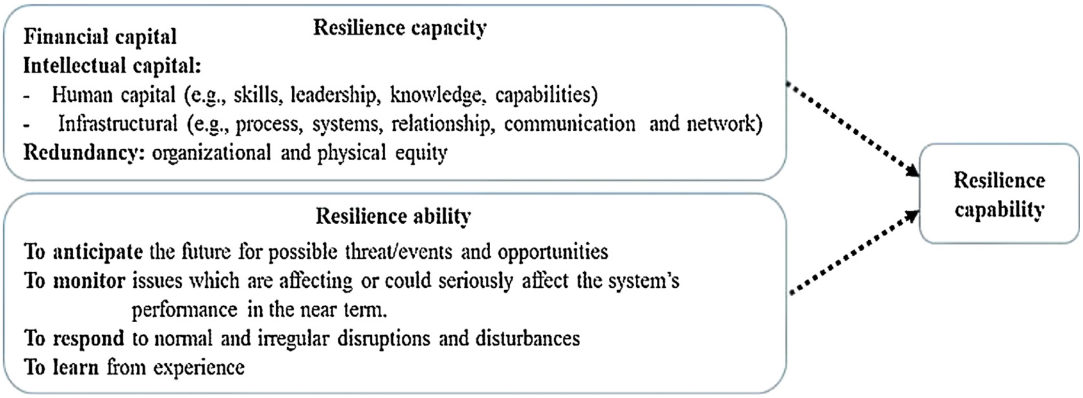

**Fig. 1.** Main components of resilience capability.

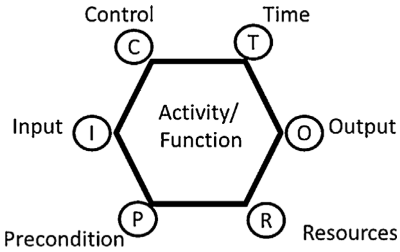

**Fig. 2.** Function and its six aspects in FRAM terminology.

be taken, Hollnagel [36] proposes the use of phenotypes or failure modes to illustrate the potential impacts of a function's performance variability. As in most safety literature, phenotypes or failure modes are here defined as different possible states of the quality and timing of the function output (i.e. speed, distance, sequence, object, force, duration, and direction among others).

The application of FRAM in analysing the resilience of a flood RM system provides a broader risk picture by "envisioning possible scenarios based on existing planning" [60].

### 2.3. *The current practices of flood RM at the municipality level*

The current practices of RM at municipalities in Norway is in accordance with the laws and requirements for municipal preparedness and the *guidance* provided by Norwegian Directorate for Civil Protection [22]. The DSB-guidance (p. 15) defines risk as "an assessment of whether an event may occur, what the consequences will be and uncertainty associated with this". Based on this definition, flood risk could be understood as an assessment of a flood event and its impacts, with associated uncertainties. The uncertainty element is involved in both the meteorological aspect (in forecasting systems) and the response and coordination process. The uncertainty elements which are associated with coordination are related to "coordination capacity, mutual trust and administrative level" [14]. We can use probabilities as a means of expressing uncertainty associated with various flood event scenarios. The uncertainty assessment in this paper stands on knowledge-based (subjective) probability approaches; for instance, a qualitative evaluation of uncertainty factors which are mainly the result of assumptions made to determine the probability. For a complete discussion about expressing uncertainty in risk assessment, see Aven [6]. The process of risk assessment starts with establishing the context, follows by the risk and vulnerability assessment (RVA) and risk treatment process. On a more detailed level, the RVA process consists of three phases, including the planning, conducting a vulnerability assessment, and the follow-up phase (see Fig. 3).

The overall objectives of conducting RVA in a municipality are as follow ([22], p. 10):

- provide an overview of adverse events that challenge the municipality
- provide awareness of the risks and vulnerabilities in the municipality
- spot risks and vulnerabilities across sectors
- provide knowledge of measures to handle risks and vulnerabilities in the municipality and identify means to do that
- provide a basis for objectives, priorities and necessary decisions in the municipality's work on civil protection and preparedness
- provide input into RVA within other municipal areas of responsibility and county

As Fig. 3 illustrates the current practices of risk and vulnerability assessment in municipalities follow, to a large extent, the standard structure of RM processes, see, e.g., ISO 31000 [41]. However, the current standard-based RVA faces several challenges. For instance, the standard is too general, regardless of the context of the situation at hand (risk type and size, risk influence factors, etc.). Thus, its application is too narrow to cover particular risks (e.g., flood risk) adequately, as it does not address the detail of the specific issues in the working environment. Moreover, Aven and Ylönen (2019) questioned the scientific quality of the ISO standard, its solidness, and the rationale for selecting the risk treatment option. According to these scholars, the ISO 31000 does not adequately pay attention to the treatment of uncertainties. Lack of focus on uncertainty hampers the ability of RM to provide sufficient support for decision making in highly uncertain situations such as flooding. This "lack" also constrains our understanding of how a system works or is supposed to work. In developing a risk management system, Aven [4] points to *two main pillars* of the RM process, namely the structure and the underlying RM strategies. These strategies include *i)* risk-assessment informed, *ii)* cautionary and precautionary approaches, highlighting robustness and resilience, and *iii)* dialogue and participation (Aven 2017). In the context of flooding, for "meeting real-life issues" [6], an appropriate strategy to improve flood RM is to incorporate resilience analyses into the RM process (ii). Examples of the robustness and resilience strategy are continuous monitoring, guided adaptability and proactive learning (Provan et al., 2020), as well as research to increase knowledge and the development of substitutes [5].

Establishing a holistic method, integrating risk and resilience-based thinking [5], enhances municipalities to handle flood risk in two bases. The first is to provide insights about potential flood scenarios and their impacts and to produce a risk picture based on the available background knowledge and identify key uncertainty factors. The second one is to enhance the resilience of the flood RM system's capabilities, i.e., to withstand any flood event (in terms of its impacts) and rapidly recover to normal functionality (or above) of the system. The resilience analysis, as a part of the RM process, investigates the functionality of the RM system without specifying concrete flood events, such as scenario

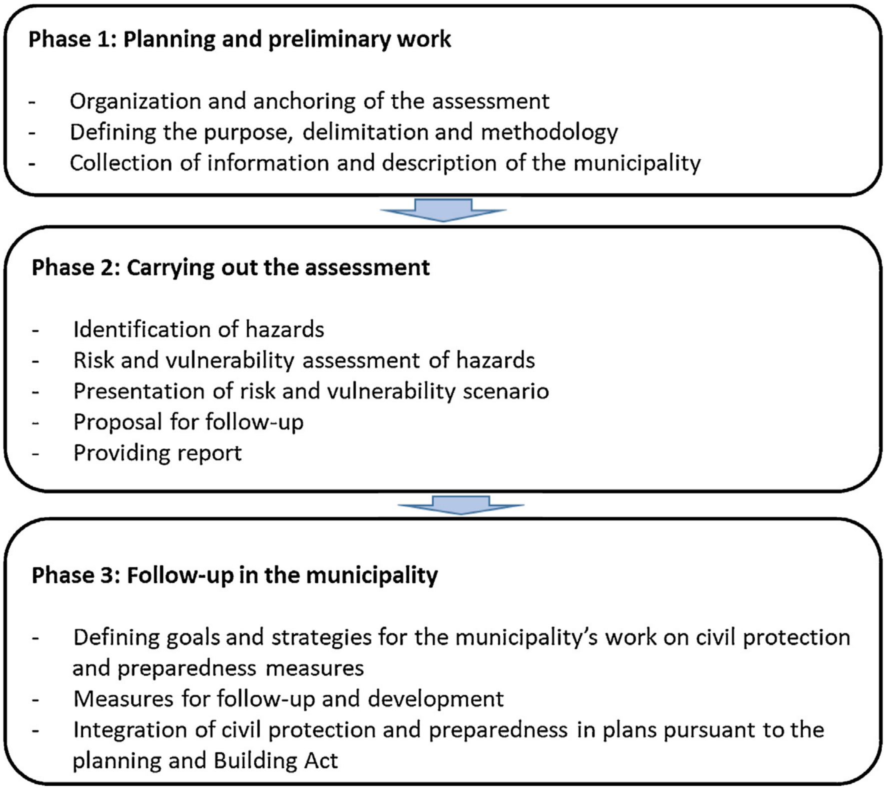

**Fig. 3.** The main steps in a risk and vulnerability assessment in the municipality, based on guidance provided by DSB [22].

"S". Instead of focusing on possible or known scenarios, resilience analysis is driven by investigating various sort of functional variability that the system might face, and the extent of the adaptive capacity of the system to deal with such variability. To analyse the RM system's resilience, we must understand how the RM system works in every detail and identify the essential activities involved in each part of the system.

## 3. Methods

This explorative paper aimed to investigate how the application of FRAM might improve resilience in flood RM systems at the municipality. The approach proposed is based on FRAM methodology, as a roadmap to systematically investigate how the four resilience cornerstones may or may not be reflected in a given RM system. The risk and vulnerability assessment (RVA) framework described in the previous section was used as a practical approach for organising functions in FRAM representation. A FRAM modelling exercise was carried out. We aimed to ascertain how different RM activities contributed to the enhancement of anticipating, monitoring, responding and learning capacities in the system, what their main performance traits are, how they are connected, and whether they can be sustained in the wake of the flooding. The factors that may lead to successful operations and how to strengthen them were also examined.

As previously mentioned, an exploratory research approach was taken. As exploration requires flexibility and open-mindedness ([65]:10), we used a triangulation of qualitative methods, consisting of document analysis, interview and workshop. Triangulating provides "a confluence of evidence that breeds credibility" ([25]: 110) by comparing and crosschecking the consistency of information derived within qualitative methods [53].

### 3.1. Document analysis

In Norway, it is mandatory for municipalities to act following the laws and requirements for municipal preparedness, as provided in the Act of June 25, 2010, on the municipal preparedness duty. It also gives detailed guidelines that present a methodology for implementing and following up a holistic risk and vulnerability assessment (RVA) at the municipal level. These guidelines are contained in the following documents provided by the Norwegian Directorate for Civil Protection (DSB) and Ministry of Justice and Public Security (JD):

- Guidance for social security instructions [43]
- Guidance for holistic risk and vulnerability assessment in the municipality [22]

We also analysed official reports and evaluations in the aftermath of the flood Synne, which struck the Egersund municipality in 2015. Documents studies revealed that there is no consensus on how risk is defined and what the main steps of RM at municipality level are. For instance, while JD defines risk as to the combination of probability and consequences of an undesired event (P: 9), DSB defines risk as "an assessment of whether an event may occur, what the consequences will be and uncertainty associated with this" (p: 15). While the RM process in the guidance for social security instructions is based on [41], DSB emphasises on three main steps in conducting RVA, including planning, conducting the assessment and follow-up phase.

The study of these documents provided insights about the main steps of the RM process and organisational requirements in practice, which we further used in different phases of our FRAM modelling. For instance, in the preparation phase (Framing of flood risk) is in line with the principle of collaboration in contingency planning provided by the Norwegian Directorate for Civil Protection [22], which proposes optimal cooperation among authorities, relevant actors and agencies involved in the prevention, preparedness and crisis management. Document analysis was also applied to the study of two evaluation reports on the flood crisis management by the Eigersund Municipality [24] and the Rogaland County Governor [58]. We examined, as well, the Eigersund Municipality Emergency Plan [23].

### 3.2. Interviews

We conducted five semi-structured interviews with representatives from the Eigersund municipality on 24. March 2017. We aimed to understand how the criteria for resilience were operationalised in the municipality, both before, during and after the Storm Synne in 2015. Participants included four municipality representatives who had a key role in the Synne- flood crisis management, as members of the municipal Emergency Management Team. The fifth representative was the municipality's chief executive officer who had a guest lecture about the different stages of crisis management during the Synne storm in October 2016. An interview guide was developed, consisting of a list of questions and topics of interest (focus on resilience capabilities). All interviews were conducted on the same day within regular working hours and the municipality's contact person selected in advance the time for each interviewee. It was initially set by 45 minutes to every interviewee, and the most extended interview lasted under an hour. After the meetings, we categorised responses, as we saw the need to be able to anchor information in categories such as anticipation, monitoring, responding and learning. The results were partly used in a paper on resilience in flood crisis management, published in Risk, Hazards, & Crisis in Public Policy journal [66].

### 3.3. Workshop

The workshop was held on 18.01.2019, within regular working hours, and attended by participants from Stavanger (the third-largest city and metropolitan area in Norway) and Egersund (southwestern Norway) municipalities and included chief municipal executives and sector managers. The involvement of representatives from Egersund was particularly important, as they experienced the most torrential rainfall since records began in 1897, a so-called “200-year flood” in December 2015 (the storm called Synne). Their response to the emerging situation caused by Synne, and the recovery operation, was considered unprecedented, as the services that responded to the flood were awarded the Social Security Prize for 2015 by the Norwegian Directorate for Civil Protection (DSB). The workshop was used as a forum for discussing how municipality conducts RVA process, regarding flood events, and what are the challenges. We have also used the workshop as a desktop exercise for the modelling FRAM, as it is explained below.

### 3.4. FRAM model development

FRAM modelling was based on data from several sources, including workshops and document analysis (guidance for risk and vulnerability analysis at the municipal level). FRAM gave way to the illustration of complexity in the wake of flood events, of the potential variability in some of the functions within the RM system, and how this variability may affect the whole RM process (resonate). The FRAM Model Visualiser (FMV) [39] was used to support modelling activities, as well as the myFRAM [50] tool. The participants of the workshop were introduced to the concept of resilience and the FRAM modelling approach. Both municipalities’ emergency members were familiar with standard RM and were involved with conducting RVA in their routine work. After a short introduction about resilience concept, they acknowledged the importance of resilience capabilities in dealing with flood events. They, however, appeared somewhat sceptical about the application of FRAM due to its complexity and level of details. During the workshop, we discussed each step of RVA. The participants were asked to perform the following tasks and share their results with us via the Microsoft Teams platform, in the coming weeks:

- Identify different activities and their crucial functions involved in the preparation, flood handling and restoration phase in flood RM, as they already exist or as they are expected to be as part of the RM system at the municipal level.
- Describe the coupling between identified functions
- Identify the potential and expected variability of each function that may lead to unwanted results (e.g., the function doesn't work as planned).

A set of trigger-questions were used to drive this process:

- Which functions are involved in the flood RM system (i.e., in anticipating, monitoring, responding and learning)?
- What are their characteristics (resonance)?
- What is the potential variability in each function, and how does this variability affect the whole RM process (resonate)?
- Can essential functions and operations be sustained in the wake of flooding (of any type)?
- What are the preconditions for acting as the function requires?
- Which controls are needed, and are they appropriate?
- What is missing?
- What variations could happen?
- What factors contribute to successful operations, and can they be applied?

The input from the workshop participants, as well as our findings from document analysis, provided insights to develop FRAM models.

## 4. Application of FRAM to improve resilience in flood-risk management

FRAM was used to model how the flood RM system would perform in practice (work-as-done) in the face of different potential flood scenarios. The models then provide insights to study resilience capabilities in the RM system. Based on the description of the RM framework (Section 2.3), and the empirical research (Section 3), we identified over 50 functions and their aspects. In our discussion, we looked closer at the foreground functions (denoted as the main functions here), rather than the background functions. According to FRAM terminology, while the background functions compose the context or working environment, the foreground functions represent the focus of the investigation, i.e., “that which is being analysed or assessed” ([36]:58). The following table presents the main functions.

We organised the FRAM representations around three RM phases: preparation, flood handling, and restoration phase. The first phase in our FRAM modelling, the preparation, corresponds to the “planning and preliminary work” and “carrying out the assessment” in Fig. 3. The second phase illustrates activities which are involved during a flood event. Finally, the third phase links to the “Follow-up in the municipality” phase in Fig. 3.

### 4.1. The preparation phase

The preparation phase is involved in proactive activities that enable municipalities to anticipate and recognise flood threats. The following two activities were identified as the main functions in this phase:

- Framing flood risk context
- Develop different flood-event scenarios
- Conduct risk and vulnerability analysis
- Prepare contingency plan
- Perform emergency training exercise

#### 4.1.1. Framing the flood risk

In framing the flood-risk context, all relevant information (e.g., flood map, pertinent stakeholders of managing the flood, land use within a floodplain, etc.,) should be gathered. It is also essential that the objectives and boundaries of the RM process be highlighted. Fig. 4 shows FRAM model for establishing a flood-risk context. Note that, to

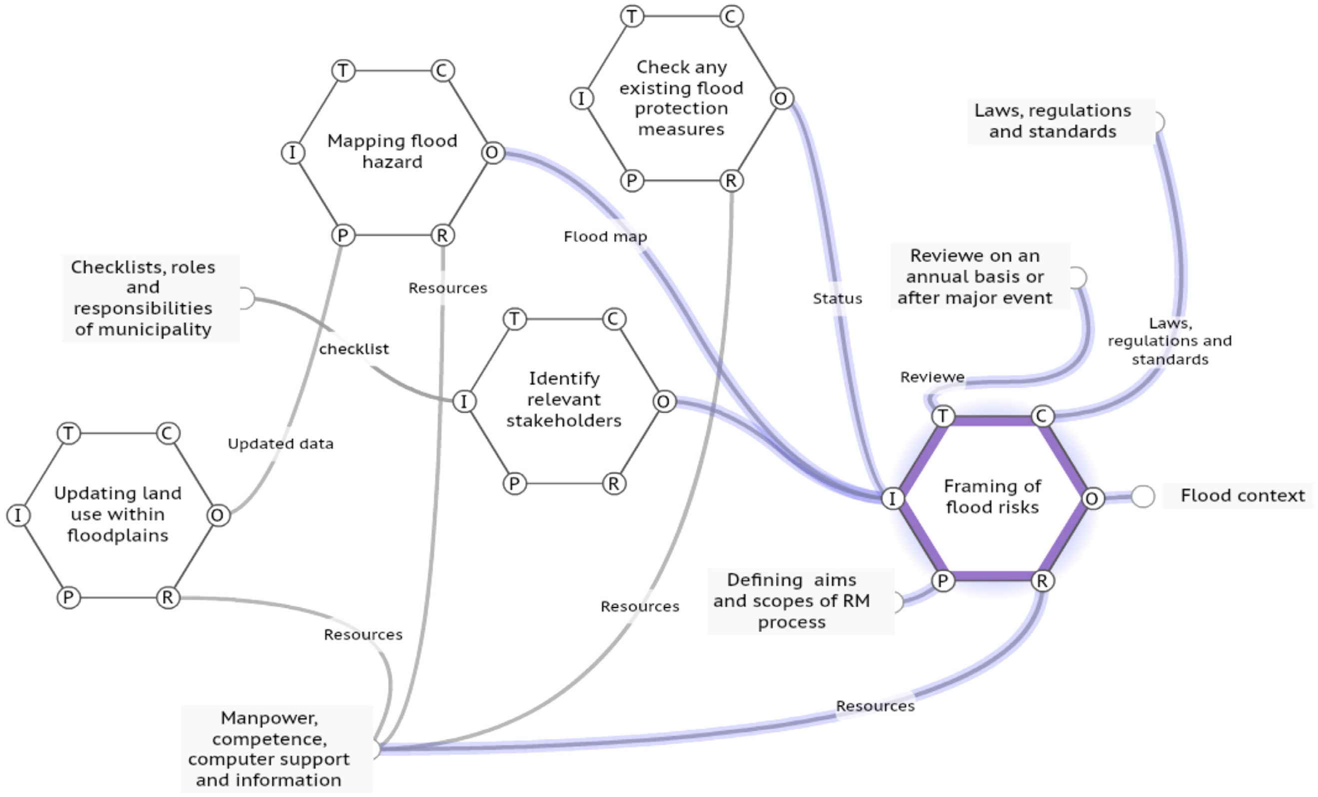

**Fig. 4.** FRAM instantiation for establishing the flood-risk context.

reduce the complexity of FRAM representation, some of the aspects of functions are not illustrated in Fig. 4.

As Fig. 4 illustrates, establishing a flood-risk context is the main output of framing flood risk. This output could be presented as a summary of general information. Framing, in our setting, is about creating a common understanding of the flood RM issue(s) being addressed. These issues include the scope, time horizon, strategy for collecting knowledge about flood risk, as well as clarification of the roles and responsibilities, power relationships and the hierarchical decision-making structures between different stakeholders involved in flood RM process. Engaging of relevant stakeholders in the framing process enable the municipality to assemble the knowledge and information required in framing flood risk. Cooperation between the pertinent organisations in terms of sharing information and experiences, allows municipalities to capture various perspectives on flood risk and develop strategies for managing floods at the local level.Table 2 outlines a description of the “Framing flood risk” function, including its potential variability and phenotype.

Several internal and external elements may cause the variability in flood risk context. For instance, the goals and extent of flood RM to which the features conflict (e.g., political climate versus economic constraints and strategic objectives). The other factor is related to the changing nature of the climate, which underlines the need to examine flood-prone areas continually. In this regard, the time horizon considered for identifying floodplains and other susceptible areas is essential.

### 4.1.2. *Conducting risk and vulnerability analysis*

In Norway, there are regulatory requirements for risk and vulnerability assessments (RAV). Municipalities should provide a holistic RVA

**Table 1**
Main functions in flood RM, disused in this paper.

| Functions | Description |
|---|---|
| Framing flood risk context | Create a common understanding of the flood RM issue(s) being addressed. |
| Conduct risk and vulnerability analysis | Provide an overview of flood events that challenge the municipality and input for preparing a contingency plan |
| Develop different flood-event scenarios | Build a range of scenarios embodying different assumptions about future flood events. |
| Prepare contingency plan | Make a plan ahead on how to manage the response to a flood event. |
| Conducting emergency training exercise | Ensure that the responders are known with plan's details, and validate and test the plans, and procedures. |
| Conduct situational assessment (SA) | Provide a platform for executing a contingency plan. |
| Execute the contingency plan | Effectuate contingency response plan. |
| Respond to media inquiries | Ensure that accurate (as possible) information is provided to the public and officials promptly. |
| Provide advice/warning to people at risk | Warn, inform and advise the community. |
| Coordinate with other involved agents | Organise and facilitate all efforts and activities during the response to a flood event. |
| Allocate resources | Assign & manage resources in a manner that supports the contingency response plan. |
| Evacuate | Evacuate residents for an extended time, to save their lives. |
| Provide an evaluation report | Examine the process for flood RM. |
| Learn from flood handling operation | Explore what worked well in the response process, and what did not, what aspects of plans should be changed. |
| Develop a multi-hazard flood mitigation plan | Update the municipal flood mitigation planning policies to reduce the future impacts of /multi) hazards, e.g., loss of life, property damage, and disruption. |
| Control and mitigate flood risk | Repair, reconstruct, reorganise or regain what has been lost as a result of the flood, and mitigate flood risk in the future. |

**Table 2**
FRAM representation of <Framing flood risk>.

| Objective | To establish the flood risk context. |
|---|---|
| Aspects | *Input:* Map of areas subject to recurring floods, internal and external stakeholders, and the current status of existing flood protection measures.<br>*Output:* Flood risk context.<br>*Precondition:* Defined and verified objectives and scope of flood RM and priorities.<br>*Resources:* Manpower, competence, computer support, and information.<br>*Control:* Laws, regulations, and standards that regulate and supervise flood control & protection measures<br>*Time:* Regularly (on an annual basis) and after significant events. If there are any changes in procedures and standards that could influence the flood RM process, it is essential to update information. |
| Phenotypes | In terms of precision:<br>*Imprecise:* Framing does not address recent changes in critical issues.<br>*Acceptable:* the outcome of “Framing” provides all relevant information (e.g., flood map, relevant stakeholders in managing the flood, land use within a floodplain, etc.,) |

**Table 3**
FRAM representation of <Framing flood risk>.

| Objective | Conducting risk and vulnerability analysis (RVA) |
|---|---|
| Aspects | *Input:* Results from a risk and consequence analysis as well as uncertainty analysis in Ss. *Output:* RVA report<br>*Precondition:* Necessary competence, knowledge, and skills to develop RVA<br>*Resources:* IT, human resources, etc.<br>*Control:* RVA guidance<br>*Time:* Not described initially |
| Phenotypes | In terms of precision:<br>*Imprecise:* The RVA report is incomplete, incorrect, or otherwise misleading.<br>*Acceptable:* The report provides adequate insight to meet the needs of the downstream functions. |

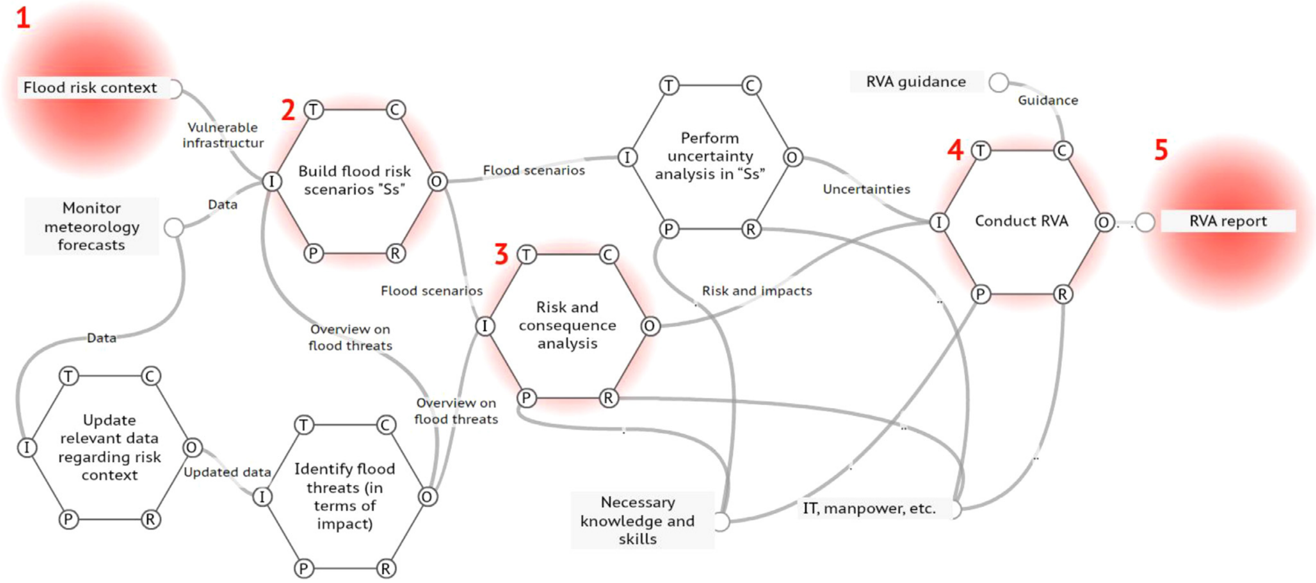

**Fig. 5.** FRAM instantiation for conducting RVA.

that addresses adverse events with potentially significant consequences, as well as events that concern the population and multiple sectors. Holistic RVA should also implicate “the adverse events that exceed the municipality's capacity to respond with the use of ordinary routines and rescue services” ([22]: 17). The two municipalities that we used in this work apply RVA guidance, as presented in Section 2. Our empirical finding uncovered many functions that are involved in conducting RVA in practice, see Fig. 5.

Conducting RVA is founded on the output from downstream functions (e.g., nr. 1-5 in Fig 5). The phenotypes of downstream functions, e.g., in terms of precision and timing, will affect the thoroughness of the RVA report. For instance, different scenarios might manifest different assumptions about future flood events. In practice, the identified scenarios use as input in risk and consequence analysis, which further provides input to conducting RVA. These scenarios are built on a sense of predictability of future events and attempt to bring the future into the present, based on the available data and underlying assumptions. The extent and the quality of available data and the uncertainties involved in premises affect how scenarios are developed. For municipalities, several relevant questions then arise (Reniers, 2017):

- Is there sufficient and available expertise in municipalities to collect and interpret information/data about future trends?
- To what extent this information is a strategic concern? How to develop a dynamic risk and vulnerability analysis techniques “using big data and real-time monitoring”?

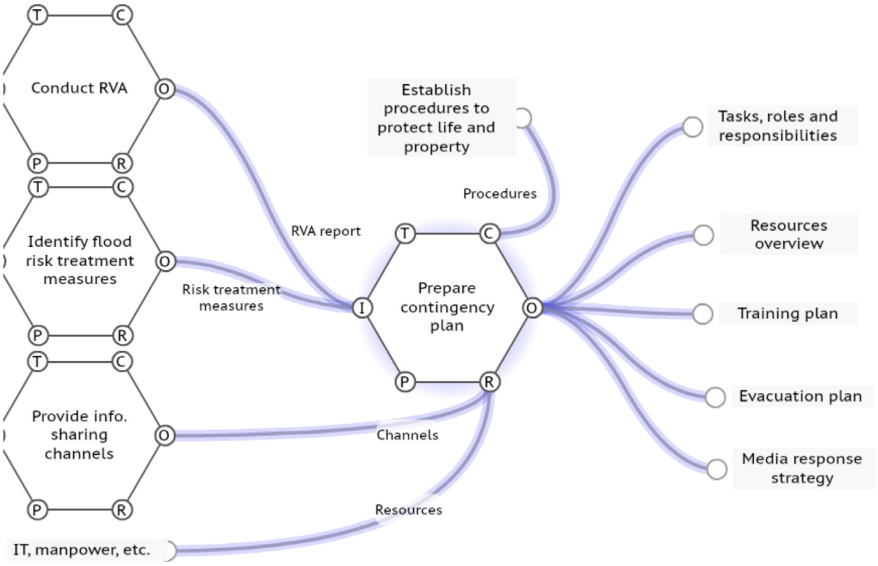

**Fig. 6.** FRAM instantiation for preparing a contingency plan.

Developing RVA requires more than a "well-written description details" as we find in standard guidelines. It is why many experts in the field of risk management highlight the crucial role of competence, knowledge, and skills of those who develop RVA, see, for instance, Aven [[7]: chapter 6]

The results from the RVA provide input for preparing a contingency plan. According to guidance provided by the DSB [22], a contingency plan should include different scenarios for natural hazards, a plan for evacuation, the development of resource overviews, and notification lists for handling flood and landslide hazards. Municipalities should coordinate their contingency planning internally and against other relevant civil protection actors (p. 3). Moreover, the contingency plan must be updated and revised annually (p.21). These elements are highlighted as outputs from the function "Prepare contingency plan" or as a result of other coupled functions (Fig. 6).

Flood risk evaluation also influences contingency plan preparation through its coupling with the identification of flood- risk treatment measures. Evaluation is, of course, a value judgment task and highly context related. It depends on the "quality" of risk and consequence analysis, as well as an analysis of uncertainty involved with those identified risk scenarios. The quality of the risk context (i.e. attention to detail, updated data, priorities, and existing resources, among others) shapes the thoroughness of contingency planning, i.e., it's precision. These elements include climate changes, working conditions, policies, priorities, and strategies (e.g., dedicating resources to deal with climate change). To ensure that emergency responders are known with the details of the plan, and validate and test the plans, and procedures, emergency response training exercise is crucial. In this regard, conducting emergency intervention training is another main function in the preparation phase. While the training plan (Fig. 6) provides input and guidance to this function, its output is trained personnel.

### *4.2. Flood handling phase*

This phase looks for ways to immediately respond to, and recover from, the impacts of a flood event. The ability to plan for, manage, and implement flood response activities is about having resources available or being able to rearrange the existing configuration so that the necessary resources become available. A flood event often develops in unexpected directions, creating challenges to responding organisations in terms of adaption and redundancy. The following functions were found to be more tightly coupled and will be discussed further:

- Conduct situational assessment (SA)
- Execute a contingency plan
- Allocate resources
- Coordinate resources
- Evacuate
- Respond to media inquiries
- Provide advice/warning to people at risk
- Coordinate with other involved agents

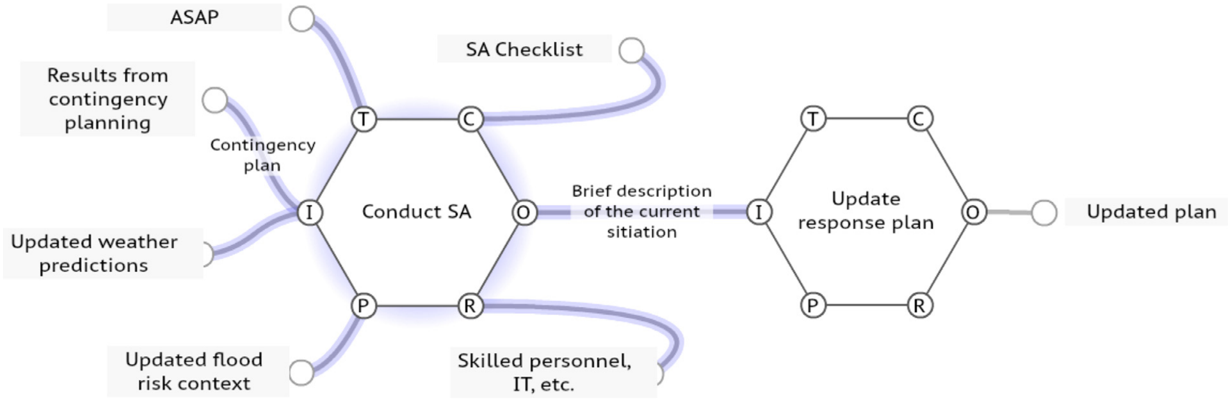

**Fig. 7.** FRAM instantiation for conducting a situational assessment.

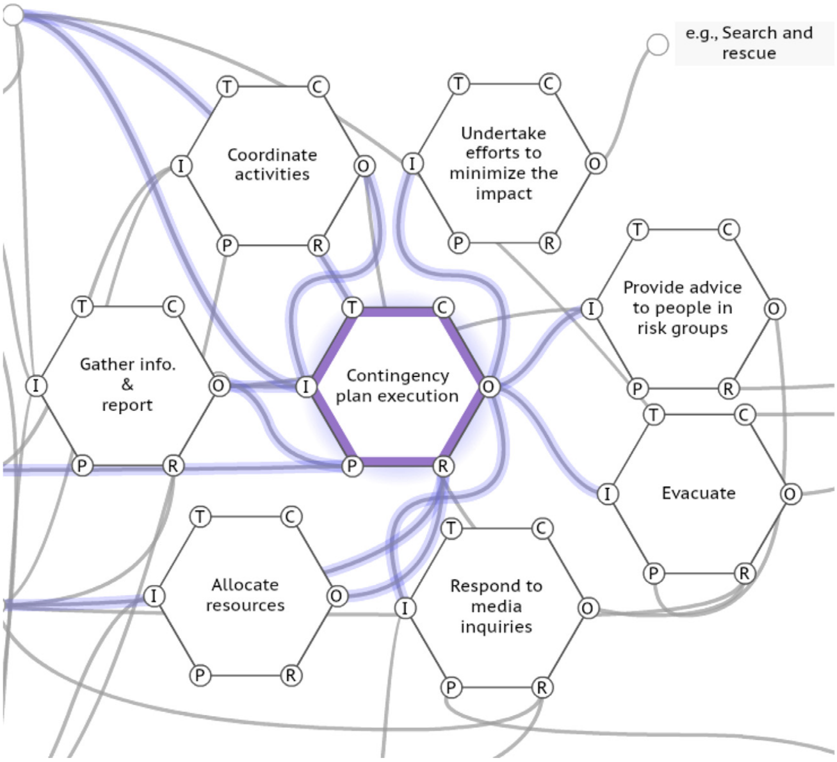

**Fig. 8.** FRAM instantiation for the execution of the contingency plan.

When a flood event strikes, the first (main) function is conducting a situational assessment (SA) (Fig. 7). It aims to provide a profound understating of the situation at hand. SA holds during the first information-sharing meeting, by receiving all briefings from participants, as well as the latest meteorological forecasting.

The contingency plan (first phase) is a generic document that does not specify which actors are the most relevant in the event of a flood. The scope of the plan's execution will vary according to the scale of the flooding and depend on the municipality's adaptive capacity. The effectiveness of the response process depends on the ability to modify the response to meet the requirements. The modification could be in terms of having available alternative forms of logistics, such as the mobilisation of all critical personnel, services, materials, suppliers, and contractors. SA support updating of the response plan, as its output is a picture of the situation at hand, which provides awareness about the threats, opportunities, resources, challenges, and barriers.

When the emergency response plan (ERP) is updated, it should be implemented. ERP execution consists of a range of various interrelated and inter-organisational activities. Its complexity is illustrated in Fig. 8.

Response to a flood event is a demanding process. Resource allocation and coordination (Fig. 8) shapes the effectiveness of the response process. Uncertainty elements associated with these two functions might be related to the issue of accountability. Resources must be available in advance, so it is crucial to identify them (e.g., who is responsible for which tasks, what kind of material, equipment, etc.), and how to access them. This information can be provided by clarifying responsibilities as a function. The following figure illustrates a baseline model for resource allocation, in terms of technical, organisational, physical, emotional, and medical support.

Emergency management teams in the municipality, and external stakeholders and agencies, have to arrange the necessary resources by “bringing together a set of differentiated activities into a unified arrangement” [3] while communicating with actors and the press. As the core concern in the response process, coordination aims to manage dependencies between activities (Malone & Crowston, 1994). The dependencies revolve around two dimensions, vertical and horizontal. The first one concerns relations between actors, and the second concerns actors who need to be coordinated at the same level, [13]. Table 4 presents FRAM for the coordination function.

As Table 4 shows, coordination faces several challenges that can jeopardise the effectiveness of the response process. For instance, the involvement of several actors from different organisations and different working cultures, difficulty in gathering information and sharing it, and making sense of the emerging situation may seriously affect responses to a flood event.

Evacuation is one of the most critical functions in flood emergency responses. Academic researches on evacuation have developed a different model to estimate the travel time of evacuation, and determine the appropriate evacuation routes. For instance, Jamrussri and Toda [42] developed an evacuation model based on the physical status of evacuees (elderly and preschool citizens), safe evacuation conditions, and the shortest time of evacuation as well as flood shelter and road capacity. The output of evacuation depends on the result from many upstream functions, for instance, the quality of available data based on continuous monitoring of the situation and thoroughness of evacuation's plan, procedures, and strategies. The multiple couplings in Fig. 8 suggest that there could be variability in the way each function is carried out. These variabilities, in turn, may affect downstream functions, as for evacuation, alongside with the authorities’ decision-making about evacuation promptly. Table 5 summaries a description of the evacuation function along with its variability aspects.

Respond to media inquiries is a part of the municipal crisis communications plan which aims to ensure that accurate (as possible) information is provided to the public and officials on time. A precondition for this function is the organisational culture in terms of openness for sharing information. Qualified personnel, procedures, and communication strategy (who says what, when, how) is required to this function serves its purpose.

### *4.3. Restoration phase*

The restoration phase (Fig. 10) corresponds to “Follow-up in the

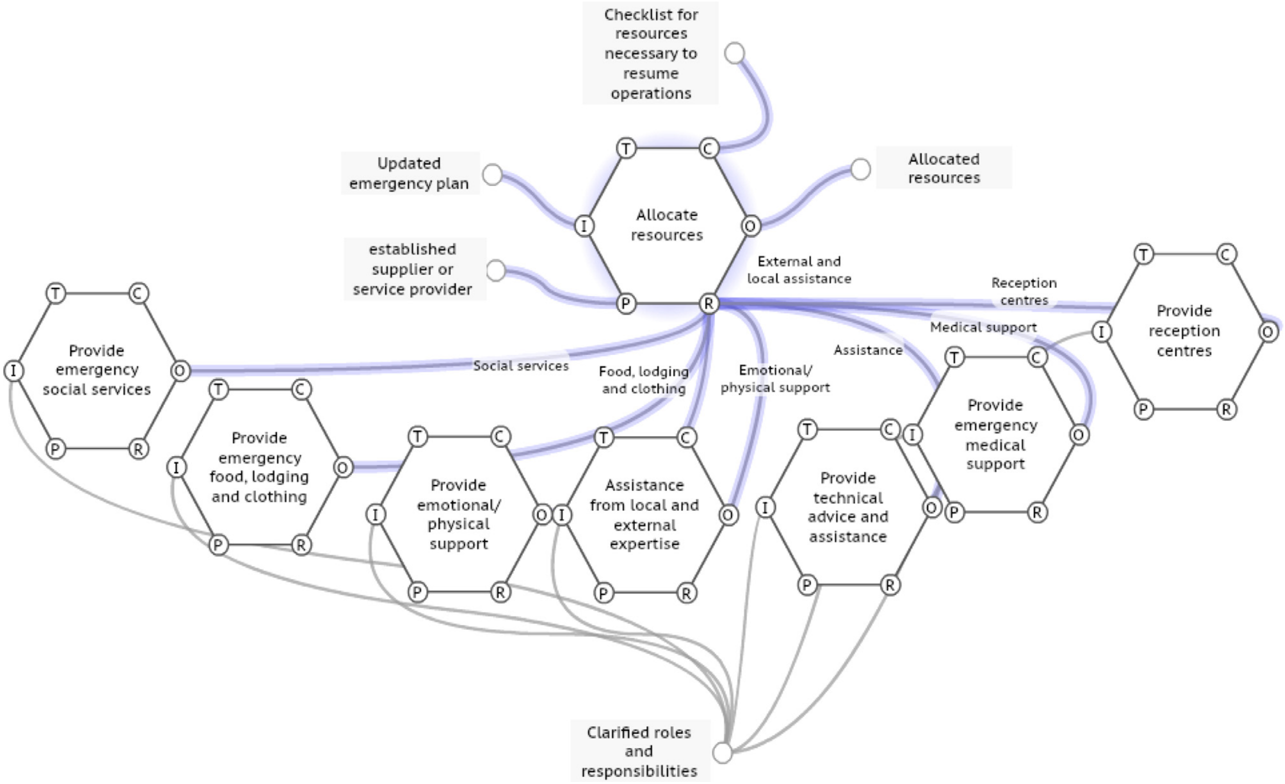

**Fig. 9.** FRAM instantiation for resource allocation.

**Table 4**
FRAM representation of < Coordination >.

| | |
|---|---|
| Objective | Organise, facilitate all efforts and activities, and provide information flow between the different actors involved in the response process. |
| Aspects | *Input:* Identified flood risk treatment measures and allocated resources<br>*Output:* Coordinated response activities<br>*Precondition:* Clarified roles and responsibilities<br>*Resources:* Manpower, competence, technological support, and information |
| Function's variability | Related to its capacity and quality due to the scope of the flooding and variability among upstream functions:<br>– Risk perceptions and thoroughness of contingency plan.<br>– Risk acceptance and the level of resources committed by the involved organisations.<br>– Changes in command and control hierarchies.<br>– Collaboration with the municipality's emergency management team in terms of joint planning, training, etc. |

municipality” phase in Fig 3. The main functions during the restoration phase are “Flood risk recovery and control”. This function aims to repair, reconstruct, reorganise or regain what has been lost as a result of the flood, and mitigate flood risk in the future. The recovery function starts immediately after the flood and aims to normalise the situation (e.g., reopening roads, cleaning and sanitising dirt, soil, and debris from surfaces, etc.). Flood risk control also has a long-term perspective – looking for a way to rebuild and rehabilitate the community and to establish ways to be better equipped for future floods.

As Fig. 10 shows, many functions are involved in this phase, including:

- Provide an evaluation report
- Learn from flood handling operation
- Develop a multi-hazard flood mitigation plan
- Control and mitigate flood risk

**Table 5**
FRAM representation of <Evacuate>.

| | |
|---|---|
| Objective | To minimise the risk or even the loss of life of the target group from the area at risk by moving them ta a safe place, as quickly and safely as possible. |
| Aspects | *Input:* Detailed data from emergency plan execution<br>*Output:* Evacuated target group<br>*Precondition:* Defined evacuation strategies and identifying the needs of the population<br>*Resources:* Leadership, human resources, transportation as well as a reception centre<br>*Control:* Evacuation plan and procedure<br>*Time:* The available time for safe evacuation based on continues monitoring |
| Phenotypes | In terms of timing and effectiveness:<br>– Collaboration between stakeholders in a time-pressured conditions<br>– Dealing with extra issues such as traffic management and stress circumstances<br>– Communication between involved organisations and with the community during the evacuation process (clarifying why, how and when, options and magnitude of situation) |

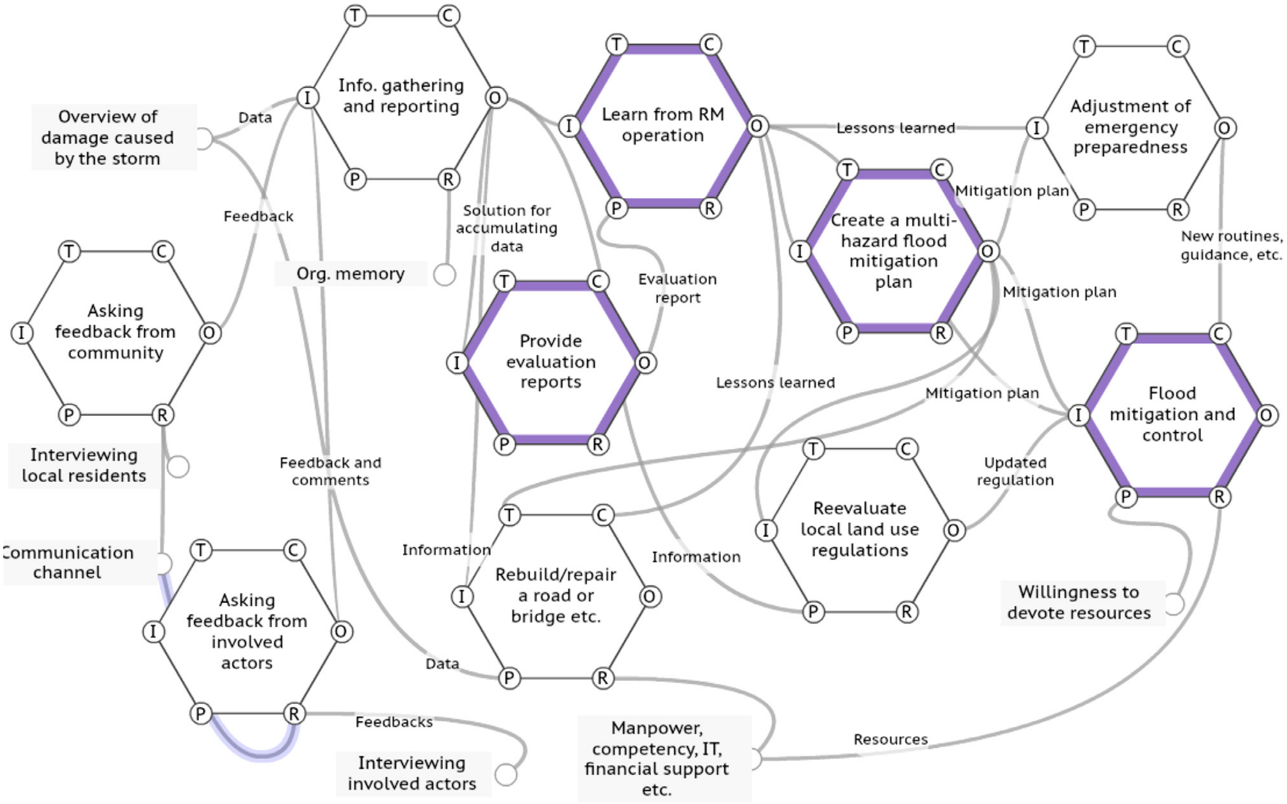

**Fig. 10.** FRAM instantiation for the restoration phase.

During the restoration phase, learning is an essential element. Activities during a previous response process need to be scrutinised and evaluated to improve the entire RM process and prepare for the next flood. Such a process can be understood as "crisis-induced learning" [12,26,70]. Understanding what worked well in a previous response process, and what did not, what aspects of emergency plans should be changed, enhances organisations' ability to deal with a crisis [44]. However, learning is a challenging task, as it is not usually linear or straightforward. Involved actors may have different opinions, strategies, and political agendas on how a crisis was managed and how the system can be improved [40]. Here, adaptation is the most vital resilience capacity. Lessons from recovery operations provide updated data that can enhance capacity building and enable that capacity to be used to improve responses to flooding. Lessons learned also imply how well the RM system works, whether the flood risk profile is changing, and whether a further alternative response strategy is required. The answers also highlight whether the municipality needs to adjust/update plans. Learning, here, is about how key actors in the municipality translated their experience during a flood event into useful knowledge for future events, and the action the municipality will take based on its newly acquired knowledge. The lessons learned could be used to streamline the RM process and improve flood risk prevention/mitigation measures in terms of "reforming contingency planning and training to enhance resilience in the event of similar episodes in the future" ([13]: 236).

## 5. Discussion

The FRAM application (Section 4) revealed important aspects of resilience within the municipality's flood RM system. As the complexity and uncertainty associated with flood events increases, the capability to anticipate and monitoring become increasingly vital, and therefore, understanding how to foster these capacities within the system also becomes critical. Regarding the function "Framing of flood risks" (Fig. 4), the model reveals the widespread couplings that must be operationally ensured, to produce a "flood context" that effectively and proactively supports risk management. This function is closely related to the development of a common understanding of what to be expected in terms of flood events and their potential impacts. Keeping in mind the definition of the four resilience capacities in Hollnagel [[38]: 26], the interdependencies in Fig. 4 outlines how the "ability to anticipate" can be explored at a system level. The "ability to monitor" takes into account any "imaginable" surprises, that may extend beyond known risk factors. This is conventionally achieved through buffer capacities and contingency plans, which in turn, are grounded on "risk and vulnerability analysis". The FRAM model not only provided insights on the operational complementarity between anticipation and monitoring capacities but also highlighted many aspects that are needed to enhance contingency planning (Fig. 6). For instance, the control aspect of the function "Prepare contingency plan" emphasise that a predefined procedure on protecting life and property, regulates priorities in the contingency plan.

Flood RM is a dynamic process, comprising functions that involve a broad range of technological, organisational, and human activities. Lagadec [46] refers to such a complex operational environment as a "kaleidoscope" (p.22). It indicates that even a small variation in functions, affect the entire RM process through highly interdependent system elements. For instance, variation in aspects of the "flood risk context" (i.e. changes in standards, stakeholders, infrastructure, flood map, land use, and land cover within a floodplain) would impact the outcome of "framing flood risk" in terms of its precision. The result of framing risk (the context) shapes the course of action [57] in the entire RM system, and it influences policy and human behaviour, such as risk perceptions and priorities (see Figs. 5 and 8).

Moreover, the response-ability depends on how the responses match the requirements of the situation at hand. Updating the response plan was shown in the FRAM model to be tightly coupled to "conducting situational assessment", which strongly relies on information processing (Fig. 7). Assessing complex situations requires cognitive capabilities, as well as the ability to evaluate options and making judgment under turbulent circumstances, frequently also involving high levels of time pressure, ambiguity, and uncertainty" ([21]: 73). The variation of SA is related to its precision. Lacking, imprecise, or inadequate situation awareness might lead to poor decision making, regarding resource allocation and coordination.

FRAM has proven useful in exploring flood RM in action, and shifting focus from a cause-effect relationship (traditional RM view) to a systemic perspective. The qualitative analysis that underlines the FRAM application in this paper offers potential for the enhancement of already available quantitative and semi-quantitative approaches, namely in the scope of evacuation models. It could be done by, for example, integration of fuzzy logic with FRAM [62] or application of Monte Carlo simulation to define the resonant system functions [51].

In facing resource limitations, the rising of conflicting goals becomes inevitable. The way each stakeholder trades-off such goals is closely related to how they perceive their operational environment and the demands it imposes [34]. Hence, coordination becomes vital to generate a shared understanding of operational conditions. The functional perspective provided by FRAM facilitates this understanding, where the roles interact with each other vertically across multiple layers, as well as horizontally over different scopes of responsibility [47]. This point highlights that distribution of information, the efficiency of shared process and actions, the appropriateness of resources, mapping interdependencies (e.g., through the application of FRAM) are the main features to managing flood risk in a resilience manner. Lack of formal coordination process increases uncertainty, which leads to disorder when the situation gets exaggerate. One of our participants highlighted this point as follows:

> "When a crisis hits, it is important to stick to our contingency plan. We don't have time to reorganise, re-plan and provide new arrangements. We should focus on our predefined tasks to manage the situation. It is, therefore, decisive for all the actors involved to understand their task. The key is having clarification regarding certain functions during responses."

The argument made above by our informant is in line with the Threat Rigidity Hypothesis (TRH) [64]. THR suggests that in stressful and unmanageable situations (e.g., a flood event) leaders tend to respond with rigidity, as they struggle with restrictions in information processing and constrictions of control. They tend to rely on previous experience and known response patterns and thus take in less information [61], and also centralise decision making and control in the emergency operation process. On the other hand, openness and flexibility are widely regarded as necessary attributes of resilient systems. Those who work at the front-end face a stream of challenges that call for practical problem-solving. This requires, however, an adaptive capacity in terms of improvisation [45].

Predefined tasks are mainly based on underlying assumptions about the working environment. Nevertheless, strongly relying on assumptions might lead to an oversimplification of the complexity and uncertainty involved in a situation. It may even lead to paralysis (an expression of brittleness) when unanticipated problems emerge since more prescribed responses tend to leave less room for decentralised influence, decision making, and improvisation. In the face of such scenarios, resilience aims to generate graceful extensibility [72], which means that systems extend their capacity to operate, despite facing extreme pressures.

Moreover, while decision making is pivotal in the response process, decisions should be communicated to actors and the community. One challenge in communicating decisions is "formulating the decision" in a way the targeted audience can understand. Conflicting information as well as "information overload and channel bottlenecks" [55] create problems in communicating decisions. As Ansell and Boin [1] put it, breakdowns in communication, when different actors communicate different messages to the public, undermine response organisations' ability to assess and reassess the situation in a timely manner. Regarding evacuation, for instance, it is crucial to inform the intended targets "why they should be evacuated". Proper communication facilitates compliance with plans, which contributes to a successful evacuation process. Communicating flood risk requires a flow of information, which is provided by municipal authorities and shared on the municipal website, in the general media, on Facebook pages, and Twitter. In general terms, some of the key elements inherent in a successful evacuation process are the emergency management's adaptive behaviour, trust-building, and the inclusion of different resources. In confronting challenges and issues regarding evacuation, one of our participants shared his experience from the Synne storm:

> "We were aware that an evacuation of the elderly would require time and the employment of several people. We decided to empty the building before an eventual flood would damage it or make the evacuation more challenging. To avoid such issues regarding the evacuation of residents at the Lundeåne Housing and Service Centre, which is a home for mainly elderly people, we asked their families to pick them up. Soon afterwards, they were mostly removed by their families. Involving families in advance of evacuation was not a part of our contingency plan."

The point made above draws attention to a culture of cooperation and seeking solutions and reflects on the ability to adapt to change. It highlights that although planning is crucial in the response process, it should not be rigid, as mentioned earlier. Hollnagel [36] argues that to meet challenges and match current conditions and demands when performing predefined tasks, adjusting the course of action (performance variability) is inevitable. Successes and mistakes due to improvisation provide learning opportunities. Improvisation, on the other hand, has its dynamics and challenges that arise from inter- and intra-organisational relationships between different actors involved in risk management activities. It depends on the decision-makers' ability and authorisation to allocate and prioritise necessary resources as well as implement them. Organisational politics and advocacy may interfere with practical problem solving and resource allocation. This might lead to increased centralisation of decision making, which in turn may weaken the capacity to improvise at the front.

Implementation of risk mitigation- prevention measures are often very costly and calls for new regulations, compliance, administration, maintenance, and restoration issues, such as the construction of community shelters or building higher and longer bridges to reduce the vulnerability of the railway infrastructure. The willingness to devote resources to implement measures is a prerequisite to mitigate flood risk. Along with economic factors, the following elements may shape variability in flood risk mitigation and control: lack of capacity for change (reorganisation, restructuring, etc.); decision maker's risk perception and socio-cultural issues (e.g., the willingness of the community to leave the flood-prone area and be permanently relocated, and lack of social support for flood victims) and low levels of political support. In reflecting on these points, one of our participants stated that:

> *"A long-term priority to devote resources to risk management in the municipality is crucial, given the extreme weather. This priority is driven mainly by political and administrative roles in the municipality."*[1]

Flood risk mitigation requires that the responsible authorities continuously monitor and update data due to the dynamic nature and complexity of flood RM. Through continuous learning from experience and recovery operations, the local authorities acquire updated data that can enhance capacity building and use it to improve responses to flooding. Variabilities in flood mitigation and control, however, may generate new hazards, which affect the quality of the flood RM process.

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[1] The quotation has been mildly edited with small changes in order to increase the clarity of the writing.

Hence, in identifying the desired and undesired variability in flood risk mitigation, we need to consider the variability of other upstream functions in the entire RM process.

## 6. Conclusion

This study outlined and discussed some of the challenges in enhancing resilience within flood RM. Resilience engineering has shown to be a useful conceptual framework to highlight critical aspects of RM processes that were poorly addressed, in particular when considering the need to adjust to a wide range of specific and often unpredictable local conditions. Enhancing a municipality's adaptive capacity is vital for dealing with variability and uncertainty. Flood RM is a complex system consisting of many interdependent functions that continuously evolve throughout different timescales.

The Functional Resonance Analysis Method (FRAM) provided deep insights into resilience capabilities based on a systemic perspective. The description of functional variability was shown to have potential widespread impacts across the whole flood RM system. Coping with uncertainty in flood RM entails the following issues: effective communication channels between different stakeholders; bidirectional communication flows supported by profound intelligence (information); continuous measurements, forecasting and functions evaluations; flexible planning; iterative processes of flood risk controls; a range of uncertainty analyses and autonomous strategic initiatives. The risk-mitigation and control strategies should be continuously confronted by emerging information and the unfolding pattern of actions (functions' variation).

Our analysis was conducted for two specific municipal's contexts (Stavanger and Egersund). Future research application of FRAM, regarding flood RM, might be conducted in a broader context. For instance, the analysis takes into account the interrelation between different response authorities, and explore how variability in anticipation and monitoring of critical elements, might affect the flood RM process from a holistic view.

## 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.

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## References

[1] Ansell C, Boin A. Taming deep uncertainty: The potential of pragmatist principles for understanding and improving strategic crisis management. Admin Soc 2019;51(7):1079–112https://journals.sagepub.com/doi/pdf/10.1177/0095399717747655.
[2] Anvarifar F, Voorendt MZ, Zevenbergen C, Thissen W. An application of the Functional Resonance Analysis Method (FRAM) to risk analysis of multifunctional flood defences in the Netherlands. Reliab Eng Syst Safety 2017;158:130–41. https://doi.org/10.1016/j.ress.2016.10.004.
[3] Argote L. Input Uncertainty and Organisational Coordination in Hospital Emergency Units. Adm Sci Q 1982;27(3):420–34. https://doi.org/10.2307/2392320.
[4] Aven T. Risk assessment and risk management: review of recent advances on their foundation. Eur J Oper Res 2016;253(1):1–13. https://doi.org/10.1016/jejor201512023.
[5] Aven T, Thekdi S. The Importance of Resilience-Based Strategies in Risk Analysis, and Vice Versa. In: Trump BD, Florin M-V, Linkov I, editors. IRGC resource guide on resilience (Volum 2): Domains of resilience for complex interconnected systems. Lausanne, Switzerland: International Risk Governance Council (IRGC); 2018. p. 33–8.
[6] Aven T. Improving the Foundation and Practice of Uncertainty Analysis: Strengthening Links to Knowledge and Risk. In: Aven T, Zio E, editors. knowledge in risk assessment and management. John Wiley & Sons; 2018. p. 103–25. ISBN 9781119317890.
[7] Aven T. The Science of Risk Analysis: Foundation and Practice. Routledge; 2020.
[8] Azadeh A, Salehi V, Arvan M, Dolatkhah M. Assessment of resilience engineering factors in high- risk environments by fuzzy cognitive maps: A petrochemical plant. Saf Sci 2014;68:99–107. https://doi.org/10.1016/j.ssci.2014.03.004.
[9] Belmonte F, Schön W, Heurley L, Capel R. Interdisciplinary safety analysis of complex socio-technological systems based on the functional resonance accident model: An application to railway traffic supervision. Reliab Eng Syst Safe 2011;96:237–49. https://doi.org/10.1016/j.ress.2010.09.006.
[10] Boin A, Lodge M. Designing resilient institutions for transboundary crisis management: A time for public administration. Public Admin 2016;94(2):289–98. https://doi.org/10.1111/padm.12264.
[11] Boin A, Van Eeten MG. The Resilient Organisation. Public Manage Rev 2013;15(3):429–45. https://doi.org/10.1080/14719037.2013.769856.
[12] Boin A. Crisis management. 2017. Access https://www.britannica.com/topic/crisis-management-government.
[13] Boin A, Hart P, Stern E, Sundelius B. The politics of crisis management: public leadership under pressure. 2nd edn. Cambridge: Cambridge University Press; 2017.
[14] Christensen T, Lægreid P. Coordination Quality in Central Government – the Case of Norway. Public Org Rev 2019;1. https://doi.org/10.1007/s11115-018-00434-0.
[15] Cinner JE, Adger WN, Allison EH, Barnes ML, Brown K, Cohen PJ, ... Morrison TH. Building adaptive capacity to climate change in tropical coastal communities. Nature Climate Change 2018;8(2):117–23.
[16] Clay-Williams R, Hounsgaard J, Hollnagel E. Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines. Implement Sci 2015;10(1). https://doi.org/10.1186/s13012-015-0317-y.
[17] Cutter S, Osman-Elasha B, Campbell J, Cheong SM, McCormick S, Pulwarty R, Arnall A. Managing the risks from climate extremes at the local level. 2012https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap5_FINAL-1.pdf.
[18] DasGupta R, Shaw R. An indicator based approach to assess coastal communities' resilience against climate related disasters in Indian Sundarbans. J Coast Conserv 2015;19(1):85–101. https://doi.org/10.1007/s11852-014-0369-1.
[19] de Bruijn K, Buurman J, Mens M, Dahm R, Klijn F. Resilience in practice: Five principles to enable societies to cope with extreme weather events. Environ Sci Policy 2017;70:21–30. https://doi.org/10.1016/j.envsci.2017.02.001.
[20] de Carvalho PVR. The use of Functional Resonance Analysis Method (FRAM) in a mid air collision to understand some characteristics of the air traffic management system resilience. Reliab Eng Syst Safe 2011;96:1482–98. https://doi.org/10.1016/j.ress.2011.05.009.
[21] Dekker, S. (2015). Safety Differently: Human Factors for a New Era, Second Edition (2nd edn.): London: CRC Press.
[22] DSB. The Norwegian Directorate for Civil Protection: Guidance to holistic risk and vulnerability assessment in the municipality. 2019. Norway, Tønsberg https://www.dsb.no/globalassets/dokumenter/brann-og-redning-bre/skogbrannhelikopter/2019/guidance_to_holistic_risk_and_vulnerability_assessment_in_the_municipality.pdf.
[23] Eigersund Municipality. Beredskapsplan Eigersund Kommune. 2014. In Norwegian file:///C:/Users/a1210168/Downloads/Beredskapsplan_Eigersund_kommune_til_h%C3%B8ring.pdf.
[24] Eigersund Municipality. Evaluering etter ekstremværet Synne 05.208;06.12.15. 2016. In Norwegian https://www.eigersund.kommune.no/getfile.php/3469098.1621.staytvcuae/K-sak+26-2015+-+Evaluering+etter+ekstremv%C3%A6ret+Synne+05.+-+06.12.15+%28L%29%28715510%29.pdf.
[25] Eisner EW. The Enlightened Eye: Qualitative Inquiry and the Enhancement of Educational Practice. NY: Teachers College Press; 2017.
[26] Elliott D, Macpherson A. Policy and Practice: Recursive Learning From Crisis. Group Org Manage 2010;35(5):572–605. https://doi.org/10.1177/1059601110383406.
[27] Ferreira P. Resilience in the planning of rail engineering work. 2011. (Doctoral dissertation, University of Nottingham).
[28] Ferreira P, Cañas JJ. Assessing operational impacts of automation using functional resonance analysis method. Cognition, Technology & Work 2019;21-3:535–52. https://doi.org/10.1007/s10111-019-00540-z. Vol.
[29] Gharajedaghi J. Systems Thinking: Managing Chaos and Complexity: A Platform for Designing Business Architecture (3. utg.). Amsterdam: Elsevier Science; 2011.
[30] Giulio DG, Riccardo P, Francesco C, Ivan S. Safety Assessment for an ATM System Change: A Methodology for the ANSPs. Promet – Traffic Transp 2017;29(1):99–107. https://doi.org/10.7307/ptt.v29i1.2121.
[31] Goessling-Reisemann S, Thier P. On the difference between risk management and resilience management for critical infrastructures. In: Ruth M, Goessling-Reisemann S, editors. Handbook on Resilience of Socio-Technical Systems. 2019. p. 117–35.
[32] Herrera IA, Woltjer R. Comparing a multi-linear (STEP) and systemic (FRAM) method for accident analysis. Reliab Eng Syst Safe 2010;95:1269–75. https://doi.org/10.1016/j.ress.2010.06.003.
[33] Hollnagel E. Barriers and Accident Prevention. Aldershot, UK: Ashgate Publishing, Ltd; 2004.
[34] Hollnagel E. The ETTO principle: efficiency-thoroughness trade-off - Why things that go right sometimes go wrong. Aldershot, UK: Ashgate; 2009.
[35] Hollnagel E. Epilogue: RAG- The Resilience Analysis Grid. In: Hollnagel E, Pariès J, Wreathall J, Woods DD, editors. Resilience engineering in practice: A guidebook. Farnham, UK: Ashgate; 2011. p. 275–96.

[36] Hollnagel E. FRAM: The Functional Resonance Analysis Method: Modelling Complex Socio-technical Systems. Farnham: Ashgate Publishing Ltd; 2012. Farnham.

[37] Hollnagel E. A FRAM Glossary. 2016http://functionalresonance.com/a-fram-glossary.html.

[38] Hollnagel E. Safety-II in Practice - Developing the Resilience Potentials. Routledge; 2018.

[39] Hollnagel E, Hill R. Instructions for use of the FRAM Model Visualiser (FMV). 2018 Available at http://functionalresonance.com/tools-visualisation/fram-visualisation.html.

[40] Hood C. What happens when transparency meets blame-avoidance? Public Manage Rev 2007;9(2):191–210. https://doi.org/10.1080/14719030701340275.

[41] ISO 31000. Risk management. Principles and guidelines. Geneva: International Organisation for Standardisation; 2018.

[42] Jamrussri S, Toda Y. Available flood evacuation time for high-risk areas in the middle reach of Chao Phraya River Basin. Water 2018;10(12):1871.

[43] JD. Guidance for social security instructions. 2019. In Norwegian https://www.regjeringen.no/no/dokumenter/veileder-til-samfunnssikkerhetsinstruksen/id2666864/?ch = 1.

[44] Kayes DC. Organisational Resilience: How Learning Sustains Organisations in Crisis, Disaster, and Breakdown. Oxford: Oxford University Press USA - OSO; 2015.

[45] Klein G. A naturalistic decision making perspective on studying intuitive decision making. J Appl Res Memory and Cognition 2015;4(3):164–8. https://doi.org/10.1016/j.jarmac.2015.07.001.

[46] Lagadec P. Preventing chaos in a crisis: strategies for prevention, control and damage limitation. London, UK: McGraw-Hill; 1993. (J.MPhelps,Trans).

[47] Park J, Seager TP, Rao PSC, Convertino M, Linkov I. Integrating risk and resilience approaches to catastrophe management in engineering systems. Risk Anal 2013;33(3):356–67. https://doi.org/10.1111/j.1539-6924.2012.01885.x.

[48] Parsons M, Glavac S, Hastings P, Marshall G, McGregor J, McNeill J, ... Stayner R. Top-down assessment of disaster resilience: A conceptual framework using coping and adaptive capacities. International Journal of Disaster Risk Reduction 2016;19:1–11https://www.sciencedirect.com/science/article/pii/S2212420916300887?via%3Dihub.

[49] Patriarca R, Bergström J. Modelling complexity in everyday operations: functional resonance in maritime mooring at quay Cognition. Tech Work 2017;19:711–29. https://doi.org/10.1007/s10111-017-0426-2.

[50] Patriarca R, Di Gravio G, Costantino F. myFRAM: An open tool support for the functional resonance analysis method 2017. p. 439–43. https://doi.org/10.1109/ICSRS.2017.8272861. 2nd International Conference on System Reliability and Safety (ICSRS), Milan, 2017.

[51] Patriarca R, Di Gravio G, Costantino F. A Monte Carlo evolution of the Functional Resonance Analysis Method (FRAM) to assess performance variability in complex systems. Saf Sci 2017;91:49–60. https://doi.org/10.1016/j.ssci.2016.07.016.

[52] Patriarca R, Falegnami A, Costantino F, Bilotta F. Resilience engineering for socio-technical risk analysis: Application in neuro-surgery. Reliab Eng Syst Safe 2018;180:321–35. https://doi.org/10.1016/j.ress.2018.08.001.

[53] Patton MQ. Qualitative research & evaluation methods. 3rd edn Thousand. Oaks, Calif: Sage Publications; 2002. utg.

[54] Pescaroli G, Alexander D. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Natural Hazards 2016;82(1):175–92https://link.springer.com/article/10.1007/s11069-016-2186-3.

[55] Pursiainen C. The crisis management cycle. New York: Routledge; 2018.

[56] Praetorius G, Hollnagel E, Dahlman J. Modelling Vessel Traffic Service to understand resilience in everyday operations. Reliab Eng Syst Safe 2015;141:10–21. https://doi.org/10.1016/j.ress.2015.03.020.

[57] Restemeyer B, van Den Brink M, Woltjer J. Resilience unpacked - framing of 'uncertainty' and 'adaptability' in long-term flood risk management strategies for London and Rotterdam. Eur Plan Stud 2018;26(8):1559–79https://doi.org/10.1080/09654313.2018.1490393.

[58] Rogaland County Governor. Evalueringsrapport: Ekstremvêret Synne 5-6 Desember 2015. 2016. In Norwegian.

[59] Rosa L, Haddad A, Carvalho P. Assessing risk in sustainable construction using the Functional Resonance Analysis Method (FRAM) Cognition. Technology & Work 2015;17:559–73. https://doi.org/10.1007/s10111-015-0337-z.

[60] Saurin T. Removing Waste While Preserving Slack: The Lean and Complexity Perspectives. 2017. Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC). https://www.researchgate.net/publication/318106992.

[61] Seeger MW, Sellnow TL, Ulmer RR. Communication and Organizational Crisis. Westport: Greenwood Publishing Group, Incorporated; 2003. Westport.

[62] Slim H, Nadeau S. A Proposal for a Predictive Performance Assessment Model in Complex Sociotechnical Systems Combining Fuzzy Logic and the Functional Resonance Analysis Method (FRAM). Am J Indust Busi Manage 2019;9:1345–75. https://doi.org/10.4236/ajibm.2019.96089.

[63] Spaaij R. Understanding lone wolf terrorism: Global patterns, motivations and prevention. Springer Science & Business Media; 2011. https://doi.org/10.1007/978-94-007-2981-0.

[64] Staw BM, Sandelands LE, Dutton JE. Threat Rigidity Effects in Organizational Behavior: A Multilevel Analysis. Adm Sci Q 1981;26(4):501–24.

[65] Stebbins, R. A. (2001). Exploratory research in the social sciences (Vol. 48). Thousand Oaks, CA: Sage. doi:10.4135/9781412984249.

[66] Steen R, Morsut C. Resilience in Crisis Management at the Municipal Level: The Synne Storm in Norway. Risk, Hazards & Crisis in Public Policy 2019. https://doi.org/10.1002/rhc3.12178.

[67] Steen R. On the application of the Safety-II concept in a security context. Eur J Secur Res 2019;4(2):175–200.

[68] Stern E. Crisis and Learning: A Conceptual Balance Sheet. J Contingen Crisis Manage 1997;5(2):69–86. https://doi.org/10.1111/1468-5973.00039.

[69] Toth E, Brath A, Montanari A. Comparison of short-term rainfall prediction models for real-time flood forecasting. J Hydrol 2000;239(1–4):132–47. https://doi.org/10.1016/S0022-1694(00)00344-9.

[70] Veil S. Mindful learning in crisis management. J Busi Commun 2011;48(2):116–47. https://doi.org/10.1177/0021943610382294.

[71] Woods DD. Four concepts for resilience and the implications for the future of Resilience Engineering. Reliab Eng Syst Safe 2015;141:5–9.

[72] Woods DD. The theory of graceful extensibility: basic rules that govern adaptive systems. EnvironSyst Deci 2018;38:433–57. https://doi.org/10.1007/s10669-018-9708-3.